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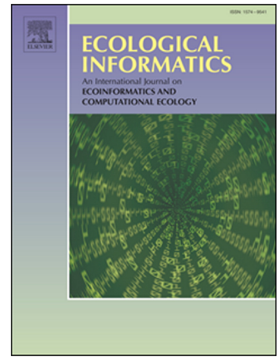

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Decision support framework for the prioritization of coral reefs in the U.S. Virgin Islands

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Abstract

The coral reef ecosystems of the U.S. Virgin Islands are some of the most intensively surveyed and threatened tropical ecosystems on earth. These coral reefs vary widely in terms of biophysical structure, seascape context, socio-economic value and exposure to threats presenting a complex challenge for resilience-based management. How and where should managers prioritize actions to maximize conservation outcomes? To meet multiple conservation objectives, a novel map-based decision-support tool was designed which synthesized large amounts of data to help managers identify and rank coral reefs according to multiple ecological qualities, ecosystem services and threats. The spatial framework integrates local expert knowledge from SCUBA divers, scientific field data and spatial models to characterize and rank priority coral reefs. With user-defined flexibility, the tool provides information to guide management processes such as risk assessments of coastal development, management of protected areas, site selection in science and monitoring design, broader marine spatial planning and community education and outreach.

Keywords: coral reefs, Caribbean, spatial predictive modeling, management, prioritization, decision-support tool

1. Introduction

The coral reef ecosystems of the United States Virgin Islands (USVI) provide a wide range of locally valuable ecosystem services including tourism and recreational uses, commercial and subsistence fisheries, coastal protection, and education and research services, with an estimated total economic value of over 200 million US$ per year (van Beukering et al. 2011). In the past few decades, however, coral reef condition has deteriorated across the USVI, and the broader Caribbean Basin, due to elevated water temperatures causing coral death and disease followed by excessive algal growth and reductions in structural complexity (Rogers & Miller 2006, Alvarez-Filip et al. 2009). In addition, declines in herbivores, increased runoff from land and impacts from fishing and other human uses have resulted in cumulative stress that has negatively affected coral reef quality and resilience (Rogers & Beets 2001, Smith et al. 2008, Rothenberger et al. 2008, Eakin et al. 2010). The problem, however, is geographically uneven across the region, with complex spatial heterogeneity in the exposure to stressors and in the ecological response of coral reef organisms to environmental change. For example, within the scale of the insular shelf of the USVI, coral reefs exhibit a wide range of biophysical characteristics and patterns of exposure to stressors, which vary with distance to shore, wave exposure and depth.

Limited resources for marine management can often result in difficult decisions made on exactly how and where to focus management actions. Typically, in coral reef conservation, identifying priority areas helps to focus strategic planning and management actions on places that are of the greatest ecological value and in greatest need of protection (Myers et al. 2000, Roberts et al. 2002). Equally, it is also useful to identify those places that are of lowest conservation concern, or some other range of values on the prioritization spectrum (i.e., hot spots through warm spots to cold spots). Conservation strategies benefit from consideration of both the most impacted coral reefs and those coral reefs with greatest propensity for resistance and resilience - the so-called 'reefs of hope' (McClanahan et al. 2009). Helping managers identify key assets in the coral reef conservation portfolio and evaluate the risk of asset loss, depreciation or appreciation, supports the development of an investment portfolio for coral reef futures that has potential to mitigate risk and lead to higher long-term performance.

Both conceptually and operationally, spatial prioritization of coral reefs for conservation action is a multiple-criteria decision-making problem. Comprehensive and reliable spatial information on ecological priorities and threats is crucial to effective geographical prioritization and avoids speculative uninformed decisions. Inevitably, inefficient decisions on where and how to prioritize management actions can result when information is patchy in geographical distribution, quality and comprehensiveness (Klein et al. 2010, Caldow et al. 2014). National legal frameworks, such as the Endangered Species Act (ESA); the Clean Water Act; Coastal Zone Management Act; and at the territorial level the Virgin Islands Code, dictate some of the criteria for prioritization frameworks. Furthermore, local community initiatives such as Local Action Strategies in the United States also guide selection of candidate features for inclusion in prioritization. In the U.S. Virgin Islands, geographical priority setting has typically been consensus-based prioritization with allocation of conservation efforts occurring with inherent geographical and thematic bias.

Making decisions informed by the best-available science is an objective for many organizations managing the environment, yet scientific information is still not widely used in environmental policy and practice due to lack of access to information and integration into decision frameworks (Pullin & Knight 2001, Segan et al. 2011, Dicks et al. 2014). With an increasing need to apply evidence-based decision-making in marine management (Cooke et al. 2017), such as spatial planning and prioritization of limited resources for threat reduction in coral reef conservation (Magris et al. 2017), software-based tools offer valuable decision-support that can lead users through clear steps and suggest optimal decision paths, or simply act as information sources to improve the evidence base for decisions (Rose et al. 2016).

