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INCORPORATING GIS AND MCE FOR SUITABILITY ASSESSMENT MODELLING OF CORAL REEF RESOURCES

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Abstract. Assessment, planning and management for coral reef ecosystems are particularly challenging tasks, especially in developing countries. In this study, a methodological approach which integrates Geographic Information Systems (GIS) and Multicriteria Evaluation (MCE) for the development of suitability assessment models for a variety of uses of coral reef resources is discussed. Such an approach is sustained by an extensive use of local expert knowledge coded in the form of automated decision trees (DTs). The usefulness of the approach and the models developed is demonstrated by their application to the participatory assessment and resources planning at "Alacranes Reef National Park" (ARNP), Yucatán, México. Overlaying of resulting suitability maps was also applied for identifying potential conflicting areas.

Keywords: coral reefs management, decision trees, expert knowledge, GIS, multicriteria evaluation, suitability assessment

1. Introduction

The spatial and ecological complexity of coral reefs and the complicated social and economic relationships resulting from the convergence of a variety of groups of stakeholder make management and planning of those ecosystems a particularly challenging task. In developing countries, multiple constraints prevent the successful implementation of management programs. Some of the most relevant constraints are the scarcity of technology, equipment, budgets, policies and ultimately high quality data, as well as the use of simplistic and largely, arbitrary criteria, and the inadequate communications among relevant stakeholders during the planning and decision-making process (Fernandes *et al.*, 1999). To achieve the sustainable use and development of coral reef resources (Crosby *et al.*, 2002) have identified an urgent need for incorporating adequate planning and management strategies that allow for the elicitation and incorporation of the views, opinions and knowledge of the key stakeholders, including technical and scientific propositions by scientists, local users and managers.

The distribution of coral reef resources in the geographical space carries a high degree of importance in resources allocation planning. The representation and mapping of the spatially variability of such resources is a fundamental step in the formulation of reef resources management plans. Consequently, the development of accurate "representation models" (i.e. a geo-referenced digital map or image depicting the spatial pattern of reef resources) is deemed essential for further work in the evaluation or assessment of the suitability of resource use for a given reef area. Geographical Information Systems (GIS) and Remote Sensing (RS) technologies have proven to be powerful tools to aid in the development of such representation models of coral reef areas. Applications of GIS and RS in coastal environments include a variety of objectives such as habitats mapping, monitoring through change detection, bathymetry mapping, fisheries management and stock assessment (Green *et al.*, 2000).

Determining the suitability of a given spatial area for particular uses is another fundamental step in resources planning. Suitability assessment is a multi-criteria evaluation (MCE) process widely used in a variety of planning and decision-making situations including natural resources planning (Ponce-Hernandez, 1998), agriculture (Ceballos-Silva and López Blanco, 2003a,b; Bydekerke *et al.*, 1998; Wandahwa and Ranst, 1996), waste disposal management (Basnet *et al.*, 2001), recreational facilities setting (Kliskey, 2000), coastal zone management (Fabbri, 1998), definition of protected areas (Villa *et al.*, 2002) and mapping fish grounds (Bergmann, 2004).

A widely used suitability assessment method based on coding expert knowledge has been implemented by the Food and Agriculture Organization (FAO, 1976). Rossiter (1990) developed an automated land evaluation system (ALES) based on the FAO framework which offers the possibility of coding local expert knowledge in terms of a hierarchy of decision rules using automated decision trees (DTs) (Wandahwa and Ranst, 1996; Ponce-Hernandez, 1998). In DTs, requirements for actual or potential resource utilization types (RUTs) and their range of possible values are organized hierarchically ranging from highly suitable to not suitable (Wandahwa and Ranst, 1996). Such hierarchy is a tree of possible decisions to be taken depending on the value of the quality that meets a particular requirement (Ponce-Hernandez, 1998). For each group of requirements for the RUTs, a decision tree is designed. In the end, there are as many DTs as RUTs and the suitability evaluation model for a determined area ends up being a collection of suite of decision tree models for each RUT and for each category of RUT requirements (Ponce-Hernandez, 1998). Results from this process are presented as suitability classes that can be exported to other analytical tools to be presented in a variety of formats such as tables or maps.

In this study, a methodological approach which integrates GIS and MCE for the development of suitability assessment models for coral reef resources is discussed. Such an approach is sustained by an extensive use of local expert knowledge coded in the form of automated DTs. The usefulness of the approach and the models developed is demonstrated by their application to the participatory assessment and resources planning at "Alacranes Reef National Park" (ARNP), Yucatán, México.

2. Study Area

The ARNP is one of the largest coral reef systems in the Gulf of Mexico. It is located approximately 130 km to the North of the northern fringe ("Puerto Progreso") of the Yucatan Peninsula (Figure 1). The extreme coordinates of the reef are: 22°21′44″–22°35′12″ North and 89°36′30″ and 89°48′00″ West (Liceaga-Correa and Hernández-Núñez, 2000). It has a semi-elliptic shape, with its main axis oriented NNW/SSE, and its maximum length and width are 26.79 km and 14.61 km respectively. The reef is made up of a platform that rises from 50 m of

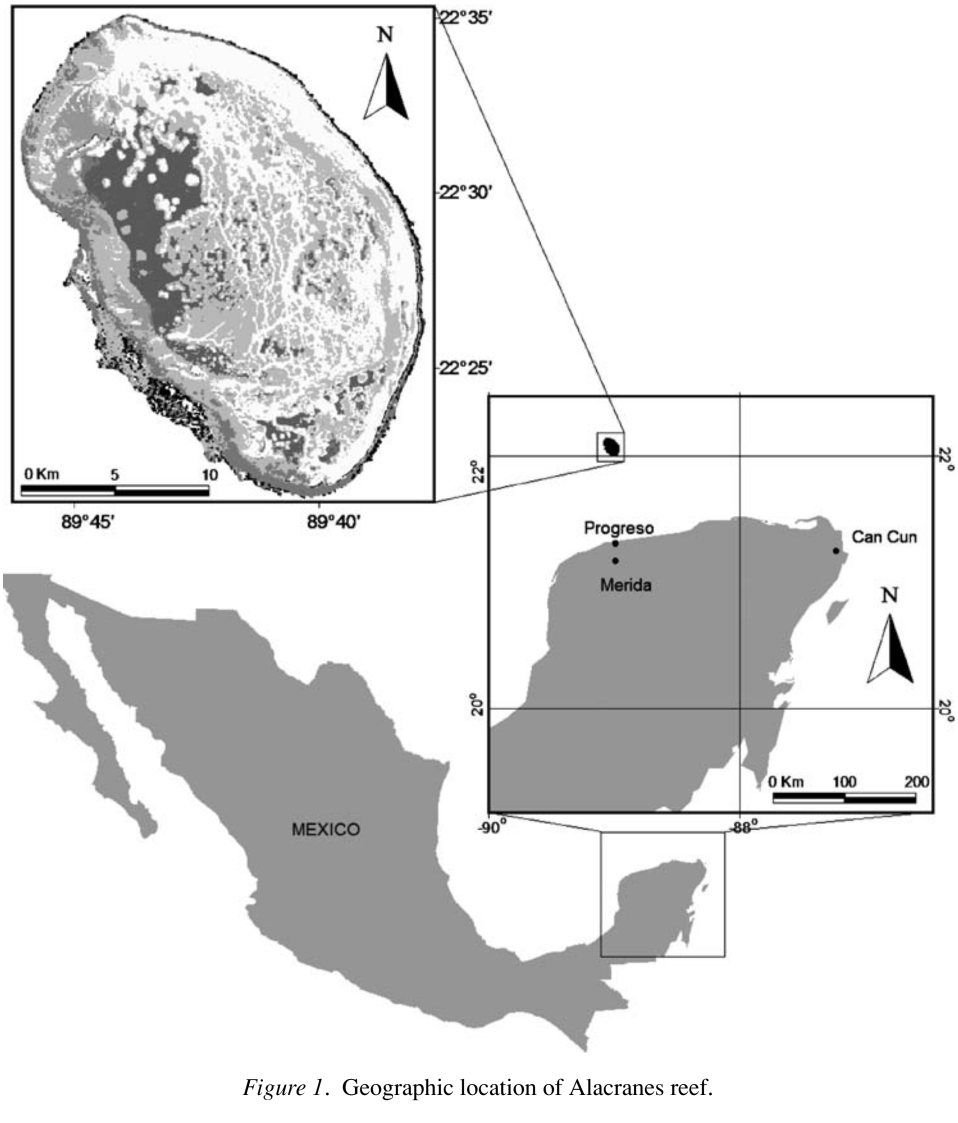

Figure 1. Geographic location of Alacranes reef.

depth and its most conspicuous morphologic features are the reef shelf, the windward barrier, the North reef ridge, the leeward reef ridge, the reef plateau and six small sandy islands known as “Pérez”, “Pájaros”, “Chica”, “Muertos”, “Desterrada” and “Desaparecida” (Bonet, 1967; De la Cruz *et al.*, 1993; Ardisson *et al.*, 1996).

3. Statement of the Problem

The Alacranes reef and surrounding area was declared a National Park in 1994 (Ardisson *et al.*, 1996). Two “nuclei zones” and one “buffer zone” were established for management purposes. For these zones the levels of protection and the types of human activities were also recommended (Ardisson *et al.*, 1996). The two nuclei zones were considered as suitable areas for developing human activities, except for extractive activities or other that impact irreversibly ecological processes and biodiversity of ARNP. The buffer zone was considered as a suitable area for developing sustainable extractive activities under appropriate schemes of regulation and control.

