Integral Approach to Coral Reef Assessment and Monitoring

Enfoque Integral para la Evaluación y Monitoreo de Arrecifes Coralinos.

Approche Intégrée pour L'évaluation et Surveillance des Récifs Coralliens

JOAQUÍN RODRIGO GARZA-PÉREZ
Programa de Investigación Espacial en Ambientes Costeros y Marinos
Unidad Multidisciplinaria de Docencia e Investigación,
Universidad Nacional Autónoma de México. Sisal, Yucatán, México.

ABSTRACT

Baseline characterization and assessment of coral reefs, combined with long-term monitoring programs are keystone for the implementation of coastal and reef resources management policies, and they are essential for assessment of management effectiveness in MPAs. An integral approach to this task has been refined over the last decade incorporating advances in knowledge and technology, implementing a set of tools that builds geographic information on: What is where? How much there is? What is its condition? And, when enough monitoring data is available it adds: What are the temporal trends? These tools have ben developed to be time and cost effective incorporating information from field surveys (fish census, benthic communities videotransects, acoustic depth-surveys, water quality sampling) and high-resolution remotely sensed imagery, coupled with spatial predictive modeling and Geographic Information Systems. A digital platform (RealReefs) has also been developed to aid in the training of personnel to conduct field surveys and its products are available for free on the internet in the form of a web portal with manuals and tutorials and a mobile application to aid in the video-transect analysis.

KEY WORDS: Benthic communities, reef fish, topographic complexity, videotransects, satellite imagery, GIS

INTRODUCTION

Over the last few decades, since the popularization of SCUBA diving, our contact and interaction (as human society) with the tropical and shallow coral reef ecosystems, has been observed and, slowly but increasingly, has also been registered; first by anecdotic accounts of the wonders of the submarine environment, and as the technology has advanced, by underwater and aerial photography, cinematography, and in the last three decades by videography and even by remote sensed imagery (airborne sensors and satellite sensors). Sadly, these historical records tell the story of negative trends in these reef ecosystems (Jackson et al. 2001, Gardner et al. 2003, Pandolfi et al. 2003, Wilkinson 2008a,b) to the current point where 35% of the reefs of the world are at risk, 19% are severely damaged without prospects of recovery. The relatively short life-span of humans, compared to the geological time needed for the full development of a coral reef, and the increasingly fast change in these ecosystems, place us scientists, decision makers, stakeholders, and common people facing the paradigm of shifting-baselines (Pauly 1995, Sheppard 1995, Hogdson 1999, Jackson et al. 2001, Brunce et al. 2008, Pinnegar and Engelhard 2008). The quote of the Spanish philosopher George Santanaya (1905) *"…Those who cannot remember the past are condemned to repeat it…"* thoroughly applies in this context, and stresses the need of appropriate documentation of the status of our coral reefs (and each and every one of the Earth's ecosystems for that matter), in order to be able to make educated decisions regarding use and management, based on scientifically supported and validated information.

Traditional coral reef condition indicators as coral and fish species diversity and abundance, percentage of benthic cover (corals, algae, sponges, etc), topographic complexity or rugosity, coral disease incidence, are estimated in the field and they represent information on discrete spatial extents usually associated to broad reef zones (*i.e.* lagoon coral patches, backreef, reef front, reef slope), and this information answers the general questions — What is in the reef? and What is its condition?

With the popularization of GPS units in the last couple of decades, this information can now be linked to its actual location on the Earth's surface, with relatively high-spatial accuracy, and most importantly: it provides the means to extend or generalize the environmental information gathered in the field to vast areas with the aid of remote sensed data (satellite imagery) and Geographic Information Systems. Thus allowing scientists and resource managers alike to answer additional questions — Where is it? How much is there? It also makes available the information to a broader audience in the form of user-defined maps to answer specific questions regarding the particular needs of organizations or individuals (*i.e.* Where are the hotspots of coral diseases in my reef? Is there a difference in herbivorous fish distribution in my MPA?).

When these types of data have been collected systematically in the same areas over an amount of time, then their inherent value increases, as temporal trends of spatial patterns can be described and analyzed, and more importantly, they can be forecasted.

The case study of Mahahual Reef is presented, to showcase the implementation of a suite of survey and assessment techniques, and the integration of the information over time. This proposal can be regarded as an upgrade of previous implementations by Garza-Pérez et al. (2004) and Garza-Pérez and Ginsburg (2008), which involve techniques refinement and technology modernization.

The objective of this study was to characterize and assess the condition of the benthic community of Mahahual for 2011, using previously implemented techniques, and to evaluate the compatibility of the obtained data for its applicability on long term monitoring.