To support future strategic spatial planning and to make available data easily accessible to decision makers, we have developed an objective, data-driven prioritization tool for coral reefs designed to support the judicious use of limited resources for effective conservation actions. This project created a conceptual and operational framework encompassing data from land and sea, to spatially characterize and subsequently identify, map and rank coral reefs and the primary threats to coral reefs to help managers assess risk and prioritize conservation actions. Spatial prioritization methods improve the efficiency of decision-making by explicitly considering cumulative impacts across the management jurisdiction and when ecosystem service values are incorporated these tools can effectively assess trade-offs between conservation and development in spatial planning (Whitehead et al. 2016).

When implemented within a web-based map service, the framework becomes a tool capable of incorporating decision makers' preferences using a flexible, transparent and repeatable approach to support ecologically (and economically) efficient allocation of scarce conservation resources in a way that is defensible within the context of data limitations. Flexibility in the user interface advances adaptive management and forward planning (Laniak et al. 2013). Here we present descriptions of the prioritization framework, associated techniques, the data types used, and a web-based mapping tool to identify, characterize, assign relative importance and rank coral reefs.

2. Methods

2.1 Project area.

The U.S. Virgin Islands is an unincorporated United States territory comprised of three main islands (St. Thomas, St. John and St. Croix) within the Virgin Islands Archipelago in the Eastern Caribbean (Figure 1). The planning area for this project included island landscapes and extended seaward to the edge of the insular shelf. Nearshore seascapes are composed of a spatially heterogeneous mosaic of patch reefs, seagrasses, sand and coastal mangroves. Offshore reefs extend to the deep sloping seafloor of the shelf edge (mesophotic reefs >30 m deep), with high coral cover over which important multi-species fish spawning aggregations occur (Smith et al. 2010). These seascapes support diverse and highly productive communities of marine organisms with over 40 species of coral, including several listed under the Endangered Species Act, more than 400 species of fish, four species of sea turtle and at least eleven species of cetaceans.

Despite establishment of marine protected areas (MPAs) and other conservation actions, the amount of living coral has declined in the past 30 years and populations of large-bodied fishes, including the largest grouper, snapper and parrotfish species are increasingly rare. Corals have suffered widespread mortality due to the damage caused by seven major hurricanes in the past 20 years, three severe bleaching and disease events caused by elevated seawater temperature, a sea-urchin die-off in the 1970s, and continual stress from land-based sources of pollution.

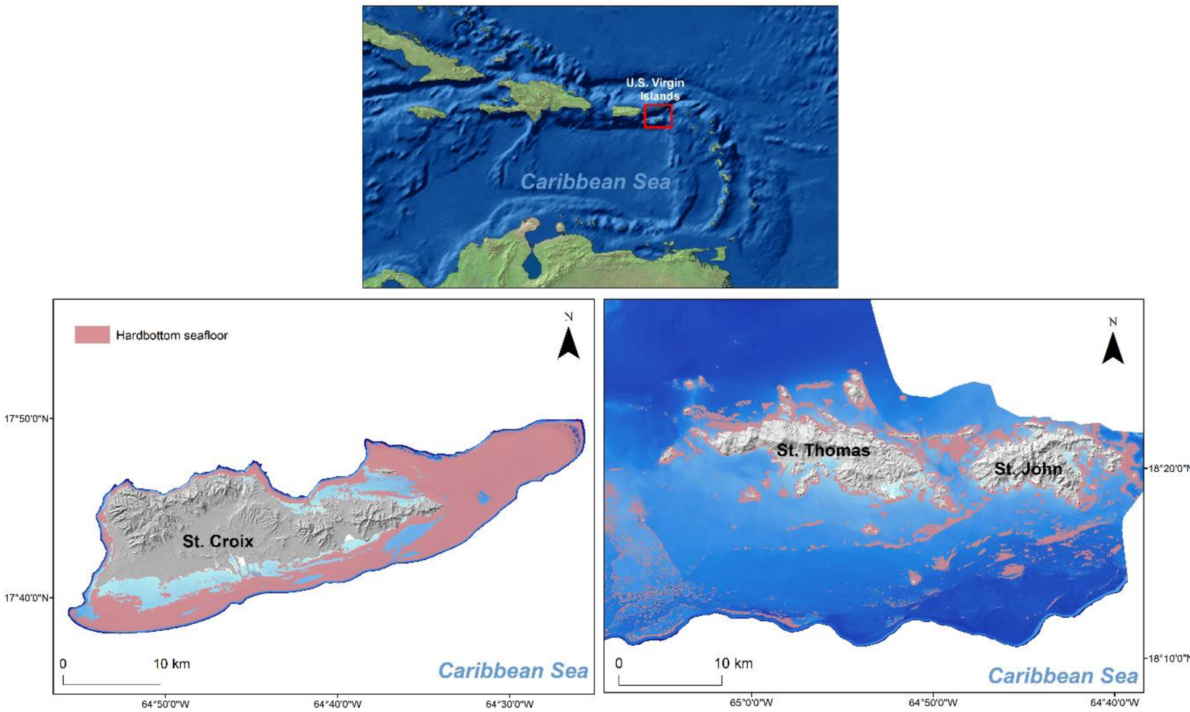

Figure 1. U.S. Virgin Islands, showing predicted coral reefs across the shelf of the three main islands (St. Thomas, St. John and St. Croix).