In that document the urgency of developing a management program for the park was emphasized (Ardisson *et al.*, 1996). However, after ten years no official management program has been established. This makes for a particularly interesting situation because despite being declared a protected area, the reef has traditional importance for commercial and subsistence fisheries of species with a high commercial value, such as lobsters, groupers and snappers (Tuz, 2002; Ríos *et al.*, 2000). More than 15% of the total lobster for the state of Yucatan is obtained from the reef and its surrounding areas, and many families depend on the income generated from this resource (Ríos, *et al.*, 1998). Moreover, the past few years have witnessed a significant increment of alternative human activities in the area, including diving, eco-tourism and sport fishing (González, 2001; Ardisson *et al.*, 1996). Scientific research activities have also increased in the last few years, contributing to a better understanding of ecological, social, cultural, and economic processes in the area (Tuz, 2002; González, 2001; Membrillo, 2000; Bello, 1998).

The coincidence of antagonist interests such as conservation versus intensive utilization of reef resources holds the potential for generating conflicts among users and authorities at various levels (Desiderius and Masalu, 2000).

4. Methodology

In the present study GIS and MCE were “loosely” coupled in order to facilitate spatial analysis. The GIS and MCE processes were first undertaken independently and then coupled by database exchanging formats. GIS were used in four phases of the study. First, for the development of a submerged habitats map for ARNP, second, as the major basis for displaying, analyzing and querying data to define "Map Units" (MUs) for the evaluation process, third for interfacing the habitats map with MCE results to produce suitability maps and finally to evaluate the usefulness of the suitability maps by comparing against field data.

MCE tools were used as the means to incorporate expert knowledge into automated decision trees (DTs) during the development of models, to assess the suitability of ARNP map units for different "Resource utilization types" (RUTs). Resulting suitability evaluation ratings for all RUTs from the model (DTs) were exported as a matrix to the GIS, where suitability maps were produced. Suitability maps developed for spiny lobster (Panulirus argus) preferential habitats and for the areas identified as suitable areas for lobster fishing using snorkel gear, were compared to results from an independent study. These data were obtained from stock assessment and fisher effort estimation in the ARNP (Bello *et al.*, 2000).

The methodological approach in this study can be divided in four major stages:

1- Definition of Map Units, 2- Suitability assessment, 3- Production of suitability maps, 4- Verification and validation of suitability maps.

4.1. DEFINITION OF MAP UNITS

According to Rossiter (1994), map units (MUs) can be defined as areas sufficiently homogeneous with respect to the characteristics evaluated. They are represented for single classes or categories and all their definitions are considered to be the same, no matter where the units are located.

In this study, the twelve MUs that were considered in the subsequent evaluation process were defined from a thematic map of submerged habitats for the reef, developed in a previous stage of the project. The map offered information on coral reef submerged habitats to a coarse scale. Methodological details of thematic map elaboration are provided in Bello-Pineda *et al.* (2004), but since such map is a major basis for analysis and discussion in this paper, a brief description of such methodology is provided here.

4.1.1. *Elaboration of Submerged Habitats Thematic Map*

In general terms the methodology used to develop the thematic map of submerged habitats consisted in combining three types of remote sensing products with different spatial and spectral resolutions, namely Landsat TM imagery, aerial photography, aerial video and a digital bathymetric model to identify and to classify the most conspicuous submerged habitats at the reef and compare resulting classes against a classification of field data.

4.1.1.1. *Classification of Field Data.* The term "habitat" used in this paper refers to the assemblages of dominant living and non-living elements (Mumby *et al.*, 1997), adapting the term: "visually dominant organisms" (VDO's) used by Done (1981) as "visual dominant elements" (VDE's) to categorize benthos. Field data were recorded by swimming a 30m plot-less belt transect using free or SCUBA diving, depending on depth (Kenchington, 1978). Three descriptive variables were recorded: VDE's apparent cover percentage, dominant geomorphology percentage and average depth. VDE's were categorized using their biological forms by adapting previous classification schemes (Human, 1994; Done, 1981); nine categories were established for living cover and four categories for non-living cover. Dominant geomorphology was described as: (D) plain, (M) algae and seagrass scattered carpets, (C) algae and seagrass beds, (Ca) coral heads, (Pa) coral patches, (Pi) coral pinnacles, (MA) coral micro-atolls and (PD) coral walls.

To define habitat classes, a matrix of data consisting of VDE's cover and geomorphology percentages was classified using a hierarchical cluster analysis. Analysis included the Bray-Curtis distance index and the unweighed pair group average (UPGMA) grouping method (Digby and Kempton, 1987; Legendre and Legendre, 1983). The dendrogram resulting from this exploratory analysis was used to identify 10 groups of stations at approximately a 20% distance, that we considered the "field-truth" classes.

4.1.1.2. *Remote Sensing and Bathymetric Model Pre-Processing.* A series of enhancement techniques were applied to the three types of remote sensing products to improve visual and digital analysis.

Bands 1, 2, 3 of a Landsat TM image obtained in February 1998 were "geo-referenced" using the Lat/Long coordinate system, referenced to the ellipsoid GRS 1980 and North America datum 1983, obtaining a mean RMS of 5.2 m (Liceaga-Correa and Hernández-Núñez, 2000). To diminish the effect of atmospheric scattering, bands were corrected by using the standard dark pixel subtraction technique (Green *et al.*, 2000). To compensate the effect of variable depth on radiance values of submerged habitats it was applied a standard water column correction technique to bands TM1, 2 and 3, to produce a new set of three depth-invariant bands (Green *et al.*, 2000).

Four black and white analog aerial photographs at a scale 1:75000 obtained in January 1996 were individually digitized to a spatial resolution of 3.8 m. Photographs were geo-referenced individually to the same Landsat TM image coordinates system obtaining an average RMS error value of 0.4 m. Linear stretching of digital values was used to enhance visual discrimination of landscape features.

Six video transects were recorded using an analog color super-VHS camera with an 8 mm lens with 570 pixels of resolution and 30.5 frames per second during a low altitude flight on July 1998. The original video was re-sampled to 400 × 280 lines resolution. The video transects were digitized to raster format and individual frames were pasted together to build mosaics of approximately 20 frames each. Every video mosaic was geo-referenced individually with an average RMS value of 0.5 m.

A digital bathymetric model previously published by Liceaga-Correa and Euan-Avila (2002) was incorporated as an extra raster layer during the classificatory process to discriminate similar habitats at varying depth. The bathymetric model was obtained using a two step unsupervised approach with multiple linear regressions, and reported an overall RMS error of 2 m for depth estimations.

4.1.1.3. *Production of the Thematic Map.* To facilitate discrimination of submerged habitats the video-mosaics were overlaid on top of the aerial photographs, the composite Landsat TM image and the bathymetric model in a GIS environment. In this way, three different spatial resolutions as well as depth information were available simultaneously.

Using the spatial resolution of video and with the experience acquired during field surveys it was possible to identify the most conspicuous habitats at the reef. Once a particular habitat was identified on the video, GIS's "on-screen" digitizing tools were used to select the pixels that represent the sample for that habitat class. Those pixels were used to generate a total of 20 "training" areas that represented variations of depth of the same 10 field habitats classified using field data.

Training areas were used to classify the Landsat TM bands 1, 2 and 3 and the bathymetric model by using a maximum likelihood algorithm. The resulting preliminary thematic map was compared against the field data classification to improve habitats definition and to assess map accuracy. Contextual editing and reclassification were used to define a total of twelve habitat classes in the final thematic map (Figure 2) with an overall accuracy of 77% an overall Kappa index of 0.73. Table I presents the dominant habitats, depth, average percentage of dominant cover and total area for the twelve map units.

4.2. SUITABILITY ASSESSMENT OF MAP UNITS

The biophysical suitability assessment of MUs was achieved outside the GIS environment by utilizing the "Automated Land Evaluation System v. 4.65" (ALES). This software was developed by Rossiter and van Wambeke (1994) at Cornell University. ALES is in essence an expert system "shell" based on the decision trees (DTs) principle, which enables modelers to build "expert systems" for the physical and economic evaluation of land mapping units according to the Food and Agriculture Organization of the United Nations (FAO) (1976) framework for land evaluation.

In this study, the ALES software, normally used to evaluate terrestrial environments, was adopted for undertaking the biophysical evaluation of coral reef

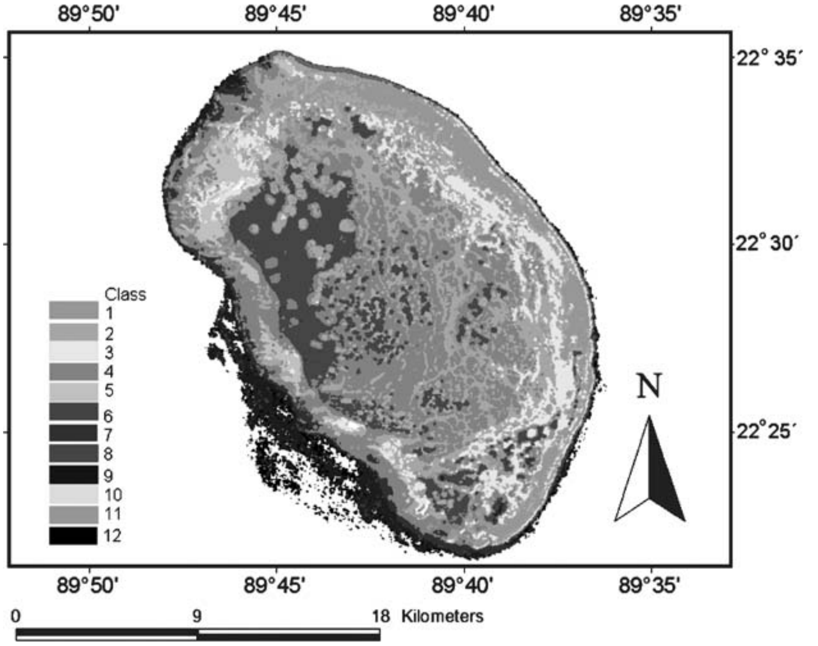

Figure 2. Final thematic map of ARNP submerged habitats. Classes were labelled as: 1-Seagrass beds 1–3 m; 2-Hard and soft coral patches 1–3 m; 3-Hard and soft coral heads 1–3 m; 4-Hard and soft coral patches 3–8 m; 5-Bare substrata 1–5 m; 6-Hard and soft coral patches 8–15 m; 7-Hard coral walls 15–25 m; 8-Bare substrata 8–20 m; 9-Hard coral walls 20–30 m; 10-Mix-Bare/Hard coral wall <1 m; 11-Bare substrata 5–8 m; 12-Deep water >30 m.

submerged habitats. ALES was chosen for this study, because it essentially uses a qualitative method for assessing the suitability of well defined map units by incorporating local knowledge and offers enough flexibility to be adapted to local conditions for a wide range of applications in any environment (Wandahwa and Ranst, 1996). ALES is a valuable tool when there is not enough information for developing quantitative models as those used for deriving land suitability indexes over an entire spatial field, usually considering continuous surfaces or divided into “small” grid cells (as opposed to map units) (Rossiter and Wambeke, 1994).

