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Conservation of Pulau Payar Marine Park and Optical Remote Sensing Models

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Abstract. An integration of strategies in conserving declining coral reefs requires a dynamic approach. In this essay, a combination of three technical approaches was applied to a coral reef area of a marine protected area in the northern Straits of Malacca as a science-based ecosystem approach for natural resource conservation measure. Optically-derived physical water quality models of Total Suspended Solids and chlorophyll-a applied to a series of satellite images to assess the distribution of physical water quality and indirect chemical water quality conditions will provide a historical view of the crucial element that governs the coral reef health. It will also provide insights to coral reef ecosystem response to direct pollution from surrounding waters or land-based pollution inputs from adjacent areas. The hydroacoustic signal classification system which measures different hardness and roughness of bottom sediment substrates stores, categorises and manipulates data received, and produces maps of sea-bed types will aid in determining the percentage of live and dead corals, and in the inventory process of applying Limits of Acceptable Change (LAC) for a large scale survey. LAC framework has a broad applicability to complex tourism setting such as marine protected areas where development of measurable objectives defining desired wilderness and the identification of management actions to provide overall quality enjoyment of tourism are possible while preserving the fragile ecosystems of coral reefs. This is considered a science-based ecosystem approach which is viable, cost-effective, time saving and is based mainly on scientific data of a sensitive ecosystem. This integrated approach with its intensity may fulfil the possibility of identifying the actual limits of acceptable change and the designing of implementation actions for our depleting resource.

Keywords and phrases: optical remote sensing models, Limits of Acceptable Change, hydroacoustic signal classification, reef conservation, natural marine resource heritage

Introduction

For several decades now, scientists and environmentalists have been combining different methods to assess our current status of environment. The complexity of the earth's ecosystems dictates that an integrated approach will be required to manage the dynamic system of the coastal and marine environment. An integrated approach necessitates integrated strategies to achieve the priority of conserving and sustaining (including the management of) coral reefs on local or global scales. Since conservation and sustainable management are inextricably linked, though not synonymous, both these objectives can be realised through the maintenance of species as well as habitat diversity and integrity for which a range of data inputs is required which can be collected through an integrated approach. These range of data input constitute the directions along which future management-based ecological research should be conducted. The multitude of current reef exploitative and degradatory practices, together with the paucity of knowledge on reef ecology, dictates that the precautionary approach incorporating an integrated course of action be speedily adopted for the sustainable management of our local coral reefs. Addressing the many threats to coral reefs cannot be approached separately when working in actual geographic areas. Implementation of activities to conserve coral ecosystems must be integrated into an ecosystem-based management approach to ensure a holistic and integrated management approach to support healthy, resilient coral reef ecosystems. Effective conservation of coral ecosystems must be based on the needs of the varying ecosystems and communities and cannot take a one-size-fits-all approach. For instance, the placement of a marine protected area can effectively address the impacts of fishing and/or conserve an area potentially resilient to climate change, coupled with efforts to address land-based sources of pollution from adjacent and associated watersheds (National Oceanographic and Atmospheric Administration [NOAA] 2011).

Coral reefs are among the most diverse and biologically complex ecosystems on earth. These *rainforests of the sea* provide economic and environmental services to millions of people as areas of natural beauty and recreation, sources of food, jobs, chemicals, pharmaceuticals and shoreline protection. Now under threat from multiple stresses that are overwhelming their natural resilience, coral reefs are deteriorating worldwide at alarming rates. The United States Coral Reef Task Force (USCRTF 2000, 3) stated that:

> Ironically, the value of coral reefs to the nation is matched only by their vulnerability to harmful environmental changes, particularly those resulting from human activities. Present estimates are that 10 percent of all coral reefs are degraded beyond recovery; 30 percent are in critical condition and may die

> within 10 to 20 years, particularly those near human populations; and, if current pressures continue unabated, another 30 percent may perish completely by 2050.

Two years later the situation had not improved. An estimated 10 percent of the world's reefs have already been lost and 60 percent are threatened by bleaching, disease and a variety of human activities including shoreline development, polluted runoff from agricultural and land-use practices, ship groundings, over-harvesting, destructive fishing and global climate change (USCRTF 2000). The trend in coral reef health is downward, and these ancient ecosystems are in peril. The intensification of global decline in coral reef health has galvanised an international movement to save these invaluable ecosystems. International Coral Reef Initiative (ICRI) and Global Coral Reef Monitoring Network (GCRMN) were amongst the first few formed as a global response to this crisis.