BACKGROUND

Mahahual is a small town located in the southern portion of Quintana Roo State in the Yucatán Peninsula, México. In the few last decades of the last century, Mahahual was a small fishermen village, relatively isolated from significant external influences, it had a poorly paved access road, no connection to the electrical grid, water was extracted from wells within the households, and its main economic activity was artisanal fisheries, focused on several scale and shellfish near the coast (grouper, snapper, barracuda, shark, white clam, conch, among others) and the Caribbean lobster fishery in Banco Chinchorro. In the last decade and a half, Mahahual has changed its main economic activity from artisanal fishing to tourism and services. As focal point of the Costa Maya project, Mahahual town has boomed, with new housing developments, hotels, streets paving, the construction of an international cruise pier along with a high-luxury shopping center, bars, restaurants, connection to the electrical, water, land-line and cellular telephone grids.

Mahahual reef has been assessed using video-transects since 1998 (Garza-Pérez 1999, Garza-Pérez and Arias-González 1999), a couple of years later in 2001 a new characterization and assessment was carried out using videotransects and satellite imagery coupled with a digital bathymetric model (Garza-Pérez 2004). In the first of those studies, the condition of Mahahual was defined as *good but with effect of disturbances*. This was after the massive bleaching event and after Hurricane Mitch, both in 1998. The average coral cover at that time was 25.24%, and the main indicators of disturbance were fields of *Acropora cervicornis* rubble – remnants of the massive Acroporids die-off from the 1980s, an 8.2% of the total reef cover of recently dead coral tissue (from bleaching) and a 6.4% of macroalgae cover.

For the second study, the condition of Mahahual was defined again as *good but stressed*, even though the average coral cover had decreased to 11.58%, macroalgae cover had increased to 19.42% and recently dead coral tissue cover was 0.08%. One new reef condition indicator implemented in 2004 was the amount of reef structure dominated by macroalgae. It was estimated for Mahahual using the field data coupled with satellite imagery and spatial predictive modeling. This indicator had a spatial distribution of 5.28% over the reef area.

METHODS

Study Area

The area of interest in this study is Mahahual reef, a sector of *ca.* 13 km of well-developed fringing reef along the coast (18º43'N, 87º41'W). It has well defined reef zones – reef lagoon with extensive seagrass beds and well developed back reef coral patches and reef crest. On the fore reef there are a transition zone/hardground bottoms, a shallow spur & grooves zone delimited by a sand channel and, a deep spurs & grooves zone in the reefs slope, adjacent to the continental drop-off (Figure 1).

Field & Lab Work

Depth Survey — A depth survey was carried out over the different reef zones using a GPS-Sounder (Garmin GPS

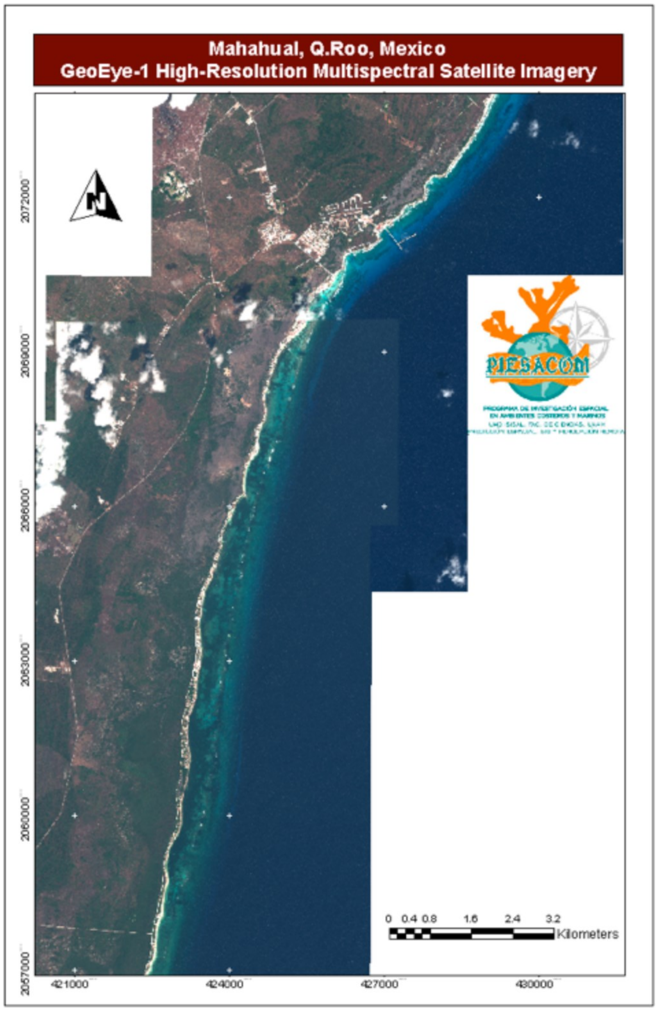

Figure 1. High-resolution satellite imagery for Mahahual Reef.