Ecological performance evaluations of three Federal marine protected areas of the USVI, using a decade of comprehensive monitoring data, revealed no significant increase in fish biomass and live coral cover (Pittman et al. 2014). Considerable government funding have been directed at identifying, monitoring and mediating threats to coral reefs resulting in the USVI being one of the most intensively studied coral reef ecosystems in the Caribbean.

2.2 Framework structure

Using techniques from landscape ecology, geoscience, marine ecology, sociology and decision science, we developed an inclusive and holistic perspective to framework construction, which we refer to as the 'no reef left behind' approach. That is, the starting place in our coral reef prioritization was to objectively identify and map all spaces capable of supporting coral reefs without discriminating on any ecological or socio-economic criteria and then to allow the user to select layers of attributes (ecological, economic, threats) to add numeric values to individual reef cells which then rank coral reefs numerically. To ensure the framework was suitable to address a wide range of management issues, we worked with marine managers to design a framework that facilitated a question-driven approach to prioritization, whereby the user selects the appropriate criterion, or set of criteria, with which to rank coral reefs (Figure 2). For example, through user-defined selections, the tool can identify and prioritize coral reefs according to cumulative threats, or reefs where legally protected coral species were known to exist, or highest biodiversity reefs with greatest exposure to ship traffic, etc. Operationalizing the framework as a map-based decision support tool required a two-pronged approach to data collection and analyses: 1.) synthesis existing field survey data and spatial models; and 2.) new data from local ecological knowledge.

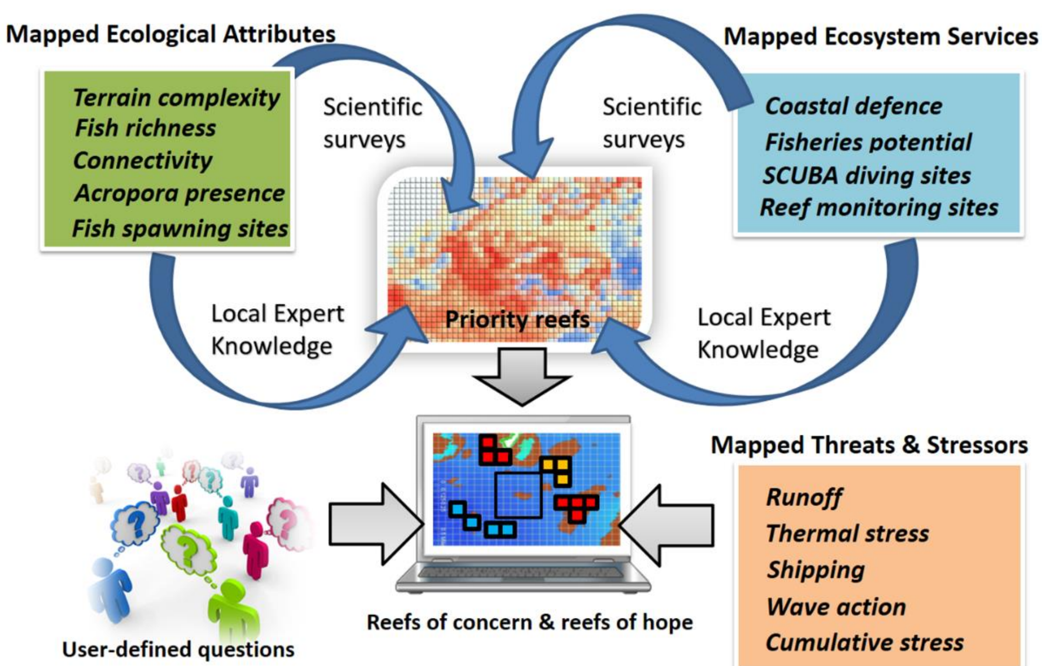

Figure 2. Key data types used to spatially characterize and prioritize coral reefs of the U.S. Virgin Islands based on ecological attributes, ecosystem services and exposure to stressors. Data acquired from underwater surveys, remote sensing and mapping, spatial modeling and local expert knowledge of coral reefs.

To fill spatial data gaps, we applied advanced spatial predictive mapping techniques using non-linear machine learning algorithms including MaxENT (Maximum Entropy Modeling; Elith et al. 2011) and Boosted Regression Trees (Elith et al. 2008) together with spatial modeling in a Geographical Information System. We also recognized that data gaps existed for un-surveyed reefs that, in part, could be addressed with the great wealth of observations made over many years by the USVI occupational SCUBA diving community. As such, a local ecological knowledge (LEK) survey was also conducted using another custom-built map tool to gather spatially-explicit diver recollections of the biophysical characteristics and perceived threats to specific coral reefs.

2.2.1 Survey data and numerical spatial modeling

Key spatial biophysical patterns across island landscapes and seascapes were mapped from point data from underwater field surveys, and broader-scale terrain and habitat mapping from ship and aerial remote sensing. Spatial predictive mapping techniques using sophisticated nonlinear machine learning algorithms were applied to map continuous surfaces in both two (benthic habitat maps) and three-dimensional space (terrain models). Data were of mixed resolution and geographical extent and therefore all data were re-sampled to populate a final analysis grid with a cell resolution of 100 x 100 m (0.01 km^2), a spatial scale relevant to the operational scales of a wide range of users.