Malaysia is situated on a continental shelf and its reefs are mostly shallow, fringing and sporadic. Pristine reefs are located further beyond reach of the human population and its impacts. For reefs nearer to shore or to the mainland, most good reefs had been gazetted into Marine Parks. These parks were established primarily for resources conservation, protection, management of the environment, habitat restoration and rehabilitation, promotion of awareness and education, to conserve and conduct research on the rich biodiversity contained in the marine park waters. Like any other country, Malaysia had become a tourists' attraction for its unique and its diverse coral reefs (Li 1998). This attraction itself—the coral reefs being a fragile and sensitive natural heritage, had increased the number of tourists to millions per year (Li 1998; Anisah Lee Abdullah 2004). Growth not only in tourist numbers but also of facilities, infrastructure, aircraft operations and tourism services have led to a booming tourist economy built around what is perceived internationally as new and exotic destination (Li 1998; Mbaiwa 2009). However, one of the greatest challenges is deciding how to provide for overall quality enjoyment of increasingly large numbers of visitors while conserving and preserving the fragile ecosystems within the marine park particularly its coral reefs. Applying certain management tool enables a park to preserve its natural and cultural resources by limiting the number of visitors and/or vehicles within an area at any given time.

Among existing frameworks, Limits of Acceptable Change (LAC) which comprises of a nine step process (Figure 1) has the broadest applicability to be applied to marine park. One of the techniques in the determination of coral health status in Pulau Payar was mapping the distribution of corals. We do not know what lies in the ocean floor be it deep or shallow. We "know" of the coral reefs through our exploration at certain spots or zones that attract us more than others but rarely do we frequent less popular zones. This gives us insights to certain reef zones in detail but not much on the adjacent or less attractive surrounding areas. Scientists have now started using sonar to sweep over to explore and map the ocean floor (National Geographic Society 2011). NOAA has started its project in 2004 to sweep the ocean floor of the Caribbean and Costa Rica using sonar to create a comprehensive map of the seabed which includes bottom substrate types, depth, bathymetry amongst others with incredible detail and frequency. This is still a new technique that can and should be applied to Malaysian waters to comprehensively map our seabed with particular priority to our natural heritage zones i.e., the coral reefs.

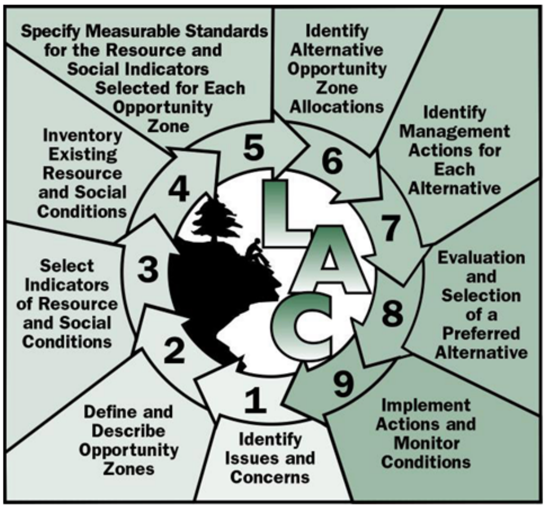

Figure 1. The nine-step process of LAC (source: United States Department of Agriculture, Forest Service)

Within the LAC framework, the first step—identification of area of concerns and its issues and step four—resource inventory, are the main concerns relating to the study. One of the techniques used in this study is hydroacoustic signal classification (RoxAnn^{TM}). It has become an alternative approach in mapping the underwater substrate as it is cheaper and applicable for mapping broad scale distribution of substrate rather than scuba diving. Furthermore, hydroacoustic method does not depend on the surface weather, underwater visibility, water depth or experiences or knowledge from the researcher for coral identification. This essay aims to show the efficiency of adopting a science-based ecosystem approach to understanding of coral ecosystem as a measure of natural heritage conservation effort through the incorporation of hydroacoustic signal substrate classification technique with LAC in substrate determination at the Pulau Payar Marine Park off the coast of Kedah. In a science-based ecosystem approach, scientific data collected from the sensitive ecosystem itself plays a major role which is crucial in its own evaluation.