Map 178 Sounder) with dual-frequency transducer (50/200 kHz) coupled with an external datalogger (Brookhouse), it was mounted on a outboard-engine boat. The collected dataset (x,y,z points -Latitude, Longitude, depth-) was transferred to a computer and filtered for null and repeated data points.

Sampling Design — An existing network of 30 sampling stations, from 2001, was expanded to 48 using a random-stratified approach -randomly placing stations on different depth strata (corresponding roughly to four reef zones lagoon, hardground bottoms, shallow spur and grooves, and deep spur and grooves) with the condition of a minimum distance of 500 m between stations on the same depth strata, and relocating stations over sand to the nearest reef structure. All stations defined in the in the design were transferred to a Mobile Mapper 6 hand-held GPS unit (Magellan Navigation Inc.). The advantage of this unit over traditional GPS units is its capacity for displaying full resolution multispectral satellite imagery along with GIS vector files (shapefiles), which gives the user flexibility to adapt to variable marine and atmospheric conditions, and in the field ensures, by visual assessment of the geo-referenced satellite image, the correct positioning of stations over the proper reef zone and substratum.

Benthic Cover Assessment — A modernization of the video -transect method proposed by Garza-Pérez et al. (2004) was used to characterize and assess the benthic portion of Mahahual reef. The method consists in recording a 50 x 0.6 m transect of the reef substratum (30 m^2) in each defined station. The modernization consisted in using a Full-HD (1080i) digital camcorder (Sony Handycam HDR-HC9), in an underwater housing (Light & Motion StingRay HD) with LED flood video lights (Light & Motion, SunRay 600). The digital video files are transferred to a computer, and using Apple iMovie (v.9.0.2) video-processing software allows for quick tone and color corrections of the video. This pre-processing enhances greatly the identification of benthic features.

The video-transect analysis consists in identifying reef organisms and substrates under 13 systematically placed points on the screen, repeated at 40 pauses evenly distributed over the length of the transect. This identifications are: hard coral and fire coral to species level, algae to functional types, octocorals and sponges to shape, zoanthids, tunicates and inert substrates (including recent dead coral tissue) at category level. The total number of points identified along one transect is 520 and these are converted to percentage of cover estimates. The second part of the analysis consists in counting the coral colonies by species for the complete length of the transect, to obtain coral colonies density by species, and at the same time identifying coral injuries by type (mechanical – *i.e.* fish bites, coral diseases – *i.e.* yellow band, bleaching and others – *i.e.* growth anomalies). All these data are recorded and stored in spreadsheets to perform further statistical analyses.

Topographic Complexity Estimation — This is carried out in the field with the Chain- transect method, which consists in placing carefully a known-length fine-link chain, along the reef surface, in a straight line, following all the calcified structures, crevices, and holes in the substrate. Then the extension of the chain is measured with a tape, and the difference between the known length of the chain and the measured extension gives the topographic complexity or bottom rugosity estimate.

Satellite Imagery Pre-Processing — A 130 km^2 scene of Mahahual reef and its adjacent coastal zone was acquired on May 2011, from the GeoEye-1 (GeoEye Inc.), high-resolution sensor (2 m Multispectral, 0.5 Panchromatic). The scene has low cloud cover (> 8%) and good visibility of underwater features. The marine area was extracted from the original scene and a deglinting procedure (Hochberg et al. 2003) was applied to correct the effect of sunglint on the sea surface. On this de-glinted imagery set (three bands) a correction of the water-column effect was applied (Green et al. 2000), and a new imagery set of 3-bands was obtained.

Depth Prediction — From the depth survey database, a subset of 1294 points was extracted and then divided in half. One half of this subset (647 points) was used to fit a General Additive Model using GRASP v.3.5 script in S-Plus 2000 (Mathsoft Inc.) for the prediction of depth in the entire Area of Interest; the depth database was used as response variable and the associated data extracted from each satellite band corresponding to the 647 points were used as predictive variables (Corrected bands 1, 2 and 3. The other half of the database (647 points) was used to assess the accuracy of the map of predicted depth.

Reef Habitat Thematic Mapping — Reef habitats were defined using the field stations data on benthic cover in a hierarchical cluster analysis (MVSP, Kovach Computing). The stations corresponding to each class from the cluster analysis were used as Regions Of Interest (ROIs) in a supervised classification procedure (ENVI v.4.7, ITT) using the corrected satellite bands. For this procedure, the image was split into Reef Lagoon and Fore Reef. Each zone was masked and classified on their respective classes, and then the classified images were merged in ArcMap v.10 (ESRI, Inc.) to generate a reef habitat map.