Within ALES, RUTs are defined by the conditions that make a specific area more or less suitable for particular uses. ALES utilizes three components to perform the evaluation:

1) A database module, where the characteristics of map units are entered. The database of characteristics is constructed with information from different sources and includes quantitative and qualitative data.
2) An expert knowledge module, where the DTs are organized. This is the core of the model and where the expert knowledge in terms of the order of criteria in the

TABLE I
Dominant habitats, depth, average percentage of dominant cover and total area for the twelve map units evaluated

MU	Dominant habitat	Depth (m)	Average % of dominant cover	Area (Km^2)
1	Seagrass beds	1–3	80% seagrass-macro algae associations	31.1
2	Hard and soft coral patches	1–3	45% coralline associations	89.8
3	Hard and soft coral heads	1–3	73% bare substrata, 15% coralline assoc.	26.1
4	Hard and soft coral patches	3–8	40% coralline associations	94.6
5	Bare substrata	1–5	97% bare substrata	11.2
6	Hard and soft coral patches	8–15	45% coralline associations	3.1
7	Hard coral walls	15–25	61% coralline associations	14.9
8	Bare substrata	8–20	98% bare substrata	38.6
9	Hard coral walls	20–30	46% coralline associations	12.6
10	Mix-Bare/Hard coral wall	<1	47% coralline associations	1.4
11	Bare substrata	5–8	97% bare substrata	3.0
12	Deep water	>30	There is not information	8.1

hierarchy and of their threshold values representing degrees of suitability, are built-in. It is used to define RUTs and their requirements, selecting the relevant characteristics for the DTs used to infer map unit quality ratings from the list of characteristics.

3) An evaluation module. It performs what is known as the “matching process”. That is, it is used to match the RUT requirements to the MUs qualities (Wandahwa and Ranst, 1996).

4.2.1. *Database of Map Unit Attributes*

A database describing the most important spatial, physical and biological attributes for the 12 MUs was developed by utilizing field data and bibliographic information from papers, theses and reports previously published for the area as presented in Table II. Attributes were described using quantitative (numerical and categorical) as well as qualitative information. Physical attributes were registered in the field during the same surveys conducted for the characterization of habitats described in 4.1. The attributes registered in a total of 379 stations included: depth, wave strength, visibility, complexity and aesthetic appeal. Average depth per map unit was estimated from the punctual registers with an eco-sounder at each station. Wave strength, complexity, visibility and aesthetic appeal were registered by the diver using a four-point qualitative scale, where: 1 = low, 2 = medium, 3 = high and 4 = very high.

TABLE II
Type of attributes, units of measurement and the source of data used to develop the database of map units characteristics

Attributes	Attribute description	Units	Source of data
Spatial	Total class area	km^2	Raster map
	Percentage of area	Percentage	
Physical	Depth	Meters	Field data
	Horizontal visibility	4 point scale	
	Current strength	4 point scale	
	Aesthetic appeal	4 point scale	
Biological			Field data
Bottom types	Relative abundance of VDE (Average)	Percentage	
	Average-geomorphology	Percentage	
	Richness	Counts	
	Diversity	0-inf	
	Eveness	0–1	
Fish	Richness	Counts	González (2001)
	Abundance	Individuals/m^2	
	Biomass	kg/m^2	
	Range of sizes	Centimetres	

Biological attributes included information on benthic habitats and fishes. Habitats information was obtained by analyzing the data from the same 379 field stations used for producing the habitats map and included average cover percentages of VDEs (see Section 4.1.1.1), average geomorphology percentage (see Section 4.1.1.1), richness, diversity and evenness (Shanon, Weiver, and Simpson indexes) estimated for every map unit.

Fish information was obtained from a study published previously (González, 2001), and it included reports on punctual estimations of species richness, abundance, biomass and fish average size from 80 field stations. To relate fish information to MUs, the GIS was employed in order to prepare a "vector" layer with stations punctual coordinates, and then overlaying it to the habitats map to obtain a database with the class where they overlapped. The average values of species richness, abundance, biomass, and the range of sizes for every map unit were calculated. It is important to say that the number of stations varied among map units, in some cases only one station matched with a particular MU and this information was used to describe its fish attributes, in others cases up to seven stations coincided with a particular MU and the average values were used instead.

4.2.2. *Resource Utilization Types Definition*

To identify the most important RUTs actually occurring at the reef and also those RUT with potential for future development in the area, a series of interviews with authorities of ARNP and the "ARNP assessor committee" (ARNP-AC) of the park were held in February 2003. The ARNP-AC was constituted during 2002 as part of the actions for developing a management program for the park, and includes most representative stakeholders in the area, namely authorities at various government levels (Federal, State, Municipal and Park), the natural resources management agency (SEMARNAT), the Mexican Navy, the Ministry for Communications and Transportation (SCT), scientific institutions and universities in Yucatan, local unions of fishermen, non-governmental organizations (NGO) and recreational tour operators. They accepted to participate in the suitability assessment exercise and provided the "expert" opinion about most important RUTs at the reef as part of the actions to get support for the development of the management program for the park.

Four main groups of stakeholders in the committee were identified: Conservation, fisheries, research and recreation.

4.2.3. *Incorporating Expert Knowledge into the Evaluation Process*

Authorities of the park organized a series of particular meetings with individual or focus groups (Myers, 1998) of experts during March 2003. During those meetings a variety of aspects of interest for ARNP were discussed including the evaluation process presented in this paper. Some experts participate in more than one meeting, and for some RUTs, meetings extended for various sessions.

The diversity of the expert's backgrounds required that the style of the meetings was adapted, varying from very informal talks to technically complex discussions. In the process, a portable computer and projection equipment were used to introduce experts to the objectives and to the methodological approach, including the use of GIS and MCE techniques. The thematic map of submerged habitats with the 12 map units was presented to experts, using the Arc view^{TM} GIS-software together with a large size hardcopy of the habitats map, and personal handouts with copies of the map and the attributes database. Using GIS functions, the map was linked to the attributes database in Spanish as well as to submerged and aerial photographs showing dominant habitat features. So, by "clicking" on map units, users had access to different support materials. The process was interactive, since experts were encouraged to display those photographs, querying attributes linked to the map and discussing about the different aspects of methodology.

Despite of the meeting style, in general terms the evaluation process consisted of asking individuals or groups of experts to:

1. Define the most important physical and biological requirements that are more likely for the successful and sustained development of the activity they work on

or the particular species they have information about, considering the types of attributes and units available in the characteristics database.

2. Rank separately physical and biological requirements, hierarchically according to their importance (open discussion among experts to reach consensus).
3. Determine the range of possible threshold values for the requirements of each RUT, by dividing it in discrete intervals and assigning a suitability class to each interval. Suitability classes were ranked according to FAO's four points scale used to measure the severity of physical limitations for the development of an activity: S1-Highly suitability (not limitation), S2-Medium suitability (slight limitation), S3-marginal suitability (moderate limitation) and N2-Not suitable (severe limitation).
4. Interact with research team to elaborate to construct DTs using ALES, for determining physical and biological qualities of MUs for all the different RUTs according to thresholds determined in step 3.
5. Interact with research team to evaluate the suitability of all MUs by matching the attributes database with the RUTs requirements according to the DTs.
6. Check out resulting suitability classes and subclasses assigned to all MUs for the RUTs evaluated.

The following RUTs were evaluated: Lobster fishing using traps, lobster fishing using compressor, lobster fishing using snorkel, lobster habitat, ecotourism, areas for anchorage, sport diving, snorkel diving, sport fishing, areas for scientific research, areas for environmental education, hawksbill (Eretmochelys imbricata) turtle habitat, subsistence "line" fishing, areas for conservation, grouper habitat, areas for major fleet fishing, areas for navigation, areas for environmental monitoring, areas for aquaculture, ornamental fishing, sea cucumber habitat, queen conch habitat, areas for sailing, green turtle (Chelonia mydas) feeding grounds, and surveillance.

Disagreements among experts were solved in open discussion with low participation of the facilitator as much as possible. The RUT evaluated together with the number and affiliations of experts consulted are shown in Table III. After all meetings concluded an evaluation matrix was obtained indicating the suitability rating assigned by experts to each map unit and for all RUT evaluated.

4.3. PRODUCTION OF SUITABILITY MAPS

The final matrix of suitability ratings produced in ALES was exported to the GIS as an "attributes" database and linked to the thematic habitats map to produce suitability maps for all RUTs evaluated. Experts reviewed again the resulting suitability maps and provided opinion about how logical they appeared, according to their own personal experience of the area. They were also asked to propose further modifications to the evaluation process.