2.2.2 Local ecological knowledge

To collect local ecological knowledge (LEK) on coral reef biophysical characteristics, condition and use, this project developed an online map-based survey tool to collect information on coral reefs in the USVI from occupational SCUBA divers (Loerzel et al. 2016). The map application used a Google® maps interface where participants could drag and drop digital markers onto a map of the USVI (Figure 3). 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. The reef characteristics included variables that overlapped with modeled variables to enable comparative analyses between the recollections from in-water observations and the spatial proxies for similar variables provided by scientific surveys and predictive mapping.

Figure 3. Screen shot of the map-based tool used to help the occupational SCUBA divers of the USVI share their knowledge of coral reefs.

2.3 Data descriptions

2.3.1 Bathymetry and the mapping of coral reefs

A 20 x 20 m resolution bathymetry dataset for the USVI was created by integrating historical sounding data from hydrographic surveys with more recently collected higher resolution bathymetric data from multibeam sonar and LiDAR. Sounding data was downloaded from the NOAA NCEI Bathymetric Data Viewer (http://maps.ngdc.noaa.gov/viewers/bathymetry). A unified point dataset was generated from the multibeam sonar, LiDAR, and sounding data, quality checked and interpolated to predict a continuous, gridded bathymetry dataset and corresponding uncertainty estimates.

2.3.2 Quantifying and mapping ecological attributes

Topographic complexity of coral reef terrain. Topographic complexity was quantified and mapped by applying a slope-of-the-slope morphometric to the digital bathymetry using a Geographical Information System (GIS). Slope-of-the-slope (*SoS*), a measure of terrain roughness, was calculated by creating an initial slope surface from the bathymetry and then calculating slope of the initial slope surface to create a second derivative of the bathymetry surface which represents the maximum rate of slope change between neighboring cells (Pittman et al. 2009). *SoS* has demonstrated high performance as a spatial predictor of coral reef organism distributions and diversity (Pittman et al. 2009, Pittman & Brown 2011), and functions as a metric to quality check terrain data for artifacts of remote sensing. Tool users were given the option of using only the highest (25 %) topographic complexity terrain as a criterion to prioritize coral reefs.

Fish species richness. The number of fish species were quantified between 2001 and 2015 using underwater visual surveys (n = 4,950) at spatially random locations over hardbottom habitat depicted in the NOAA benthic habitat map (Kendall 2001). Scientists with SCUBA recorded all fish observed two meters either side of a 25 m transect line during a controlled 15 minute swim at each location. These data were quality checked and processed as georeferenced point data. In addition, these data were statistically linked to environmental predictors using boosted regression trees to predictively map fish richness across the entire project area.

Structural seascape connectivity. Structural connectivity between seagrasses, mangroves and coral reefs has profound effects on the distribution and diversity of coral reef communities, ecosystem resilience and the performance of protected areas (Olds et al. 2016). Existing benthic habitat maps (NOAA) for the USVI were used to generate continuous gridded datasets of straight-line distance to seagrass and distance to mangrove and reef-to-reef distance. Coral reefs were deemed strongly connected where they existed within 300 meters of seagrasses, mangroves and other reefs. Connectivity between distinct patch types such as coral reefs and seagrasses can also be used to identify some of the structurally connected seascapes that multi-habitat species such as the ESA-listed Nassau grouper require during the early developmental stages (post settlement juvenile and sub-adults). This importance of seascape composition and configuration was recognized by Nagelkerken et al. (2013) with the term 'seascape nurseries' described as a spatially explicit seascape consisting of mosaics of patches that are functionally connected.

At the time of writing, the absence of reliable nearshore hydrodynamic models precluded the development of larval connectivity patterns into the framework.

Threatened coral species. The distributions of branching reef-building corals, *Acropora palmata* and *A. cervicornis*, were mapped from georeferenced sightings data (point data). Both species were listed as endangered under the U.S. Endangered Species Act (1973). To generate continuous data on the presence of Acroporid corals, sightings data was linked with environmental data to predictively map the likelihood of occurrence across the project area using MaxENT (Maximum Entropy Modeling). The mapped prediction represents suitable habitat conditions for the two coral species rather than confirmation of actual coral presence. In addition, the locations of confirmed sightings of acroporid corals were also available as data layers for prioritizing coral reefs.

Fish spawning areas. Known multi-species fish spawning aggregations were delineated with polygons to include the four existing shelf edge fisheries closures and surrounding coral reefs, which function as staging areas for fishes attending the aggregations (Nemeth 2012).

Index of perceived reef quality from local knowledge. The number of unique reef qualities were aggregated into indices that facilitate comparison across reef locations. The index of reef quality (IRQ) was an aggregation of seven reef quality attributes including 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. Highest scores were calculated for coral reefs assigned three or more of the reef quality attributes by occupational SCUBA divers using the participatory mapping tool.