Spatial Prediction of Benthic Components — Spatial predictive maps of coral and macroalgae cover were generated with GRASP, in the same way as the depth prediction, using the benthic cover data from the video-transects by station as response variables and the new satellite bands from the corrected imagery and the digital bathymetric model as predictive variables.

RESULTS

A Digital Bathymetric Model for Mahahual Reef was generated at a spatial resolution of 2 x 2 meter square. Accuracy assessment of the map ($r = 0.88$ with a RMSE of 1.02m), using a subset of the original data as observed values, and the predicted depth in the same points (Figure 2).

The average coral cover estimated for Mahahual reef in 2011 is 6.33%; the coral community has a species richness of 32, and is dominated by *Undaria agaricites*, which stands for 20% of the total coral colonies in the fore reef. Main reef building corals account for 35% of the colonies, being *Montastrea faveolata, S. siderastrea and M. annularis,* the three most important among these (Figure 3).

The benthic cover assessment estimated the average hard coral cover in the reef front at 8.56%, macroalgae (brown, green, red and *Halimeda*) 12.4%, octocorals 9%, sponges 3% and the vast majority of otherwise bare substrata (coral rock and calcareous pavement) was overgrown with filamentous algae/cyanobacteria (55%) (Figure 4).

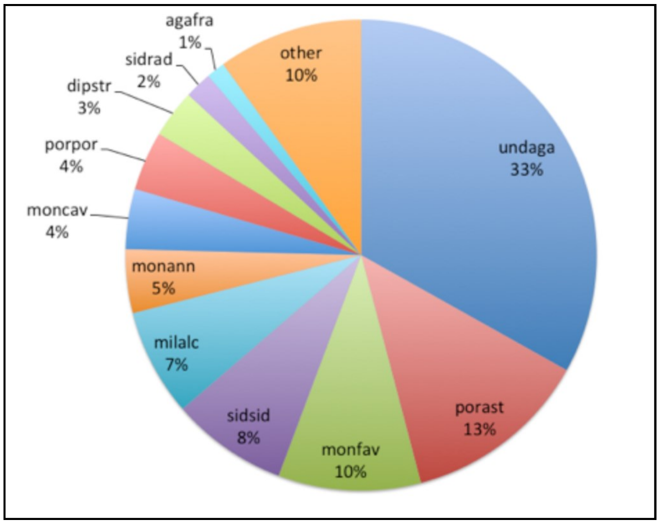

Figure 3. Coral species assemblage for Mahahual reef in 2011, percentage in terms of recorded coral colonies (n = 3,293), during the survey.

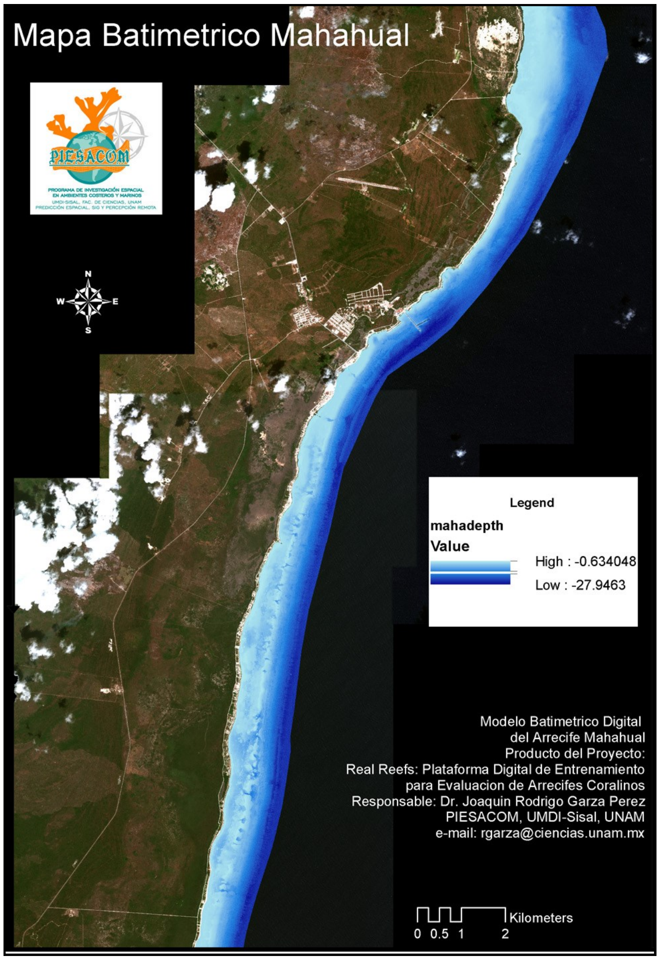

Figure 2. High-resolution depth prediction map for Mahahual Reef, derived using GRASP, bathymetry surveys and a GeoEye-1 multispectral image.