RoxAnn Hydroacoustic Signal System

Hydroacoustic signal was first introduced as an active sound in water (sonar) to study and to determine fish biomass and spatial distribution. Nowadays, the system was extended and applied as an alternative survey tool in coral ecology and coral management. Although the conventional scuba diving method for direct measurement and censusing still provides the most reliable survey technique and first-hand data collection to date, this method poses high risks, time-consuming and less cost-effective. Scuba diving method is more restricted by water depth, weather condition, tidal and current condition and on certain days, poor visibility. These risks and restrictions made scuba diving method almost impossible to produce a broad-scale map of coral coverage. To date, the hydroacoustic system is more applicable for mapping coral in broad-scale area as it is cost-effective, more time-effective and less effort is needed compared to the conventional scuba diving method. This acoustic mapping provides a good representation of coral and substrate distribution for broad-scale area especially in areas impossible to be reached by scuba diving method.

RoxAnn bottom classification system is an example of hydroacoustic signal method and this system was chosen to be applied in substrate determination in Pulau Payar Marine Park. RoxAnn is a broad-scale acoustic ground discrimination system which visualises seabed bathymetric under a survey vessel (Chivers et al. 1990). It is widely used for marine habitat and community mapping (Magorrian et al. 1995; Pinn and Robertson 1998; Brown et al. 2005) and for environmental monitoring (Service 1998; Rukavina 2001).

The principle of RoxAnn method is basically processing single beam sonar using echoes integrated approach emitted by an echo sounder which interprets two distinct echoes from the seabed (Chivers et al. 1990). It then listens and processes the signals returned by the transducer. The first echo (E1) which is the acoustic backscatter of the substrate measured the roughness of the substrate. The rougher materials scatter more acoustic energy back towards the transducer. Smoother substrate will act like a mirror and reflect most of the acoustic energy from the transducer. Further information of the seabed is obtained from the second echo (E2) which is more sensitive to the hardness of the substrate than the first echo (Chivers et al. 1990; Heald and Pace 1996). The second echo return is a measure of the acoustic impedance of the substrate. The softer the substrate, the greater is the acoustic impedance of the substrate. The timing diagram for E1 and E2 is shown in Figure 2.

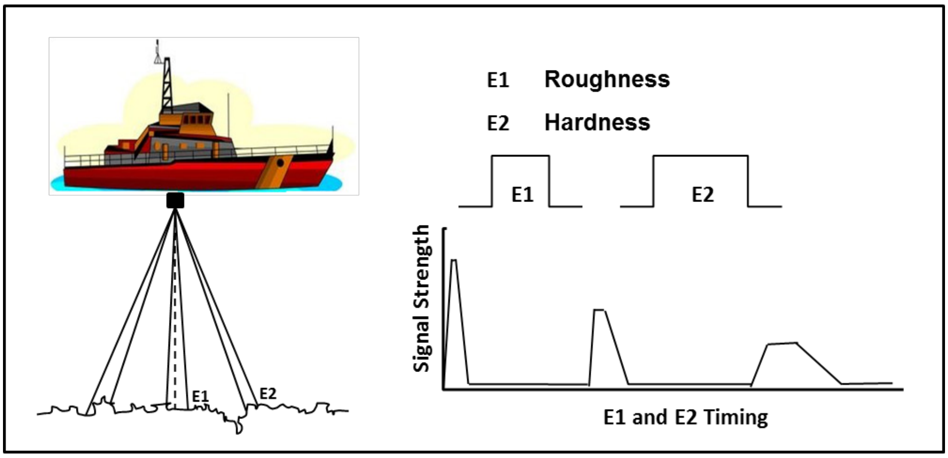

Figure 2. Echo signal processing technique (source: Chivers et al. 1990)

A complete RoxAnn hydroacoustic signal system incorporates the input of real time, geo-referenced survey data, i.e., longitude and latitude. For each valid E1 and E2 signal collected, the RoxAnn system sends a RS232 string containing depth, E1 and E2 information to the PC/laptop for processing using the RoxMap Scientific Software. With the information gathered from E1 and E2, a RoxAnn Square is configured (Figure 3). It is a Cartesian XY graph, where E1 (index of roughness) is plotted along the Y-axis and E2 (index of hardness) is plotted along the X-axis. Since every substrate will have a different range of E1 and E2 values, the different range of E1/E2 will give different types of substrates. These areas can be "boxed off" or classified with an assigned colour and is shown diagrammatically as user-defined RoxAnn RoxSquare (Cholwek et al. 2000). The data from RoxAnn were compiled with additional data such as integrated GPS, depth, time and data information and interpreted by using geographical information system (GIS) to produce contour maps of the factor interest (Davies et al. 1997; Sotheran et al. 1997).