2.3.3 Mapping ecosystem services.

Coastal protection service value. Coral reefs are the most effective natural barrier in dissipating wave energy through breaking and friction.The coastal protection value of coral reef ecosystems in the USVI is estimated at an annual value of 1.2 million US$ attributed to friction by shallow water coral structures (van Zanten et al. 2014). We used an existing map which quantified the spatial distribution of total coastal protection value (CPV) for shallow-water coral reefs (< 35 m) by integrating flood insurance rate maps (FIRMs), reef typology, a wave model and a depth-damage model (van Zanten et al. 2014).

Reef tourism service value. In the USVI, tourism accounts for 80% of the Gross Domestic Product. In 2015, the USVI hosted approximately 2.6 million visitors. The tourism-associated economic value (102 million US$ per year) attributed to shallow-water coral reefs (< 35 m) by Beukering et al. (2011) based on beach use, proximity to hotels and snorkeling and diving was used to map total reef tourism value (US$) with the premise that coral reefs closer to recreational sites are more valuable.

Potential fisheries service value. In addition to tourism and coastal defense, coral reefs provide a locally important ecosystem service by provisioning of fish biomass to the Virgin Islands people through the commercial reef fishery, with an average estimated production value of $ 3.3 million USD per year. To map fisheries value across coral reefs we first predicted biomass for adults of commercially fished species using boosted regression tree models and then multiplied predicted biomass by the local market value (USD$) for each reef cell.

Occupational SCUBA diving use service. Eighty-seven members of the occupational SCUBA diving community in the USVI provided locations for coral reefs used by them, either professionally or recreationally, with a Google-map based participatory GIS tool (Loerzel et al. 2017). The total number of individual divers that recorded information at each coral reef cell was used as a proxy for the relative importance ('best dive sites'), of these coral reefs to the local SCUBA diving community. No information on the economic value of coral reefs to the diving industry was recorded in this study.

Long-term monitoring sites. Approximately 39 reef cells (32 Territorial Coral Reef Ecosystem Monitoring Program & 7 National Park Service) were identified as valuable 'sentinel sites' because of the presence of long-term permanent scientific monitoring sites used for territorial and national reporting of coral reef status and trends to inform adaptive management. Data collection at these sites represents a substantial strategic investment for Federal and Territorial government agencies tasked with coral reef conservation, which qualifies these coral reefs as offering a monitoring service to society. Furthermore, users of the prioritization tool will be able to visualize the locations of the long term monitoring sites and can increase the weighting to allow these sites to play a more important role in the prioritization scenario. This could be useful when reviewing the existing monitoring network relative to the distribution of high bio-complexity reefs across the region, or those priority coral reefs experiencing high exposure to stress.

2.3.4 Mapping threats and stressors.

The availability of reliable spatial proxies for stressors is a major data challenge that urgently needs addressing to support attempts to understand local, regional and global threats to coral reef health. Spatial proxies for relatively broad geographical scale stressors to coral reefs were developed to map relative exposure and assess potential threats from human impacts and wave exposure. Fishing could not be represented here due to insufficient spatial resolution and quality of the fishing effort data for the region.

Thermal stress. Stress events were defined using the NOAA Coral Reef Watch Degree Heating Weeks (DHW) metric for 1985-2012 using the Pathfinder v5.2 ~4km Sea Surface Temperature dataset (NOAA Coral Reef Watch 2013). Cells with coral reefs present were identified where the bleaching-level threshold for thermal stress had been exceeded for sufficient duration to induce bleaching (i.e. DHW≥4) representing moderate to severe thermal stress.

Land-based sources of pollution. Landscape structure is one of the most important land factors influencing nutrient and organic matter runoff into the marine environment (Fabricius 2005). On steep-sided oceanic islands such as the USVI, the geology, topography, and vegetation are key factors influencing coastal hydrology and runoff to coral reefs (Macdonald et al. 1997). The approach here builds on an earlier U.S. Caribbean project called 'Summit to Sea', a collaboration between the U.S. National Oceanic and Atmospheric Administration (NOAA) and the World Resources Institute, to develop spatial models of sediment load and coral reef exposure (World Resources Institute & NOAA 2005). Spatial and statistical techniques characterized watersheds across the USVI and modeled the relative erosion rates and sediment and pollutant delivery to coastal waters. A simplified version of the Revised Universal Soil Loss Equation (RUSLE) using slope, land-cover, precipitation, and soil characteristics was applied, as well as indicators of road density and erosivity by watershed. In the absence of a hydrodynamic model to predict the fate of runoff in marine waters, a simple diffusion model (based on spatial interpolation) determined patterns of coral exposure to runoff within a maximum extent of 1 km from the pour point.

Shipping. Ships have impacted coral reefs through noise pollution effects on fauna, resuspension of sediments, chemical pollutants and physical destruction from groundings (Grech et al. 2013). In general, shallow reefs are more susceptible than deeper reefs. Ship vessel traffic density was calculated from Automatic Identification System (AIS) data (year 2014) collected by the U.S. Coast Guard through onboard navigation on commercial vessels (e.g., ferries, cruise ships, cargo ships) which transmit their locations to land-based receivers. A Python script was used (Track Builder www.marinecadastre.gov/ais) to convert the collection of points into track lines of ship traffic density using GIS software. Users can evaluate relative impact by identifying reefs at different depths exposed to different levels of ship traffic. Highest ship traffic density over coral reefs in less than 20 meters of water received the highest perceived potential threat score.