The thematic map of reef habitats was generated using two separate classification schemes of 7 and 8 classes for the reef lagoon and the reef front and slope respectively, and merging the resulting supervised classification images (Figure 5). The benthic cover of nine of those classes was compatible with the previous thematic map of 2001, and three new classes were defined, one for seagrass beds (in the lagoon) and two more for the transition zone (in the reef front). This map was also used to assess the condition of the reef, based on a previous definition of a reef habitat:

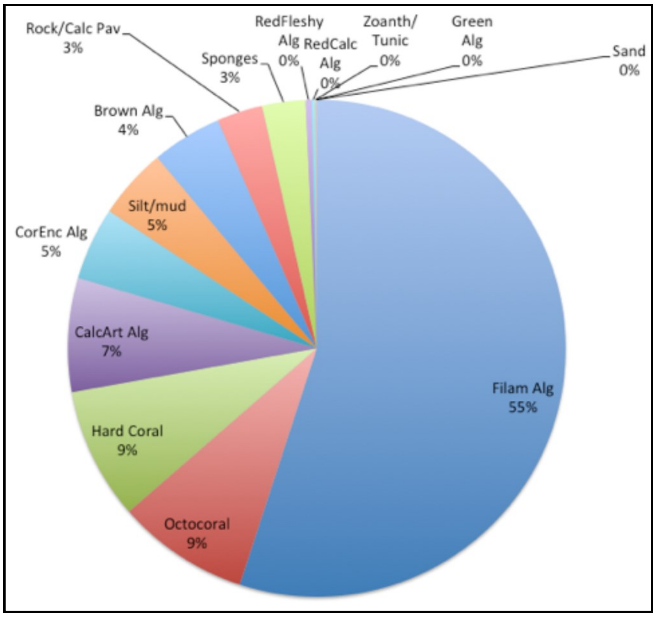

Figure 4. Benthic community composition for Mahahual reef in 2011, percentage in terms of recorded cover.

Developed Spurs & Grooves, dominated by Macrolagae; the estimated reef area occupied by this habitat was 2.09%.

The predictive maps of cover of hard coral and macroalgae for the reef front had a general accuracy of 76% and 86% respectively, and represented adequately the range of cover values for each benthic component: 0 – 15% for hardcoral and 0 – 17% for macroalgae (Figure 6).

DISCUSSION

The benthic community for Mahahual reef, has experienced a sharp decrease in average coral cover, from 20.5% in 2001 (Garza-Pérez 2004), to 9.83% in 2011. This, according to Perry et al. (In press) jeopardizes the reef's capacity to preserve its rugosity (topographic complexity) via coral accretion, thus risking the significant loss of reef functions as refuge. The proportion of main reef building coral species for both dates remain relatively constant (30% in 2000 vs. 31% in 2011), pointing to a relatively even decrease of all coral species, and a shift in dominance from *U. agaricites* and *M. faveolata* in 2001, to *S. siderea* and *U. agaricites* in 2011 (Figure 7).