Based on RoxAnn's principal and potential applicability, it is hoped that the method of hydroacoustic signal classification system will be proven as an effective broad-scale mapping procedure in the natural heritage conservation strategy. This is because rapid, frequent and large scale coverage of an invaluable coastal resource and fragile ecosystem such as the coral reef is required bearing in mind that higher tourist influx will increase the environmental impacts on the coral health, hence the integrity of our natural heritage fragile ecosystem.

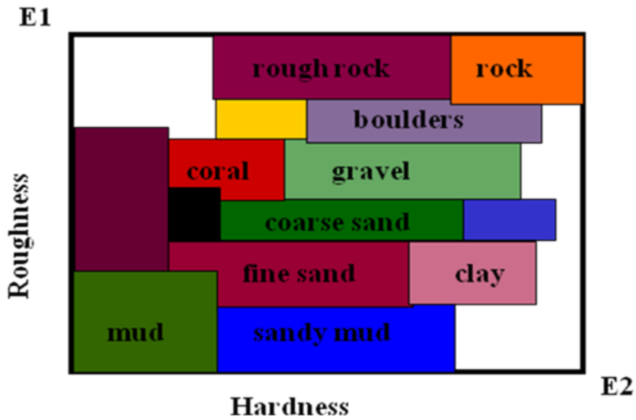

Figure 3. A typical RoxSquare showing different substrates (source: Cholwek et al. 2000)

Remote Sensing System: Application of Optically-derived Water Quality Models

In our efforts to enhance scientific knowledge of marine biodiversity for the purpose of conservation and sustainable management in coastal and marine zones with turbid waters, not only do we measure or catalogue the living resources, it also involved our understanding of the factors affecting the very existence and the survival of these resources. There are two leading water quality parameters that have significant direct and indirect effects on the coral environment—total suspended solids (TSS) and chlorophyll-a (Chl-a). TSS is a direct measurement of physical pollutants over time and space visible to the human eye which affects light penetration in the water column crucial for photosynthetic activity. Trends of TSS distribution in surface waters normally provide scientists and environmentalists the status and condition of body of water (Anisah Lee and Yasin 2000; Anisah Lee 2004).

Chl-a concentrations and its distribution over time and space is a valuable and functional parameter to evaluate water quality, nutrition status and the extent of organic pollution. It is a good indicator for the possibility of nutrient loading or organic pollution and the productivity status of reefs. Chl-a is the pigment that participate directly in the light requiring reactions of photosynthesis. Chl-a concentration provides useful information for the management of water quality (Scherz 1972) and the monitoring of water pollution (Johnson and Harris 1980). The coastal water is dynamic in nature; consequently Chl-a concentration changes rapidly and continuously. The spatial distribution of Chl-a in coastal seawater is not homogeneous either. Charting of Chl-a concentrations spatially over large areas through remote sensing can provide an alternative synoptic view and a speedy and cost-effective method compared to the lengthy and expensive conventional practice (Curran and Wilkinson 1985; Anisah Lee 2004).

A great deal of research has been carried out for the measurement and building of TSS and Chl-a concentration models using remote sensing data such as Landsat MSS, Landsat TM, SPOT, IRS-1C and SeaWiFS (Dekker and Peters 1993; O'Reilly et al. 1998; Thiemann and Kaufmann 2000; Hanna et al. 2001; Harding et al. 2005). These models can be built theoretically (Hoogenboom et al. 1998; Carder et al. 1999; Bricaud et al. 1995), empirically or semi-empirically (Dekker and Peters 1993; Gitelson 1992; Han and Rundquist 1997; Rundquist et al. 1995), optically (Lim et al. 2009; Beh et al. 2010; Asadpour et al. 2011) or based on artificial neural network method (Keiner and Yan 1998) and genetic algorithm (Doerffer and Fischer 1994; Anisah Lee 2004).

Remote sensing models can be applied alone to determine temporal and spatial distributions of water quality parameters, or be applied as an integrated approach with other techniques to assess the environment.