TABLE III
RUTs evaluated, number and affiliation of experts consulted

RUT	Number and affiliation of experts
Conservation	
Monitoring	2 SEMARNAT authorities
Surveillance	1 Mexican Navy official
	1 SCT authority
Fisheries	
Lobster diving	1 Expert in lobster fishery
Lobster traps	1 Fisherman
Groupers and snappers fishery	2 Experts in Groupers biology and fishery
(“Escama” in Spanish)	1 Fisherman
Recreational activities	
Ecotourism	1 Yacht club member,
Diving	1Sport fishing tournament representative
Snorkeling	1 Tour operator
Recreational fishing	
Navigation	
Scientific research	
Coral reefs	2 Experts in coral reefs
Lobster (*Panulirus argus*)	1 Expert in lobster ecology
Green turtle (*Quelonia midas*)	1 Expert in marine turtles
Queen conch (*Strombus gigas*)	3 Experts in Queen conch ecology
Groupers	2 Experts in groupers biology and ecology

By overlaying the resulting suitability maps, areas rated as highly suitable for more than one RUT were identified as possible areas where conflicts would arise.

4.4. VALIDATION AND VERIFICATION OF THE SUITABILITY MAPS

Validation and verification of the usefulness of suitability models usually relies on the use of independent sets of geo-referenced data to assess their accuracy or reliability in predicting the performance of the map unit for the intended use (Kliskey, 2000). However, the validation of models using the ALES framework is more difficult because biophysical evaluation results are not expressed in any quantitative measure of performance and, for the most they are qualitative or categorical terms that indicate the degree of suitability. Usually these ratings refer to a range of the criterion or resource characteristic values. Therefore, usually they are considered valid if they reflect the evaluator’s best judgment (Wandahwa and Ranst, 1996). In the particular case of ARNP, another limitation is the scarcity of previous studies reporting on about the spatial distribution of species or the distribution of

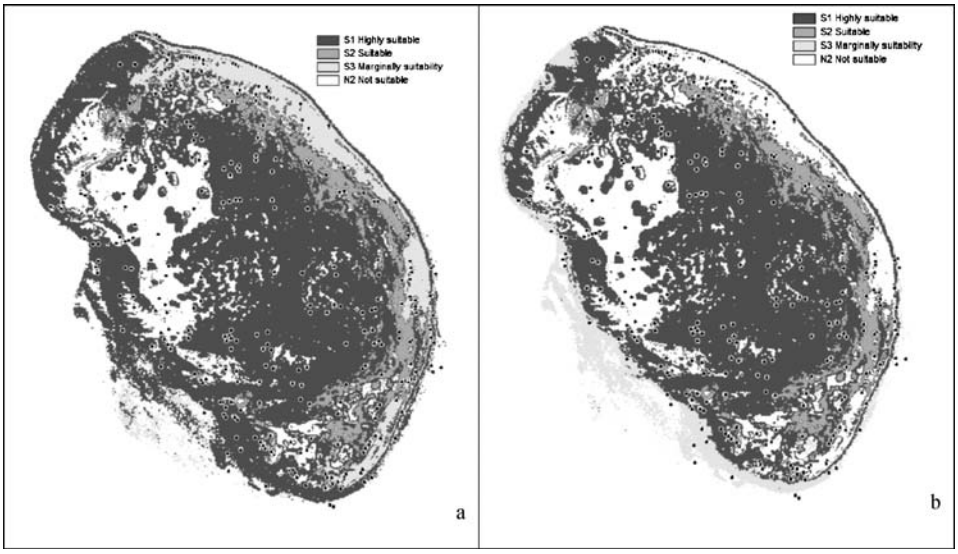

Figure 3. Suitability maps for a) lobster habitat and b) lobster fishery. The darkest areas correspond to the most suitable areas. Black dots represent lobster sampling stations.

human activities at the reef, in order to compare the suitability maps with activities undertaken in reality.

One of the most important and better studied economic activities in the ARNP area is the spiny lobster (*Panulirus argus*) fishery (Ríos, 2000). At the time of writing, the only set of "geo-referenced" data accessible was a database from an independent assessment of the lobster stock and the distribution of fisher effort at ARNP (Bello *et al*., 2000). Therefore, those data were used to verify two of the suitability models developed by experts particularly for lobster, to be precise: 1) "Suitable habitat for lobster" (Figure 3a); and 2) "Suitable areas for lobster fishing" (Figure 3b).

4.4.1. *Lobster Data*

The independent database consisted of geo-referenced field data for lobster catches obtained from two surveys, July 1998, and February 1999. Those months were selected so as to identify seasonal patterns on fisher effort distribution, because they represent the beginning and end of the fishing season (Bello *et al*., 2000). The research team continuously accompanied a fishing ship during its working days at ARNP, and dived together with fishers during their search for lobsters using snorkel gear or air pumped from a compressor. GPS was used to locate ships and divers positions. For each station, the number of lobsters caught, their weight, and abdominal length were registered as well as a broad description of dominant bottom types.

4.4.2. *Comparing the Suitability Maps Against Field Data*

Two “vector” files with point coordinates of the lobster sampling stations for July and February were created using GIS and then overlaid on top of both suitability maps (Lobster habitat and fishing areas) to extract information on the suitability class assigned, where they overlapped (Black dots on Figure 3a and 3b respectively).

A “T-test” for independent samples was conducted to find out differences between the mean number of lobsters caught on July and February. The frequency of visits and the number of lobsters caught per suitability class were calculated for the beginning and the end of the season. Total number and proportion of visits, as well as the total number, average and proportion of lobster captured, were estimated for every suitability class.

5. Results

Physical and biological suitability DTs were elaborated separately. The number of discrimination levels (criteria) and decision branches for each criterion in DTs varied considerably for the different RUTs evaluated. For some RUTs, experts considered that only one level was sufficient to reach a decision (e.g. Navigation). Yet, for others, up to four levels were defined (e.g. Diving).

The collection of DTs for all RUTs evaluated, is too extensive to be published here, so, as an example, part of the DT elaborated for assessing the physical suitability for the RUT “Diving” is presented in Figure 4. Experts considered that the most limiting physical characteristics for diving are depth followed by visibility, currents and finally aesthetic appeal. Therefore, “depth” is allocated in the first level of the DT. If depth is 0–5 m, a final decision is reached and a rank of not suitable (N2) is directly awarded. When depth ranges between 5–10 m, decision is suspended temporarily and a decision branch leads to the following level where “visibility” is called upon to be evaluated (i.e. with 4 possible ranges of values). If visibility is **bad** (0–5 m), a N2 quality is directly assigned, if visibility is **regular** (5–10 m), then the characteristic “currents” in the following level down on the tree is called upon to be evaluated (also with four possible qualitative values). If current strength is **low**, then again, a decision is suspended temporarily and the characteristic “aesthetic appeal” in the last level is called upon for evaluation (also with four possible qualitative values). At all these levels traversing the tree the model holds in memory the corresponding suitability rating at each level (i.e. criterion) and its threshold value met by the data. For instance, if aesthetic appeal is “low” or “medium” a N2 is awarded, but if it is “high” or “very high” a quality of S3 (marginally suitable) and S2 are awarded respectively. The rest of decision branches follow a similar structure and sequence in processing (not presented in Figure 4).

For the particular case of the RUT “Diving” a biological DT was also elaborated. Experts considered that the most limiting biological characteristics in order of

```
DIVING Physical quality

1> depth (depth)

   0-5m (shallow) [0-5 m]... : N2

   5-10m (medium) [5-10 m]

        2> visib (visibility)

         bad (bad) [0-5 m]....... : N2

         regular (regular) [5-10 m]

             3> currents (current strength)

              low (low)

                 4> aestappeal (aesthetic appeal)

                   low (low).............. : N2

                   med (medium )........... : N2

                   high (high)............. : S3

                   v high (very high)...... : S2

                    --------------------------------

              med (medium) ...........
```

Figure 4. Fragment of the decision tree for evaluating physical suitability for diving. Limiting characteristics are introduced by “>”and the level in the branch is indicated by a numeric value. Values for characteristics are boxed “[]”. Resulting values are abbreviated as: S1-Highly suitability (not limitation), S2-Medium suitability (slight limitation), S3-marginal suitability (moderate limitation) and N2-Not suitable (severe limitation).

importance are: “Total coral cover” followed for “Diversity of bottom types” and finally “Abundance of fishes” and “Fish size”.

In the evaluation stage, ALES utilized both the physical and the biological DTs to assign a final suitability class and subclass to every MU respect to all RUTs evaluated. Subclass refers to the most limiting factor (Physical or biological) that determines the suitability of a MU for the development of a particular RUT.

Evaluation resulted in the suitability matrix presented in Appendix 1. Rows represent the MUs and columns the RUTs. In every cell, the suitability class awarded is followed by the subclass code referring to the most limiting factor that determined such value; e.g. “S3Bio-cortot”, “S3”: means that it is an area marginally suitable,

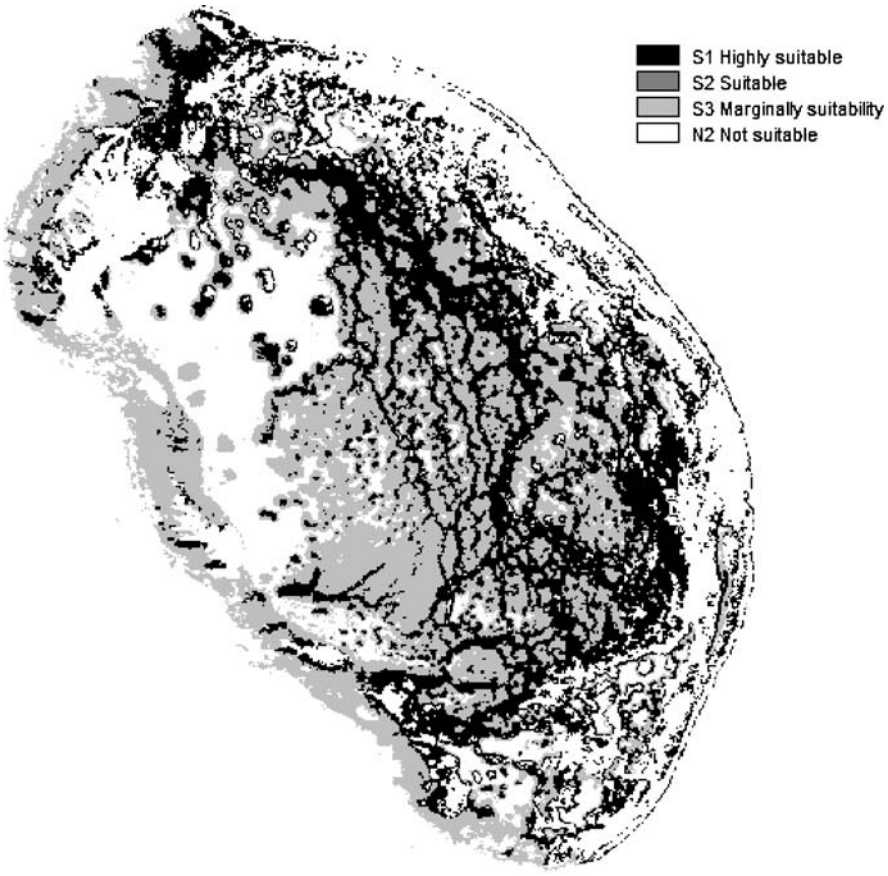

Figure 5. Suitability map for snorkeling. The darkest areas correspond to the most suitable areas.