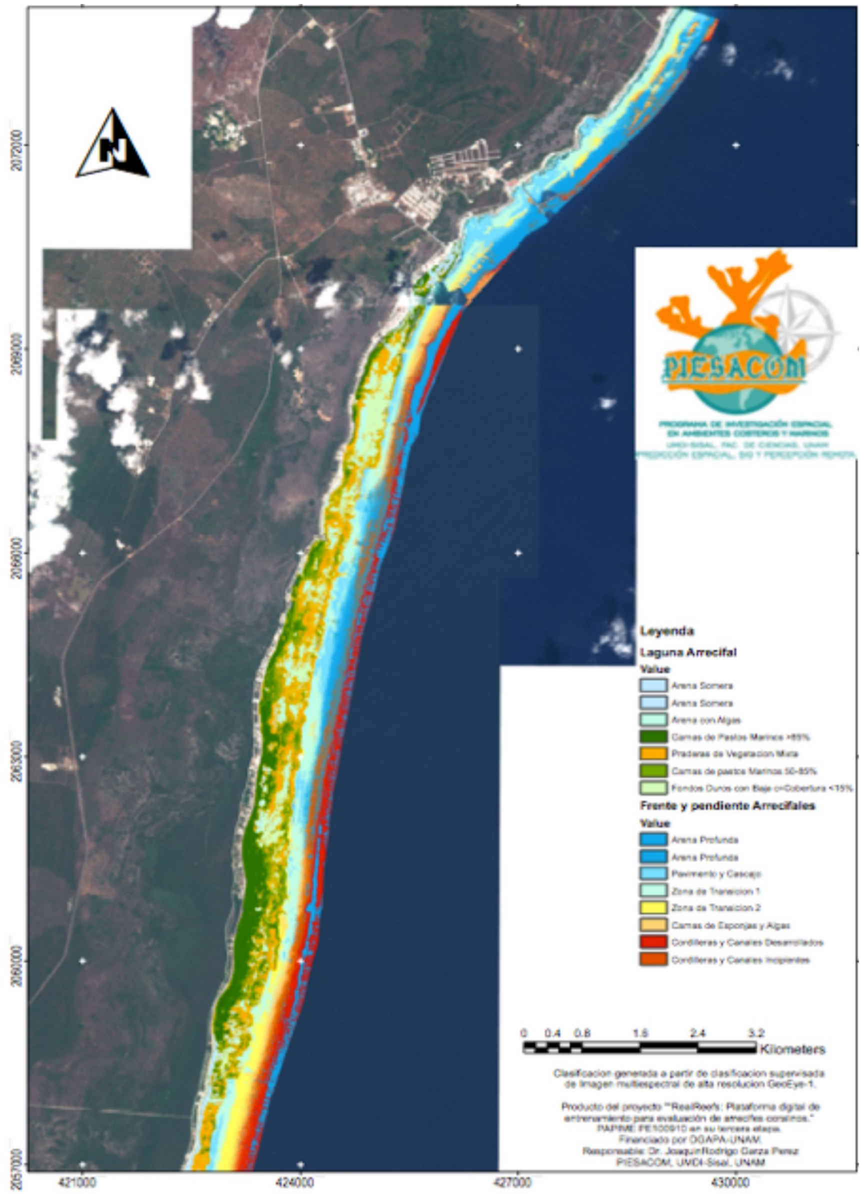

Figure 5. Mahahual reef habitat thematic map, 13 classes with a general accuracy of 85.4%.

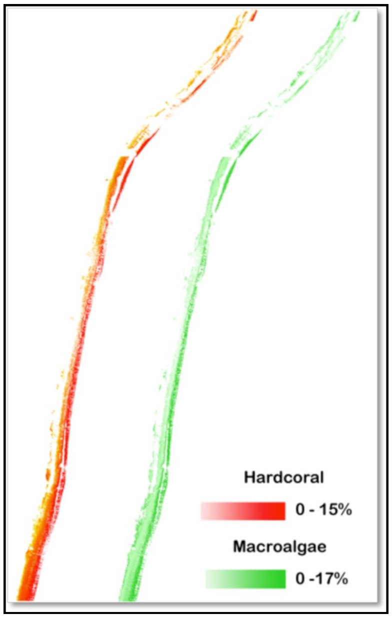

Figure 6. Predictive layers of hard coral cover and macroalgae cover for the reef front and reef slope zones in Mahahual, 2011.

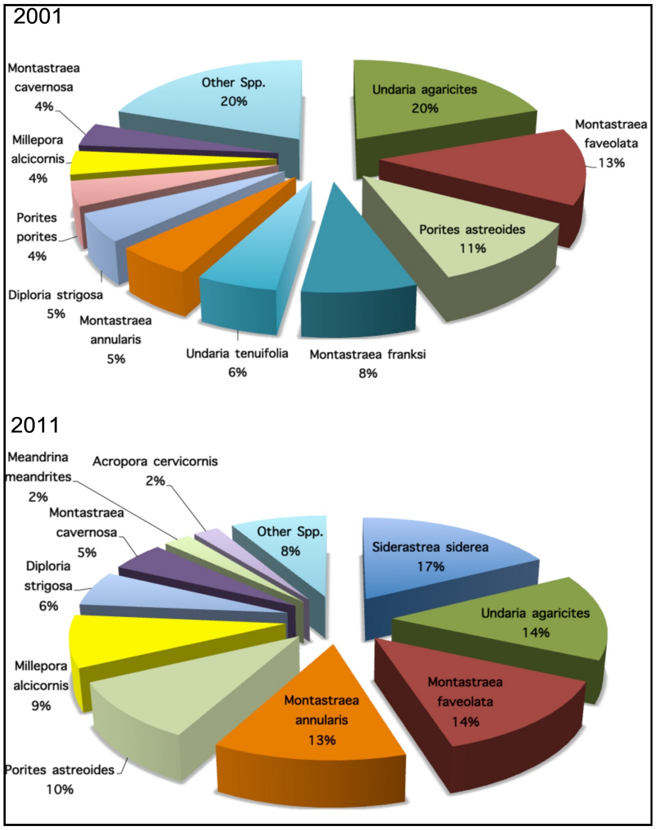

Figure 7. Coral community comparison for Mahahual reef 2001 vs. 2011. In 2001, the average coral cover was 20.5% ± S.D. 11.8, with a proportion of 30% of primary reef building coral species. For 2011, the average coral cover was 9.83% ± S.D. 5.7, with a proportion of 31% of primary reef building coral species.