Materials and Methods

Survey site

Pulau Payar Marine Park is situated off the coast of Kedah, between Pulau Langkawi and Pulau Pinang (Figure 4). There are four islands within the jurisdictional area of the Marine Park. Pulau Payar is the largest having an area of 31.2 hectares with an approximate length of 1.75 km (Aikanathan and Wong 1994). The survey was conducted on January 2010 at the main island of Pulau Payar Marine Park located between 6.055°–6.070° N and 100.035°–100.045° E. The exact location can be derived from the acoustic mapping from the RoxAnn substrate classification. The entire length of its north-western coast is predominantly rocky and characterised by steep cliffs and wave-cut gullies. The survey area was closely tracked by boat along the shoreline of Pulau Payar where shallow reefs can be found. This location was chosen mainly because Pulau Payar still holds pristine and healthy reefs amongst the very few reefs found existing in the more turbid waters off the west coast compared to the east coast of Peninsular Malaysia.

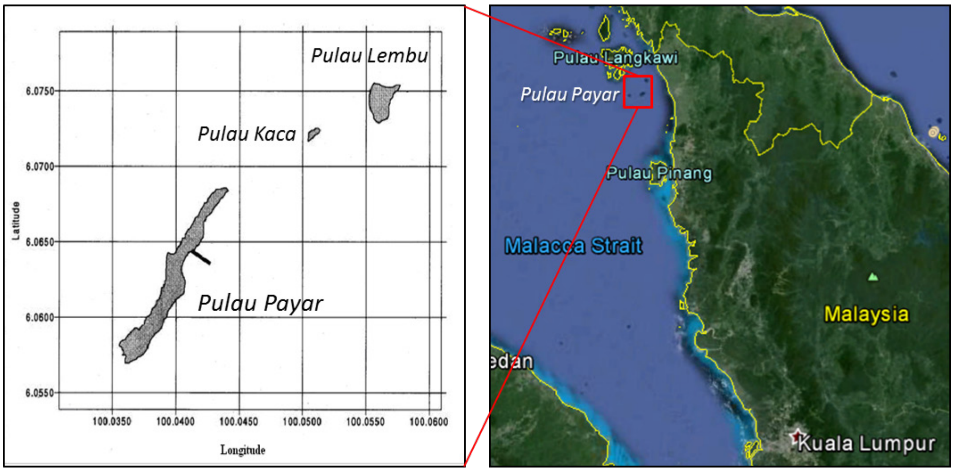

Figure 4. Map of sampling location and enlargement of sampling area at Pulau Payar Marine Park (survey run around Pulau Payar only. Source: Google Earth)

RoxAnn Survey Methodology

The RoxAnn system was calibrated to synchronise all system components where substrate conditions were known. The survey vessel will then be stationed at the desired location of particular substrate. RoxAnn Hydroacoustic Signal Processor will extract the echoes through the transducer and convert the signals to classifiable readings. Different substrates will be classified and assigned using different colours based on the range given by E1 and E2 which will then be displayed on RoxSquare. Six common reef substrates were targeted, i.e., live hard coral, dead coral, rubbles, soft coral, sand and rock. A Differential Global Positioning System (DGPS) modulator was used to fix position with the GPS antennae positioned above the transducer to minimise heading error. After calibration, the full system was connected and ready for transect run.

During the survey run, the data-logging software RoxMap Scientific was used to reveal the real-time position of the survey vessel and the previous track runs, besides recording the bottom type. The skipper could always refer to the laptop screen to reconfirm if the tracks were well spaced between each other. The vessel ran at an average speed of 3–4 knots at 5–10 m of surface intervals parallel to the island. The vessel conducted two survey runs around the island. Short continuous "U" transects were formed at the southwest and near the pontoon area.

All data collected were then processed and split according to start and finish times of surveys using Surfer software for thematic map productions.

Application of optical models for water quality distribution

Two important models derived optically using remote sensing applied to the most recent satellite images of Landsat 8 dated 9 December 2013 to map the distribution of total suspended solids (TSS mg/L) and chlorophyll-a (Chl-a mg/m^3) were as follows:

TSS model: $TSS = (-731.11) + 30.31R_1 + (-39.32)R_2 + 5.70R_3 + 0.92R_1R_3 + (-0.05)R_2R_3 + (-0.37)R_1^2 + (-0.43)R_2^2 + (-0.0006)R_3^2$

Chlorophyll-a model: $\text{Chl-a} = (-0.0411)R_1^2 + 7.5288R_1 + 327.1$

where,

R_1 = Reflectance for red band
R_2 = Reflectance for green band
R_3 = Reflectance for blue band

These models, derived by Lim et al. (2009), will provide synoptic views of the dynamic distribution of TSS and Chl-a within the study area. A broader region of the study area will be mapped using these models in order to offer a more holistic picture of the water quality condition. An RGB composite of the satellite image used in the mapping process is shown in Figure 5. Image processing was conducted using IDRISI Kilimanjaro software.