"Bio-": means that it is because of the biological quality and "cortot": means that the most limiting factor is total coral cover.

The suitability matrix was imported to GIS as an attributes data file and suitability maps for all RUTs were produced by assigning the suitability class awarded to every MU for every RUT. The total set of maps is presented in Appendix 2. In the suitability maps generated, "not suitable" areas (N2) are represented in white, while "marginally suitable" (S3), "suitable" (S2) and "highly suitable" (S1) areas are represented using increasingly darker tones of grey. Here, the suitability map elaborated for "Snorkelling" is presented in Figure 5 only as an example to facilitate interpretation of the rest of the maps.

For "snorkelling", it is evident that the areas rated as highly suitable (S1), are those located in the shallow areas of the reef, which according with the attributes database are mostly dominated by coralline habitats with high diversity of bottom types, high abundance of fish, good visibility, high aesthetic appeal and low strength currents.

After experts reviewed the entire set of suitability maps, they considered them logical and likely representations of reality, according with their experience. For instance, the areas defined as suitable for snorkelling were identified by users as the same areas where they have practiced this recreational activity. On the other hand, due to the lack of independent data and other constraints it was not possible to derive formal verification and validation processes for most of the suitability maps. As mentioned before, the only maps that actually went into verification were those for lobster habitat and lobster fisher grounds.

The "T-test" for independent samples showed that the mean values of lobsters caught on July (13.6) and February (1.03) were significantly different to $\alpha = 0.05$.

After overlaying the vectors with stations for July and February over the maps for "Suitable habitat for lobster" (Figure 3a) and "Suitable areas for lobster fishing" (Figure 3b) respectively, Table IV and V were obtained.

In Table IV the total number, average and percentage of lobster caught estimated for the four suitability classes of the "Suitable habitat for lobster" map for July and February are presented. It is evident that in both months, the areas rated as S1 (Highly suitable), are those where most of the catches were obtained (79.4% in July and 55.56% in February).

In Table V the number and percentage of visits to the areas corresponding to the four suitability classes, according to the "Suitable areas for lobster fishing" map, are presented. It is evident that areas ranked as S1 for lobster fishing coincide with the areas actually most visited by fishers for both months (79.41% in July and 58.79% in February). Nevertheless, it is interesting to notice that areas ranked as

TABLE IV

Total number, average, standard deviation and percentage of lobster captured for suitability classes according to the "Suitable habitat for lobster" model for the beginning and end of fishing season

Suitability class for "Lobster habitat"	No. lobsters	Average	SD	% of total
July 1998				
S1	767	13.46	17.73	79.40
S2	28	28.00	0.00	2.90
S3	48	24.00	33.94	4.97
N2	123	11.18	11.12	12.73
Total	966			100
February 1999				
S1	105	0.92	3.35	55.56
S2	6	1	1.55	3.17
S3	18	2.25	3.37	9.52
N2	60	1.11	2.21	31.75
Total	189			100

TABLE V

Number and percentage of visits to suitability classes according to the “Suitable areas for lobster fishing” model

Suitability class for “Lobster fishing”	No. visits-July	% visits-July	No. visits-February	% visits-February
S1	54	79.41	107	58.79
S2	1	1.47	6	3.30
S3	0	0	7	3.85
N2	13	19.12	62	34.07
Total	68		182	

not suitable are the second most visited for both months. This can be explained in terms of one of the most important factors considered to determine MUs suitability, which was depth, since fishers use snorkel gear, a large extension of deeper areas of the reef were rated as not suitable for that activity. Yet, in reality, fishers venture themselves to deeper areas when captures are reduced in shallow habitats; this is more evident during February, when they have to use compressed air for the search of lobsters in the external reef cliff because lobsters have been exhausted in shallow areas (Rios *et al.*,1998). It is important to notice that a great extension of area considered as suitable habitat for lobster (Figure 3a) are located at depths not suitable for lobster fishing and therefore mapped as not suitable for lobster fishing (Figure 3b).

6. Discussion

Results obtained in this study, indicate that the integration of GIS and MCE is useful in providing with the analytical tools for coral reef resources planning. This methodological framework showed to be a feasible approach to incorporate expert knowledge for the evaluation of the biophysical suitability of reef habitats for a series of human activities, as well as for the distribution of marine species. The researched literature indicates that the GIS-MCE integration proposed in this methodological framework is one of the first attempts to adapt this type of evaluation methodology, traditionally used for terrestrial environments, to the assessment of coral reef resources. The use of expert knowledge for land evaluation in terrestrial environments has been largely used and considered as a valid approach for selecting suitable areas for agriculture (Ceballos-Silva and Lopez-Blanco, 2003 (a), (b)), mapping species distribution (Merrill *et al.*, 1999) and for defining protected areas (Store and Kangas, 2001). Nevertheless, for marine environments, only two studies were found in recent literature. The first incorporated expert knowledge to identify possible ground fish (Bergmann, 2004) and the second utilized GIS for determining the suitability of different areas to develop a zoning scheme for a MPA (Villa *et al.*, 2002). Both approaches are applied in temperate latitudes developed countries. However an example for tropical coral reefs could not be found. Thus, there are indications that the range of applications for this type of approaches in different areas of marine sciences can be vast. In our study, the use of a "loose-coupling" approach for integrating GIS and MCE techniques was sufficient to reach the objectives. However, full integration of these groups of tools and procedures can be achieved into what have come to be known as spatial decision support systems for coastal and marine environments.

As discussed by Wandahwa and Ranst (1996), results from evaluations using ALES can be considered valid if they reflect the evaluator's best judgment. The decision trees DTs constructed in this study express the expert's best knowledge on what are the most relevant factors and threshold values to determine suitability, and are based on the use of the available information for the area. When high quality data and empirical models are available, it is possible to verify these evaluations and improve their accuracy. Yet, in the case of marine environment and particularly in developing tropical countries, this type of data and models are rare. The use of knowledge from local experts in a systematic framework is a good alternative to formal experimental knowledge when time is limited or there are information, data and major research constraints in an area, as it was the case of ARNP. In the area of this study, it was not possible to use geo-referenced data for most of the human activities and species distribution. They were limited to scattered punctual data. In the case of the lobster maps, the access to field data, allowed identification of good agreement between local expert's appreciation of the most suitable habitats and suitable fisher grounds, as reflected in the DT models, and actual lobster catches and fisher effort distribution, as obtained from an independent study. Additionally in this particular case, the observed reduction of lobster catches by February, even in areas ranked as highly suitable; agrees with the diminished densities for the whole reef by the end of the season, as reported by Rios *et al.* (1998).

The database with MUs characteristics used for the suitability assessment was obtained from different sources of information and from previous studies (González, 2001) designed to cover needs different from those of this study. Therefore, all relevant factors for evaluation of all RUTs in ARNP could not be included or were limited to availability of data. On the other hand, the performances of the models developed can only be as good as are the data fed into them. Results can be substantially improved if higher quality data are available and can be included in the analysis. The availability of data with higher resolution and detail and at larger scales, together with the development of future empirical studies for other resources would improve the knowledge and the decision on what factors are the most limiting and what threshold values should be the most appropriate for determining the suitability of habitats. The methodology presented here presents a first approximation to the suitability assessment of resources for a range of uses and human activities and for the suitable distribution of particular species in the ARNP habitats. However the methodology here proposed is deemed systematic and flexible enough to incorporate new findings that might contribute to fine-tuning the suitability models or even to develop and to compare alternative models according to different expert's opinions.

Presently, the authorities of the ARNP face the need for counting with a management program for the park, in order to establish management zones with clear indications on the type of human activities allowed in different areas of the reef. As shown in the resulting suitability maps, there is overlap in large areas of the reef that are considered suitable for the development of diverse human activities as well as for the distribution of species of commercial or conservation value. For instance, map unit **2** representing hard and soft coral patches at 1 to 3m depth was rated as highly suitable (S1) for "hawksbill" turtle habitat, scientific research activities, conservation, lobster habitat, lobster fishing, environmental monitoring, sea cucumber habitat, queen conch habitat and recreational snorkelling. Many of those RUTs are not compatible (conservation against fishing) and this fact may be the breeding ground for conflicting interests among users. Satisfactory participatory resolution to these conflicts can only be achieved as constant improvement in the participatory decision-making models and tools. The following stage of our study will be aimed to the development of participatory multi-stakeholder and multi-criteria decision-making planning scenarios for ARNP resource allocation. It will be based on the incorporating stakeholders' priorities and preferences through a participatory resource allocation planning process.