Other important benthic components that experienced shifts in covers are the macroalgae – they decreased from an average cover of 15.04% in 2001 (Garza-Pérez 2004) to 5.33% in 2011, and the filamentous algae, that only represented a 5% of cover in 2001, spiked to 37%. This might be related to what we assume an increase in the nutrients in the coastal waters due to the increase in the human population density and coastal land modification in the last decade. On the one hand, there was an explosive housing and tourist infrastructure in the area related to the international cruise pier built in 2000 and hurricane Dean in 2007 devastated an important mangrove forest area behind the town, rendering non-operational its nutrient-buffering function. In relation with the high filamentous algae cover (55%) growing over encrusting coralline algae, and the medium macroalgae cover (12.4%) recorded in 2011, the results by Littler and Littler (1984), Lapointe et al. (1997) Lapointe (1999), and Thacker et al. (2001), would point to a high-availability of nutrients, and very low herbivore biomass (1.54 g/m^2) in Mahahual reef.

The predictive maps of coral and macroalgae cover were obtained using more refined geospatial products. In the one hand, the high-resolution (2 x 2 m/pixel) satellite imagery was used to derive the bathymetry map and to extract a very precise depth range encompassing the only the reef front and reef slope. On the other hand, the predictions of cover using the same imagery were spatially accurate, depicting clearly the reef structure, thus avoiding over-estimations of area covered by corals and algae.

The bathymetry product from 2001 was generated using geostatistical modeling -kriging- and data from a field bathymetry survey, forcing the final product to a 4 x 4 m/pixel resolution (Garza-Pérez 2004), and the result was a bathymetric model depicting accurately the general geomorphology of the reef, but lacking the inherent rugosity of the reef structures.

The comparison between the predictive maps of cover from 2001 and 2011, make relevant the spatial resolution of the imagery products used, even when 2001 imagery was also high-resolution multispectral (Ikonos) at 4 x 4 m/pixel, there are substantial qualitative differences among the maps. Nevertheless, these differences can be leveled performing pan-chromatic enhancements – pan-sharpening – (Vrabel 1996, Yuen 1999) to the multispectral bands of the Ikonos image, to resample the multispectral bands to a higher-resolution image, and then re-predicting the coral and macroalgae cover using the 2001 field data with the enhanced archival imagery. This can be used in combination with the depth range extract from 2011, or deriving a new bathymetry model from the 2001's enhanced imagery.

Among of the combined messages that these results convey is the necessity of thorough planning for long-term monitoring activities. This involves aspects such as the selection of the monitoring stations, the data that will be recorded and the methods to achieve it, data base management, and the preservation of the original media (field annotations, video media, etc.) that ultimately will provide the necessary contextualization of the data and the feasibility for valid comparisons. On the other hand, it brings to attention the advancement of technology. Media and files containing the monitoring data must be upgraded or transferred to new devices, and to be converted into new formats, compatible with current hardware and software, while the previous generation of hardware and software is still available and working. We have run into media backward-compatibility issues, trying to access old Video8 tapes, and database files stored in 3.5" diskettes or ZIP cartridges, and current hardware not supporting those media formats.

Another important issue that must be stressed is – as long as the original datasets (field data records and videos, satellite imagery, depth surveys) are available, all archival products (maps, models, databases) can be re-processed and upgraded using the latest advancements in techniques such as habitat mapping or spatial prediction, thus making possible the direct comparison between products.

CONCLUSIONS

The main message of this study is that, as many others point out, we are recording the demise of our reefs, and the information we are producing is still in a bottleneck. We have not found yet the most useful and optimized way to communicate our scientific knowledge to the decision makers and to the stake-holders. Maps and the inherent synoptic information they convey might be one of the most powerful tools to communicate what we know to those in need of that information. In this regard, the combined environmental monitoring and assessment and the generation of maps depicting the change trends along the coral reefs, can and must be used for decision making support and towards the modeling of future scenarios to further support those decisions and policies.

LITERATURE CITED

Aronson, R.B., J.F. Bruno, W.F. Precht, P.W. Glynn, C.D. Harvell, L. Kaufman, C.S. Rogers, E.A. Shinn, and J.F. Valentine. 2003. Causes of coral reef degradation. *Science* **302**:1502-1504

Bunce, M., L.D. Rodwell, R. Gibb, and L. Mee. 2008. Shifting baselines in fishers' perceptions of island reef fishery degradation. *Ocean & Coastal Management* **51**(4):285-302.

Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant, and A.R. Watkinson. 2003. Long-term region-wide declines in Caribbean corals. *Science* **301**:958-960.

Garza-Pérez, J.R. 1999. Análisis comparativo de cuatro comunidades coralinas arrecifales del Caribe Mexicano, Tesis de Maestría, CINVESTAV-IPN, México. 64 pp.

Garza-Pérez, J.R. and J.E. Arias-González. 1999. Temporal change of a coral reef community in the south Mexican Caribbean. *Proceedings of the Gulf and Caribbean Fisheries Institute* **52**:415-427.

Garza-Pérez, J.R. 2004. *Información y Manejo para la Protección de la Biodiversidad de la Barrera Arrecifal de México: Evaluación de Variables, Modelación Espacial del Hábitat y SIG*. Tesis Doctoral Depto. de Recursos del Mar, CINVESTAV-IPN, Unidad Mérida, México. 189 pp.

Garza-Pérez, J.R., A. Lehmann, and J.E. Arias-González. 2004. Spatial prediction of coral reef habitats: integrating ecology with spatial modeling and remote sensing. *Marine Ecology Progress Series* **269**:141-152.

Garza–Pérez, J.R. and R.N. Ginsburg. 2008. Replenishing a near-collapsed reef fishery, Montecristi National Park, Dominican Republic. *Proceedings of the Gulf and Caribbean Fisheries Institute* **60**:465-474.

Green, E.P., P.J. Mumby, J.E. Alasdair, and C.D. Clark. 2000. *Remote Sensing Handbook for Tropical Coastal Management.* UNESCO Publishing, Paris, France.

Hochberg, E.J., S. Andréfouët, and M.R. Tyler. 2003. Sea surface correction of high spatial resolution Ikonos images to improve bottom mapping in near-shore environments. *IEEE Transactions on Geoscience and Remote Sensing* **41**(7):1724-1729.

Hodgson, G. 1999. A global assessment of human effects on coral reefs. *Marine Pollution Bulletin* **38**(5):345-355.

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.A. Lenihan, J.M. Pandolfi, E.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**:629-638.

Lapointe, B.E., M.M. Littler, and D.S. Littler. 1997. Macroalgal overgrowth of fringing coral reefs at Discovery Bay, Jamaica: bottom-up versus top-down control. *Proceedings of the 8th International Coral Reef Symposium* **1**:927-932.

Lapointe, B.E. 1999. Simultaneous top-down and bottom-up forces control macroalgal blooms on coral reefs (Reply to the comment by Hughes et al.). *Limnology and Oceanography* **44**(6):1586-1592.

Littler, M. M., & Littler, D. S. (1984). Models of tropical reef biogenesis: the contribution of algae. Pages 323-364 in: F.E. Round and D.J. Chapman (eds.) *Progress in Phycological Research, Volume 3*. Biopress, Bristol, England.

Pandolfi, J.M., R.H. Bradbury, E. Sala, T.P. Hughes, K.A. Bjorndal, R.G. Cooke, D. McArdle, L. McClenachan, M.J.H. Newman, G. Paredes, R.R. Warner, and J.B.C. Jackson. 2003. Global trajectories of the long-term decline of coral reef ecosystems. *Science* **301**:955-958.

Pauly, D. 1995. Anecdotes and the shifting baseline syndrome in fisheries. *Trends in Ecology and Evolution* **10**:420.

Pinnegar, J.K. and G.H. Engelhard. 2008. The 'shifting baseline' phenomenon: a global perspective. *Reviews in Fish Biology and Fisheries* **18**:1-16.

Santanaya, G. 1905. *The Life of Reason: Or, The Phases of Human Progress, 5v Volumes* Available free online from Project Gutenberg. 1998. Volume 1 abridgement by the author and Daniel Cory. Prometheus Books, Amherst, New York USA. 512 pp.

Sheppard, C. 1995. The shifting baseline syndrome (editorial). *Marine Pollution Bulletin* **30**:766–767.

Thacker, R.W., D.W. Ginsburg, and V.J. Paul. 2001. Effects of herbivory exclusion and nutrient enrichment on coral reef macroalgae and cyanobacteria. *Coral Reefs* **19**:318-329.

Vrabel, J. 1996. Multispectral Imagery Band Sharpening Study. *Photogrammetric Engineering & Remote Sensing* **628**(9):1075-1083.

Wilkinson, C.R. 2008. *Status of Coral Reefs of the World: 2008*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia. 298 pp.

Wilkinson, C., and D. Souter. 2008. *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia. 148 pp.

Yuen, P.W. 1999. *Enhancing the Resolution of Multispectral Image Data with Poanchromatic Image Data Using Super Resolution Pansharpening*. U.S. Patent #5,949,914.