Wave exposure. Wave exposure can have a considerable influence on the structuring of coral reef ecosystems. To map relative exposure, we mapped average wave power (Kw/m) from August 2012 to July 2014 at ~1.1 km horizontal grid resolution from the CariCOOS (Caribbean Coastal Ocean Observing System Nearshore Wave Model (Canals-Silander in press) based on the Simulating WAve Nearshore SWAN model (Booij *et al.* 1999).

Cumulative stress. Mapping and evaluating cumulative impacts of human activities was computed as a sum of all stressor exposure values for each cell in the analysis grid to map relative total threat from the thermal stress, runoff and shipping (high =3, medium =2, low=1, none=0). Other frequently used stressor data, such as fishing, could not be included due to insufficient information on the spatial patterns of fishing effort across the USVI. The approach is a simple estimate of threat, i.e., 'threat footprint', and does not account for complex synergistic interactions between stressors, or the variability in vulnerability and exposure to coral reefs, that will be influenced by spatial and temporal heterogeneity in biotic communities, water depth and hydrodynamics, etc.

To prepare the input data for tool use several steps of data processing were required including aggregating data to a standardized analytical grid. We chose a cell resolution of 100 x 100 m (0.01 km^2) for the entire region (from island coastlines to 100 m isobaths at the insular shelf edge). Scale selection was informed by the level of detail required for a range of localized management foci (i.e. within a single bay or across the entire region) and without being so detailed that spatial errors and information gaps increase uncertainty. All data were then normalized (index of 0-1) to put the many input layers in the same variable space to facilitate the summing of cell values. Finally, data were processed to the same map projection.

2.4 Operationalizing the framework within a web-based suitability modeling application

Our solution for the operationalization of the prioritization framework was to customize an existing weighted overlay analysis tool called the Suitability Modeler available through ESRI's ArcGIS Web AppBuilder service (http://www.esri.com/). Weighted overlay has a long history in landscape suitability analysis (McHarg 1969), with many applications in characterizing landscape terrains, evaluating risk in land use planning and mapping of ecological inventories (Collins et al. 2001).

The prioritization tool guides the user through a simple set of decisions that allows creation of a range of scenarios by adding layers, changing layer weights and individual feature class weights to reflect relative importance making it easy for non-GIS experts to use. After assigning weights, the user then runs the suitability analysis to produce a map with colours representing a range of values from low to high suitability (prioritization index). Examining the spatial patterns of color in the output map, the user can identify areas of potential opportunity and risk. The weighted overlay analysis has three key analytical steps (Figure 4). First, a percentage weighting is assigned to each data layer to emphasize its relative importance in the analysis. Second, values within each data layer are mapped to a common suitability scale to facilitate comparison. Third, data layers are overlaid and each raster cell's suitability value is multiplied by its layer weight and totaled with the values of other cells it overlays (http://www.esri.com/). The resultant map is the geographic representation of the coral reef prioritization index.

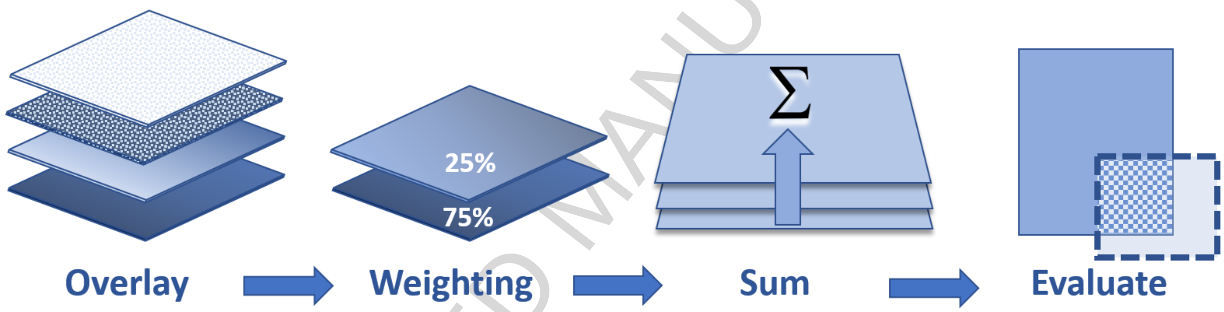

Figure 4. Processing steps in the weighted overlay analysis for ranking priority coral reef cells.

3. Results and Discussion

This spatial ecoinformatics project integrated data across multiple disciplines into a unified spatial framework in order to build a decision-support tool to support efficient, flexible, transparent and inclusive management decision-making in coral reef conservation. Users can prioritize vulnerable sites and have the flexibility to include or exclude specific ecological characteristics or stressors depending on the specificity of questions (Figure 5). The tool was conceptualized to answer multiple questions that use one or several attributes of coral reefs to both support the geographical targeting of specific management driven actions, inform scientific studies, as well as to increase public awareness of where different types of coral reefs and their associated ecosystem services are distributed across the region. To acquire a synoptic regional overview the ranked coral reefs can be easily visualized, or fed back into the model using weighted threats to prioritize reefs according to potential risk. This will allow decision makers to evaluate the relative threat to health and ecosystem service value from individual stressors or from cumulative stress and possibly even to examine relative ecosystem resilience. For example, application of the coral reef prioritization tool will allow the users to explore patterns of coral reef resilience where data on coral reef characteristics are integrated with patterns of exposure to stress.