Figure 5. An RGB composite of Landsat 8 image dated 9 December 2013 of the northern Straits of Malacca used in the mapping process

Results and Discussion

Mapping from RoxAnn survey (hydroacoustic signal classification technique)

From this survey, 14 substrate classes were classified from the survey runs. There were other substrates found and were categorised under unclassified substrates. These are shown in Figure 6. Sand, rubble and rocks were the dominant substrates found in this survey. Lee et al. (2000) also reported that RoxAnn categorises sand and rubble dominating the area at a depth of 20 m. The depth ranges reached by RoxAnn in this study were between 2 and 25 m. From the observation, there were many coral distributions in the shallow area with big boulders.

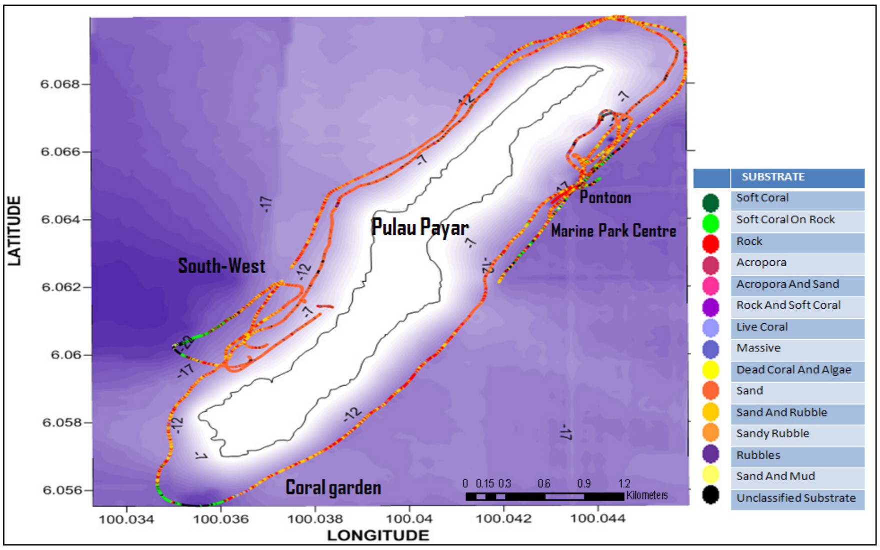

Figure 6. Substrate determination at Pulau Payar with substrate classes

Track length from this survey was approximately 6.556 km using the RoxAnn system comprising 15 substrate classes including unclassified substrate. Figure 7 shows the 2D track run of substrate determination at Pulau Payar. Track lines with different colours indicated variations of substrate within the study area. Results showed that sand was the most dominant substrate (39.29 percent) followed by combination of sand and rubble (22.56 percent) and then rocks (21.80 percent). Unclassified substrate constituted 9.30 percent while the remaining 7.05 percent was made up of corals and other benthic organisms. Composition of different substrates characterised by RoxAnn during the track runs is shown in Figure 8. Approximately 6 percent of live coral was found along the track run which was equivalent to 0.373 km of total length of track run. The group of genus Acropora corals are readily detected using RoxAnn. From the parallel track runs, 0.49 percent of live corals are Acropora while the soft corals made up 3.33 percent.

Based on the track run lines, most coral was found more abundant in the eastern side especially the House Reef area near the pontoon, followed by the Coral Garden at the southern tip of Pulau Payar followed by the south-west of the island. These areas were more frequently visited by tourists for snorkeling and scuba diving rather than the western side of Pulau Payar. At the House Reef, southern tip and also in the south-west areas of the island, soft coral colonies were found in abundance. The distribution of corals decreased at the western side perhaps due to rough waves and current which resulted in high turbulence and sedimentation. According to Lirman et al. (2003), these conditions could affect coral growth, diversity and abundance. At the eastern and southeast tip of Pulau Payar, the underwater slopes are more gradual and are more protected from the rough waves hence providing suitable conditions for higher coral diversity and distribution within the area (Sy et al. 1981).