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Appendix 1. Suitability Class and Subclass Awarded to Map Units Considering the Different RUTs Evaluated

Code for suitability class: **S1** Highly suitable; **S2** Suitable; **S3** Marginally suitable; **N2** Not suitable. Code for suitability subclasses and limiting factors: **Phys** = Physical quality: depth, currents, aesthetic (appeal), visib (visibility), naviga (navigation), complex (complexity). **Bio** = Biological quality: cortot (Total coral cover), sgrss (Seagrass cover), Malgae (Macro algae cover), Fishabu (Fish abundance), FishBio-M (Fish biomass), richfish (Fish richness).

MapUnits	Lobster traps	Anchorage	Turtle (carey)	Scientific Research	Conservation value
1	N2Phys-Depth	S3Phys-bare	S3Phys-complex	S1	N2Bio-richfish
2	N2Phys-Depth	N2Bio-Cortot	S1	S1	S1
3	N2Phys-Depth	S3Bio-Cortot	S2Phys-complex	S1	S2Bio-richfish
4	N2Phys-Depth	N2Bio-Cortot	S1	S1	S2Phys-aestethic
5	N2Bio-/Phys-Depth/complex	S1	S3Phys-complex	S1	N2Bio-/Phys-Cortot/aestethic
6	S2Phys-Depth/complex	N2Bio-Cortot	S1	S1	S1
7	S1	N2Bio-Cortot	S1	S2Phys-Depth	S1
8	N2Bio-Depth	S1	S3Phys-complex	S2Phys-Depth	N2Bio-/Phys-Cortot/aestethic
9	S1	N2Bio-Cortot	S1	S2Phys-Depth	S1
10	N2Phys-complex	N2Bio-Cortot	S1	S1	S1
11	N2	Phys-complex	S1	S3Phys-complex	S1
12	S1	S1	S3	S2Phys-Depth	N2Bio-Cortot
MapUnits	Sport diving	Ecotourism	Environmental education	Artisan fishing	
1	N2Bio-/Phys-Cortot/depth	S3Bio-Fishabun	S3Bio-Cortot	N2Bio-Fishadun	
2	N2Phys-depth	S3Phys-Navega	S3Phys-navega	S3Bio-Fishadun	
3	N2Phys-depth	N2Phys-Navega	N2Phys-navega	S3Bio-Fishadun	
4	N2Phys-depth	S2Bio-/Phys-Fishabun/Navega	S2Phys-navega	S3Bio-Fishadun	
5	N2Bio-/Phys-Cortot/depth	N2Bio-Fishabun	N2Bio-Cortot	N2Bio-Fishadun	
6	S2Phys-depth	S1	S1	S1	
7	S2Phys-depth	N2Phys-depth	S2Phys-visib	S2Phys-visib	
8	N2Bio-/Phys-Cortot/depth	N2Bio-/Phys-Fishabun/depth	N2Bio-/Phys-Cortot/visib	N2Bio-/Phys-Fishadun/visib	
9	S2Phys-depth	N2Phys-depth	S2Phys-visib	S3Bio-Fishadun	
10	N2Phys-depth	N2Phys-Navega	N2Phys-navega	S3Bio-Fishadun	
11	N2Bio-/Phys-Cortot/depth	N2Bio-Fishabun	N2Bio-cortot	N2Bio-Fishadun	
12	N2Bio-/Phys-Cortot/depth	N2Bio-/Phys-Fishabun/depth	N2Bio-/Phys-cortot/depth	N2Bio-/Phys-Fishadun/depth	

(*Continued on next page*)

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MapUnits	Grouper habitat	Mayor fishing	Habitat lobsterJuly	Navigation
1	N2Bio-/Phys-Fishabun/depth	N2Bio-/Phys-FishBio-m/depth	N2Bio-cortot	S2Phys-navega
2	N2Phys-depth	N2Phys-depth	S1	N2Bio-/Phys-cortot/navega
3	N2Phys-depth	N2Phys-depth	S2Bio-cortot	N2Phys-navega
4	N2Phys-depth	N2Phys-depth	S1	N2Bio-cortot
5	N2Bio-/Phys-Fishabun/depth	N2Bio-/Phys-FishBio-m/depth	N2Bio-cortot	S1
6	S1	S1	S1	N2Bio-cortot
7	S1	S1	S1	N2Bio-cortot
8	N2Bio-/Phys-Fishabun/complex	N2Bio-FishBio-m	N2Bio-cortot	S1
9	S1	S3Bio-FishBio-m	S1	N2Bio-cortot
10	N2Phys-depth	N2Bio-/Phys-FishBio-m/depth	S1	N2Bio-/Phys-cortot/navega
11	N2Bio-/Phys-Fishabun/complex	N2Bio-FishBio-m	N2Bio-cortot	S1
12	N2Bio-fishabun	N2Bio-FishBio-m	N2Bio-cortot	S1
MapUnits	obster fishing Compressor	obster fishing Snorkel	Environmental monitoring	Aquaculture
1	N2Bio-/Phys-cortot/depth	N2Bio-cortot	S2Bio-cortot	S2Phys-current
2	N2Phys-depth	S1	S1	N2Bio-sgrss
3	N2Phys-depth	S2Bio-cortot	S1	S3Bio-sgrss
4	N2Phys-depth	S1	S1	N2Bio-sgrss
5	N2Bio-/Phys-cortot/depth	N2Bio-cortot	N2Bio-cortot	N2Bio-sgrss
6	N2Phys-depth	S1	S1	N2Bio-sgrss/currents
7	S1	S3Phys-depth	S3Phys-depth	N2Bio-sgrss/depth
8	N2Bio-cortot	N2Bio-/Phys-cortot/depth	N2Bio-cortot	N2Bio-sgrss/depth
9	S1	S3Phys-depth	S3Phys-depth	N2Bio-sgrss/depth
10	N2Phys-depth	S1	S1	N2Bio-sgrss/currents
11	N2Bio-/Phys-cortot/depth	N2Bio-cortot	N2Bio-cortot	N2Bio-sgrss
12	N2Bio-/Phys-cortot/visib	N2Bio-/Phys-cortot/depth	N2Bio-/Phys-cortot/depth	N2Bio-sgrss/currents

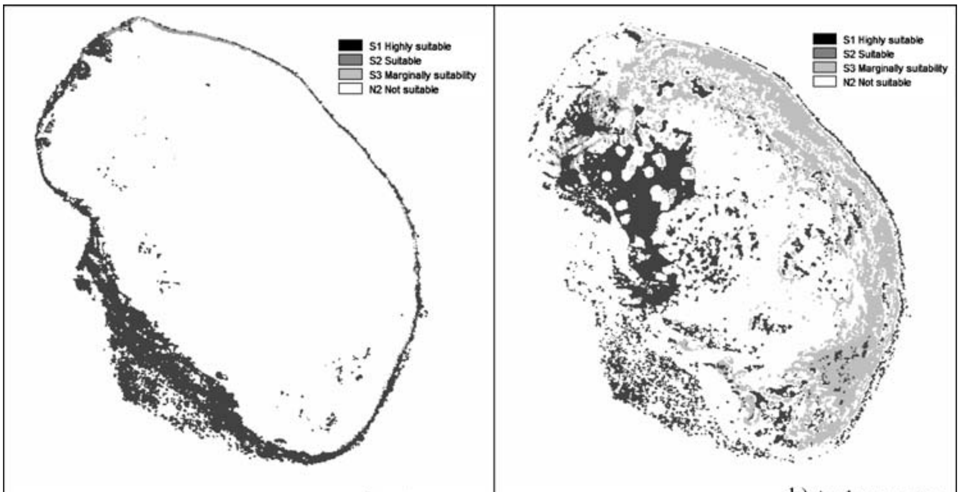
(*Continued on next page*)

(*Continued*)

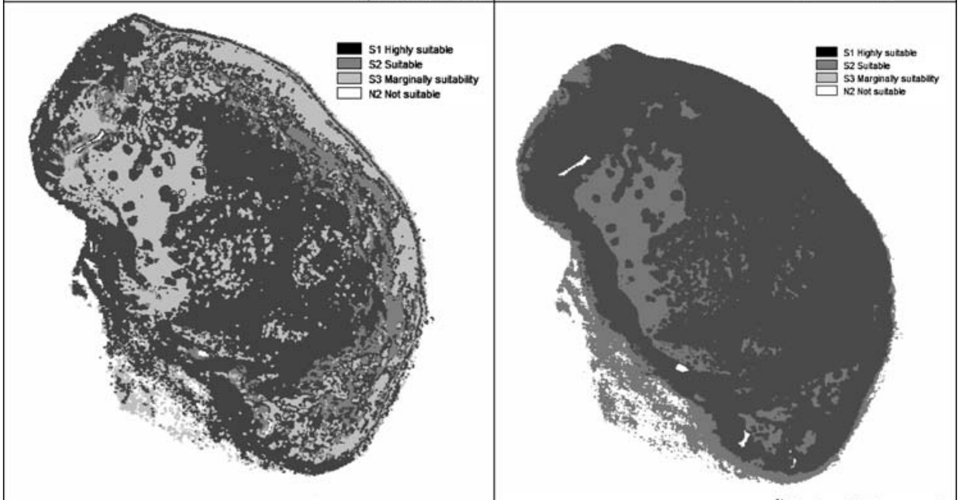
MapUnits	Fishing ornamental	Sea cucumber habitat	Queen conch habitat	Sailing
1	N2Bio-fishrich	S1	S1	S3Phys-depth
2	S2Phys-visib	S1	S1	S3Phys-depth
3	S1	S3Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S3Phys-depth
4	S3Phys-visib	S2Bio-sgrss_Malgae	S1	S3Phys-depth
5	N2Bio-cortot	S3Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S3Phys-depth
6	S1	N2Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S1
7	S2Phys-visib	N2Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S1
8	N2Bio-/Phys-cortot/visib	S3Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S1
9	S2Phys-visib	S2Bio-/Phys-sgrss_Malgae/depth	S1	S1
10	S2Phys-visib	S3Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S3Phys-depth
11	N2Bio-cortot	S3Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S1
12	N2Bio-/Phys-cortot/visib	S3Bio-sgrss_Malgae	S2Bio-sgrss_Malgae	S1
MapUnits	Recreational snorkeling	Sport fishing	Turtle feeding grounds	Surveillance
1	N2Bio-cortot	N2Bio-/Phys-Fishabu/depth	S1	S2Phys-navega
2	S1	N2Phys-depth	S1	S3Phys-navega
3	N2Bio-cortot	N2Phys-depth	S3Bio-sgrss_Malgae	N2Phys-navega
4	S3Phys-visib	N2Phys-depth	S2Bio-sgrss_Malgae	S2Phys-navega
5	N2Bio-/Phys-aestethic	N2Bio-/Phys-Fishabun/depth	S3Bio-sgrss_Malgae	S1
6	N2Phys-currents	S2Phys-depth	N2Bio-sgrss_Malgae	S1
7	N2Phys-depth	S1	N2Bio-sgrss_Malgae	S3Phys-depth
8	N2Bio-/Phys-cortot/depth	N2Bio-Fishabun	S3Bio-sgrss_Malgae	S3Phys-depth
9	N2Phys-depth	S1	S2Bio-/Phys-sgrss_Malgae/depth	S3Phys-depth
10	N2Phys-currents	N2Phys-depth	S3Bio-sgrss_Malgae	N2Phys-depth
11	N2Bio-/Phys-cortot/aestethic	S3Bio-Fishabun	S3Bio-sgrss_Malgae	S1
12	N2Bio-/Phys-cortot/depth	S2Bio-Fishabun	S3Bio-/Phys-sgrss_Malgae/depth	N2Phys-depth