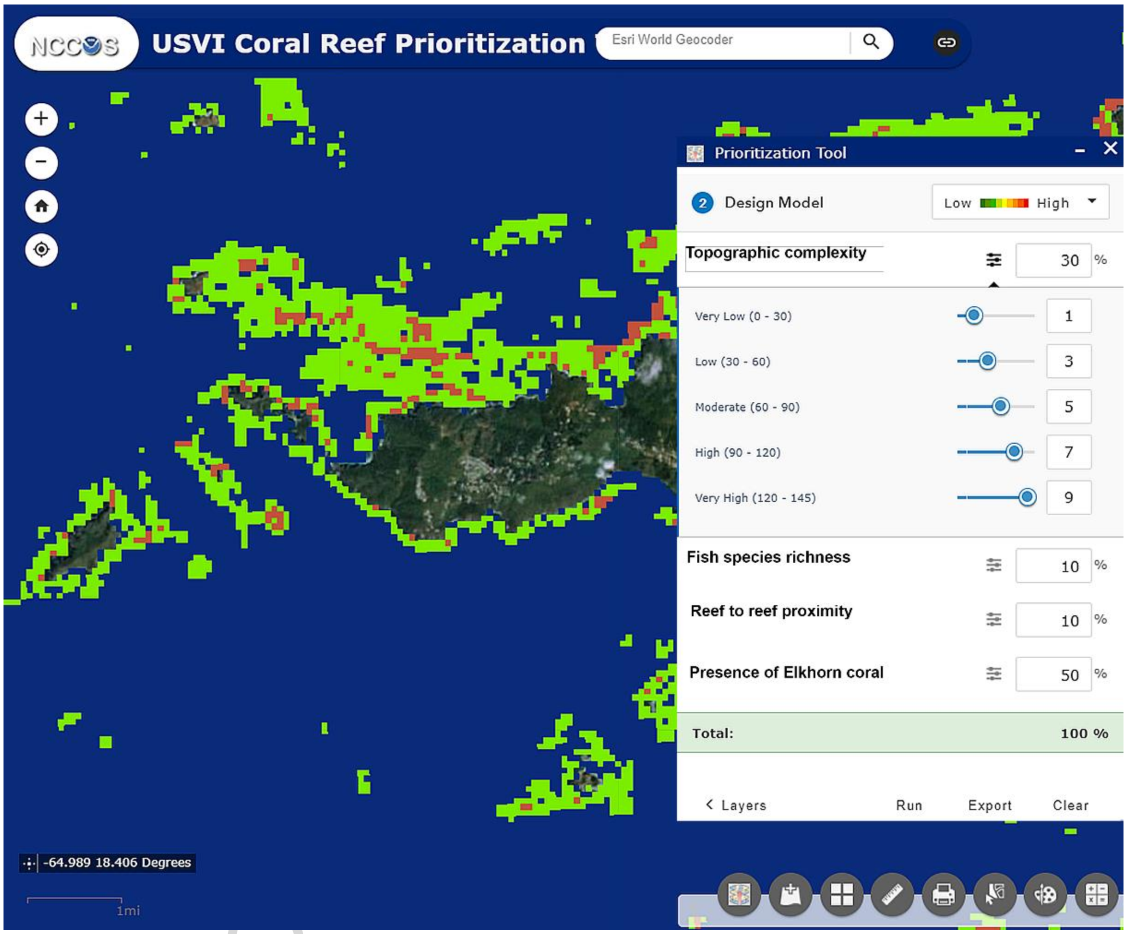

Figure 5. Demo version of the prioritization tool showing seafloor with high to low topographic complexity within 0.01 km^2 cells around the island of St. Thomas. The pop up window allows the user to add weightings to both the individual data layers, and when expanded, weightings can be assigned to the feature classes within each layer. In the model run shown here, coral reefs with highest biophysical complexity that are most geographically connected to another reef and with threatened elkhorn coral will receive highest total scores in the prioritization.

In addition to allowing user defined weightings, to further help the user we provide a selection of pre-configured models with equal weightings on sets of individual attributes including: 1.) all attributes combined; 2.) only biodiversity; 3.) only ecosystem service value; and 4.) only reefs with ESA protected corals (initially just elkhorn and staghorn coral). The maps and site reports will assist managers in evaluating risk from coastal development, and help target sites where management actions such as coral restoration are most likely to be effective.

Two examples of spatially explicit information needs addressed by the prioritization tool are provided here to illustrate the application to management:

Q1. The U.S. Endangered Species Act (ESA) of 1973 requires information on the geographical distribution of the endangered corals, *Acropora palmata* and *A. cervicornis*, with the requirement to eliminate or sufficiently abate global, regional, and local threats across their geographical range.