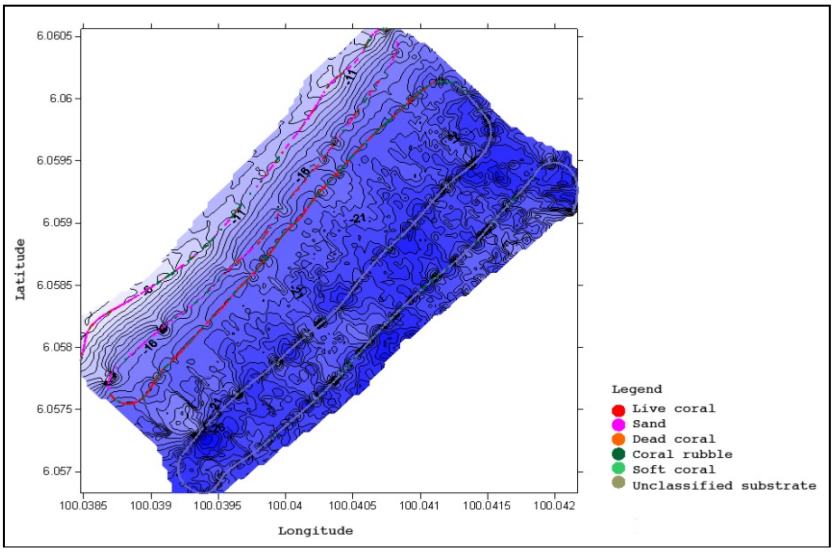

Figure 7. A 2D track run of bottom substrates in Pulau Payar

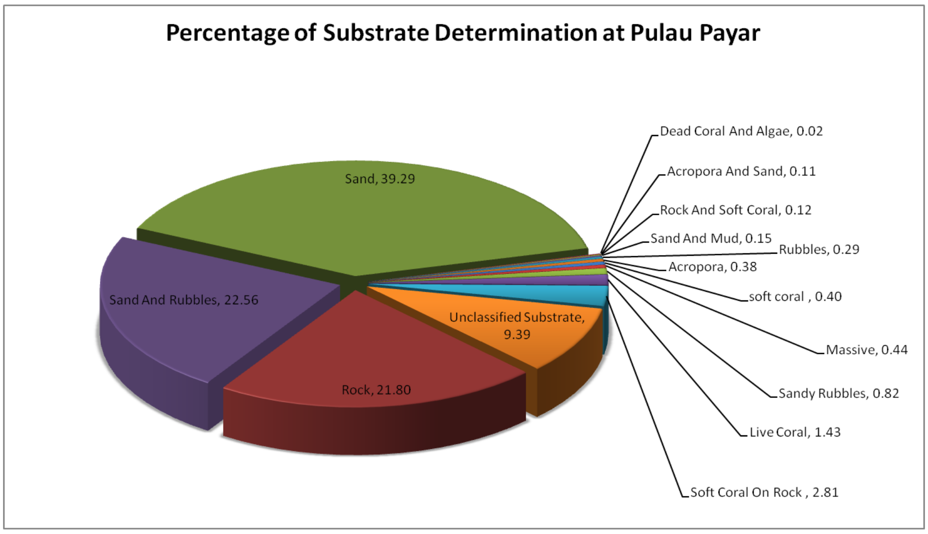

Figure 8. Percentage of substrate determination at Pulau Payar

Data collected by RoxAnn were then interpolated into a 3D depth model as shown in Figure 9. A very steep underwater slope at the Southwest of Pulau Payar was observed from the depth profile map interpolated from RoxAnn data where rough wave actions were experienced within this particular region. This result and observation agree with the findings of this study as well as those by Lirman et al. (2003) and Sy et al. (1981), i.e., areas with higher or rougher wave actions and current tend to result in lesser coverage of coral and its diversity compared to a more gradual and protected slope.