Appendix 2. Suitability Maps for All RUT Evaluated at ARNP

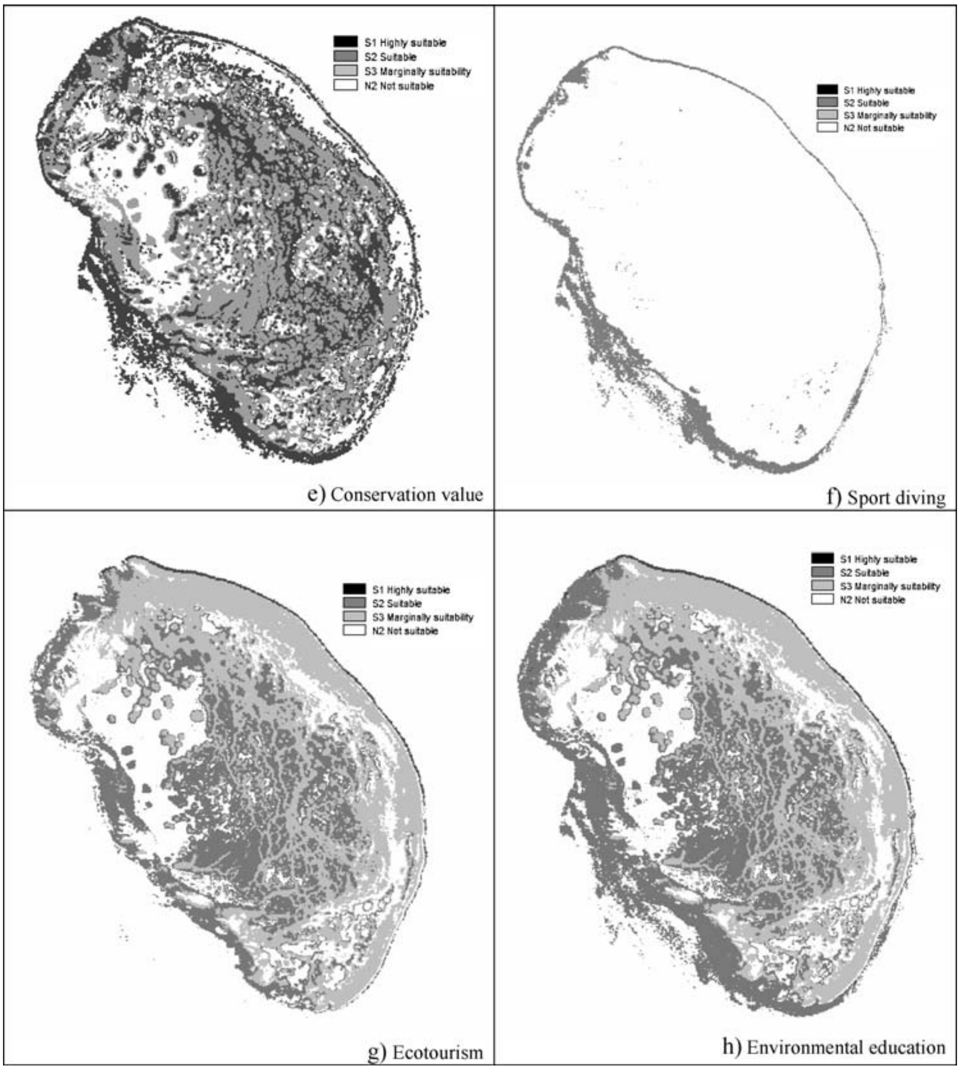
“Not suitable” areas (N2) are represented in white, “marginally suitable” (S3), “suitable” (S2) and “highly suitable” (S1) are presented in increasing dark tones of grey. Darker areas represent higher suitability.

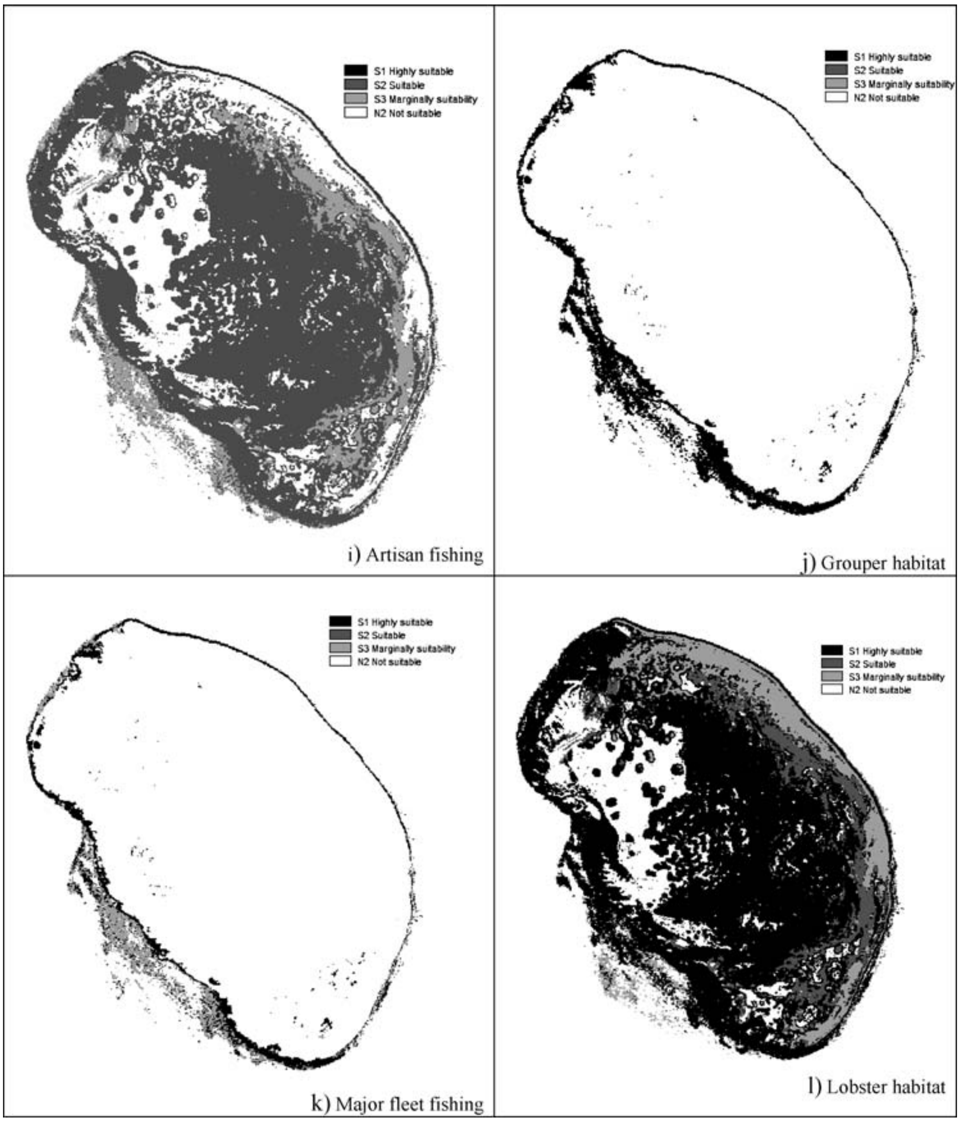


a) Lobster traps b) Anchorage areas



c) Carey turtle habitat d) Scientific Research


S1 Highly suitable
S2 Suitable
S3 Marginally suitability
N2 Not suitable
e) Conservation value
S1 Highly suitable
S2 Suitable
S3 Marginally suitability
N2 Not suitable
f) Sport diving
S1 Highly suitable
S2 Suitable
S3 Marginally suitability
N2 Not suitable
g) Ecotourism
S1 Highly suitable
S2 Suitable
S3 Marginally suitability
N2 Not suitable
h) Environmental education