Step 1: Prioritize coral reefs with high predicted high habitat suitability for acroporid corals using the MaxEnt model output (40% weight) but with a higher weighting to coral reefs with confirmed presence (underwater sighting) of listed endangered coral species (60% weighting). Export this map to be used in Step 2 as a pre-configured weighted overlay.

Step 2: Prioritize acropora coral reefs using a cumulative threat layer to display the most to least threatened coral reefs. Report out the individual and cumulative threat scores for selected areas of coral reef (imported polygon or manually drawn area). This will inform effective targeting of management actions to evaluate individual and cumulative stressors and determine which, if any, to mitigate first.

Q2. To determine the risk from a proposed hotel and marina development to priority reefs of highest socio-economic value especially those of importance to the SCUBA diving industry.

Step 1: Rank all coral reefs using only the known ecosystem service values layers giving greater weighting to the highest value feature classes and 50% weighting to cells identified by occupational SCUBA divers.

Step 2: To assist with risk assessment, map and report out to an exportable file the scores for the entire proposed development area (imported polygon or manually screen drawn area) with average and maximum values for each of the selected individual ecosystem attributes (e.g. tourism value, coastal protection, etc.), as well as the ranked summed values. By changing the area of interest, this tool would then allow decision makers to find areas with lowest value to explore as alternatives to consider for potential development.

To evaluate the design of the existing MPA network, MPA polygons can be used by the user to identify the locations of priority coral reefs and calculate the total area of priority coral reefs inside and outside of the existing network of protected areas. Furthermore, the tool provides a visual assessment of the magnitude of potential threats to coral reef inside and outside MPAs.

Although the tool generated new data sets for the region challenges still exist with geographical data gaps and temporal dynamics, which will require periodic updating of the tool. It will be incumbent upon the users to assess the weight of evidence and uncertainty for each scenario generated with the tool. At this stage, the tool does not evaluate and map spatial uncertainty in the data, but the metadata descriptions provide details of data sources, original resolution, any data processing completed and any caveats to consider with data use.

The maps of priority reefs will help inform local communities about the reefs (and stressors) in their own areas of interest. Maps are powerful communication aides and it is likely that the data available will result in increased community awareness of coral reefs and associated threats across the USVI. In turn, this will support the development of a more coherent regional conservation strategy, as well as finer-scale community-based efforts targeting individual bays.

There are a number of opportunities for integration of local resource users' knowledge of coral reef condition and in documenting exposure and ecological responses to stress. For instance, working in partnership with the fishing community to conduct participatory mapping of fishing behavior and coral reef values would fill a key data gap. Stephenson et al. (2016) consider fishers' knowledge a necessary element in the integration of ecological, economic, social, and institutional considerations of future management and best practice in improved fisheries governance. Co-production of knowledge (e.g., LEK and conventional science) can improve conservation outcomes and is a desirable process in the design of effective decision support tool according to Rose et al. (2016). In fact, co-production of knowledge is increasingly facilitating proactive mitigation of risks in marine resource management. In addition, co-production of data could play a role in the maintenance and legacy of the tool if citizen science data was used to patch up data gaps and update existing data.

At the time of writing, the prioritization tool was in the final stages of software development with the next step being a beta testing phase with marine managers and scientists in the U.S. Virgin Islands and within NOAA. When fully operational, it is expected that the tool will support management in prioritizing actions to streamline costs and increase effectiveness, as well as engaging stakeholders in the evaluation process through the exploration of site suitability scenarios that are flexible and clearly interpreted through pictures. For some objectives such as systematic conservation planning for biodiversity, the scoring method of prioritizing spaces for conservation have been found to be unreliable (Pressey & Nicholls 1989). This can occur where metrics such as species richness are used to rank sites giving highest priority only to diversity hotspots (i.e., locations of highest species richness) without consideration of other principles of conservation planning that can influence outcomes of management strategies (Game et al. 2013, Brown et al. 2015). Therefore, we emphasize the importance of tool use in exploring multiple scenarios across ocean space, together with expert local knowledge placed firmly within a management context, as a way to evaluate and rank the 'reefs of hope', as well as developing the 'hopeful actions' in coral reef conservation. Furthermore, several other decision support software (e.g., Marxan) are available that prioritize actions based on a set of systematic planning principles and mathematical optimization to deliver prioritization scenarios. These approaches typically prioritize places and evaluate risk with respect to performance of specific management objectives. In the US Virgin Islands, additional efforts will be required to develop specific management targets for coral reef conservation and invest in building a more holistic suite of data to include socio-economic variables to evaluate a more diverse range of influences on specific objectives, such as local social enabling factors that can influence the success of specific management actions. More research is also required to determine the interaction between coral reef characteristics across spatial and temporal scales since the simple linear summation of cell values across diverse and static ecosystem characteristics is unlikely to reflect the true non-linear dynamic behaviors of real living systems.

Nevertheless, placed within a holistic and adaptive management framework, the simple and flexible map-based prioritization tool for coral reefs of the US Virgin Islands will allow decision makers to make good use of the best-available information to begin to implement evidence-based decision-making in strategic marine management.

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Highlights

- A novel spatial prioritization framework was developed to support coral reef conservation
- Occupational SCUBA divers contributed local ecological knowledge
- A web-based tool integrated predictive models, local ecological knowledge and field data