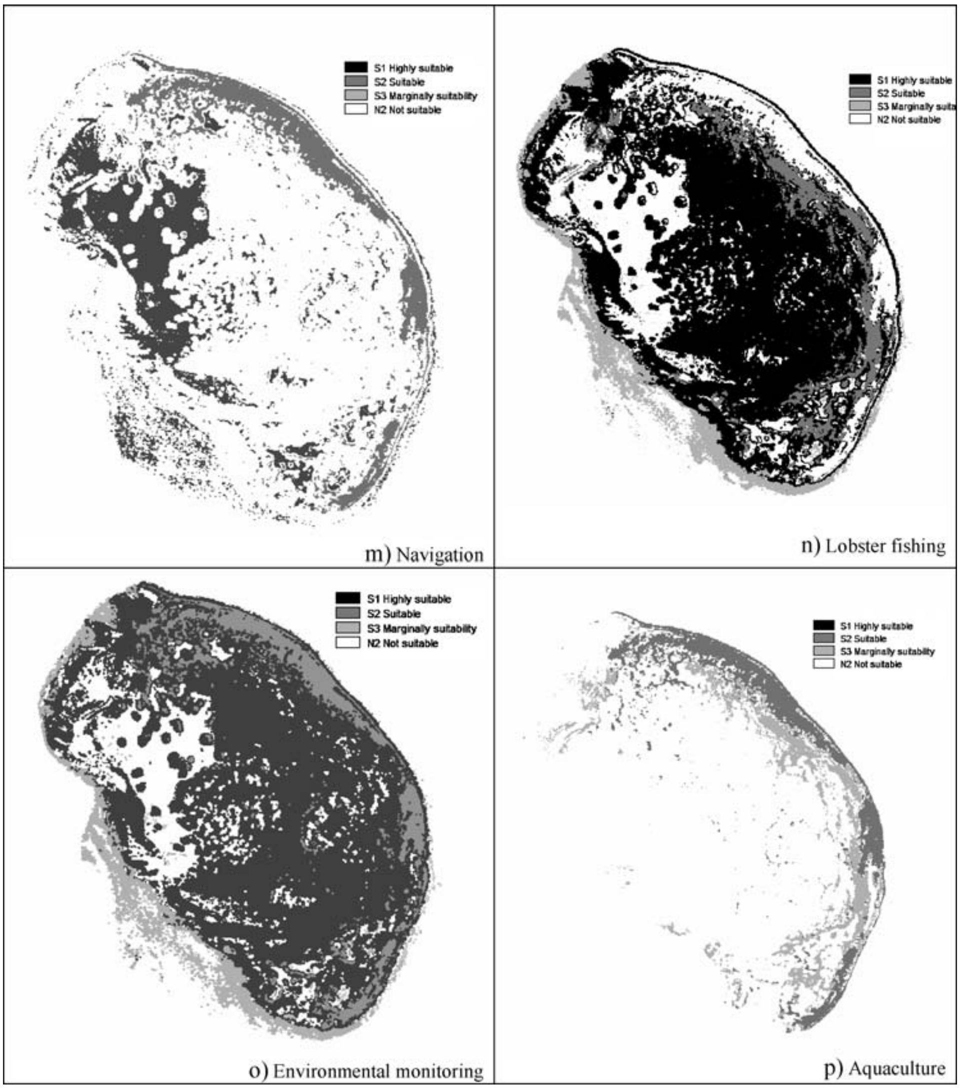


i) Artisan fishing

j) Grouper habitat

k) Major fleet fishing

l) Lobster habitat

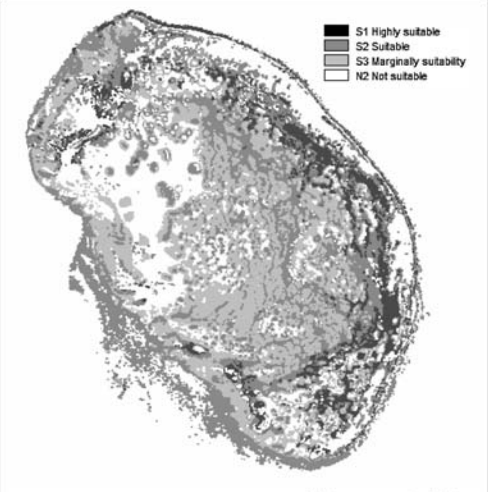


m) Navigation

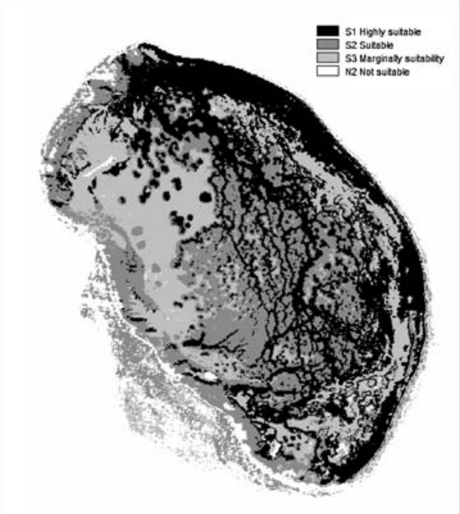
n) Lobster fishing

o) Environmental monitoring

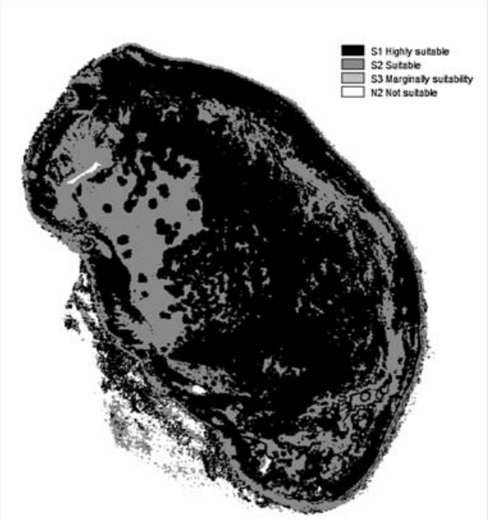
p) Aquaculture



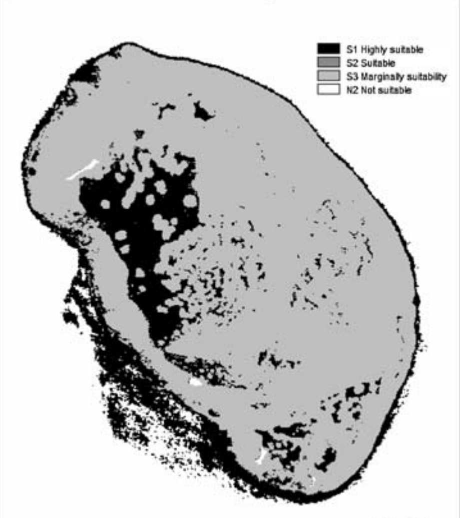
q) Ornamental fishing



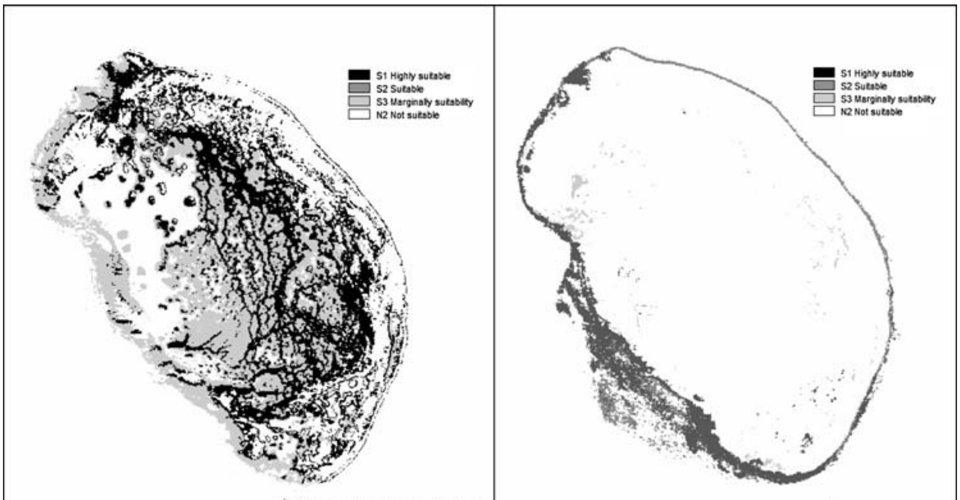
r) Sea cucumber habitat



s) Queen conch habitat

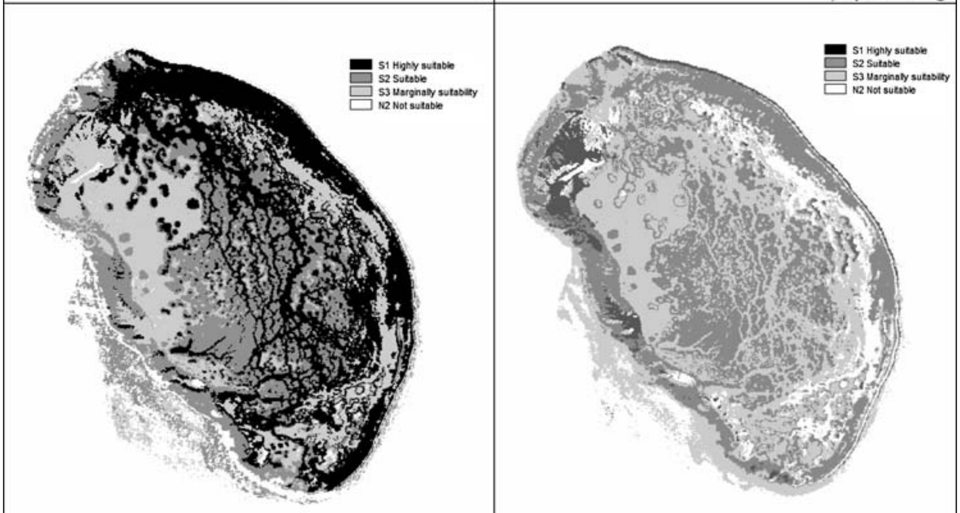


t) Sailing



u) Recreational snorkeling

v) Sport fishing



w) Green turtle feeding grounds

x) Surveillance

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