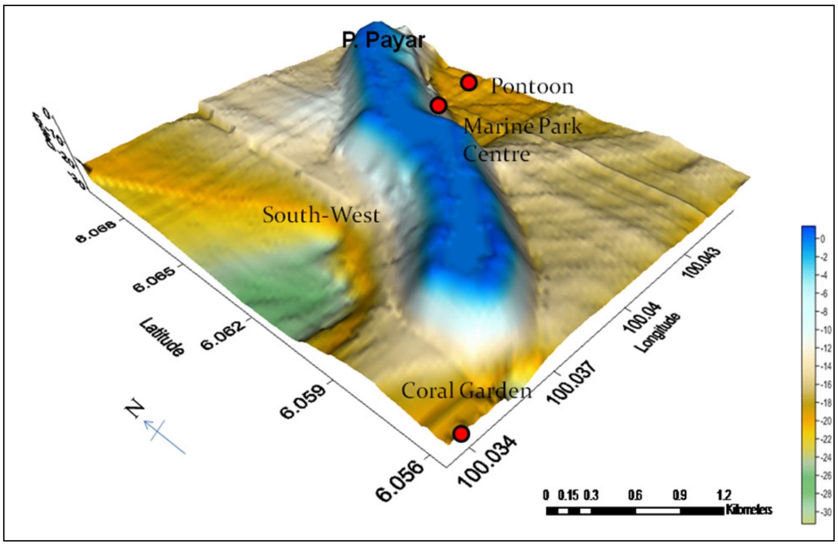

Figure 9. Depth profile of Pulau Payar based on field and interpolated data

Interpolated data and production of 3D model shown here provided a more holistic view of the bathymetric characteristics around the island. This makes interpretation of collected data clearer and more digestible compared to the usual charts or the 2D maps. The findings in this study has shown that using hydroacoustic technique proved to be an efficient and cost effective method in bottom reef type determination and mapping within a limited time frame. With increased track runs in the future, we should be able to map the coral reefs extensively and change detections of the reef area over time at different scales will be a much easier task to perform. For further level of details, incorporation of intensive ground truthing will be required as well as other combination of techniques to produce detailed natural resource mapping or even at biodiversity level.

Since LAC is a process to define: (1) what kind of resource conditions; (2) what kind of social conditions are acceptable; and (3) to prescribe actions to protect or achieve the desired conditions, the use of hydroacoustic technique in this study has proven invaluable to satisfy particularly the initial process of LAC and later the managerial conditions. Apart from being cost effective over time, the use of hydroacoustic technique provides stability over time as it allows quicker and frequent change detection analysis of resource conditions which is also trackable and traceable within the framework of LAC. The basis of LAC follows a nine-step process designed to include public input and involvement at all steps, and it moves from a broad description to specific prescriptions which require setting standards and monitoring conditions. The broad description of natural resources within the chosen reef area is proven to be capably and effectively carried out by hydroacoustic technique using RoxAnn. Undoubtedly the specific description and later its prescription can be carried out using more intensive and comprehensive track runs and a combination of readily available low risk and cost-effective techniques.

Mapping of Water Quality through Application of Optically-derived Remote Sensing Water Quality Models

Surface water TSS distribution

Distribution of TSS on surface water of the northern Straits of Malacca (Figure 10) portrayed an overview of high TSS concentrations (depicted by the darker orange-red tones) along the immediate coastal strip of the peninsula. The range of TSS was >226 mg/L indicating very high values but an acceptable range because the coastal region lies within the rice bowl region of peninsular Malaysia. Erosion and runoffs of sediments as a result of continuous agricultural practices along the coast are highly probable (Anisah Lee et al. 2014). Fluctuations of TSS levels are normal since the coastal and marine waters are very dynamic owing to the continuous tidal and current movement over the shallow zone of the continental shelf. A strip of lower TSS levels (<75 mg/L) running along the coastal region adjacent to the mainland seaward to approximately 15 km could be the result of tidal mixing. This is possible during mid tidal condition either during flooding or ebbing. Further out into the sea, the range of TSS appeared to be higher. There is a high possibility that this could be the residue of haze that could not be filtered out during remote sensing image processing. The original data contain cloud coverage and certain level of visible haze. Another possibility is the influx of water body during flooding tide carrying suspended materials from neighbouring south Thailand or Sumatera where landuse/landcover change is rapid.

The Pulau Payar Marine Park was surrounded with waters with high levels of TSS (up to a maximum of 200 mg/L) during the satellite overpass on 9 December 2013. Considering the sensitivity of corals to environmental change particularly water quality, the duration of these reef organisms being exposed to the high levels of TSS may impact on its productivity, hence, the reef's overall health. TSS concentrations mapped in Figure 10 showed only detected values through modelling for surface waters because remote sensing of water quality barely able to penetrate turbid waters. Therefore, if the reef of Pulau Payar lies deeper, chances are the levels of TSS will be much lower providing a fairly healthier water quality condition for corals to thrive and sustain its biodiversity within the marine park. However, this can only be ascertained through water quality profiling.

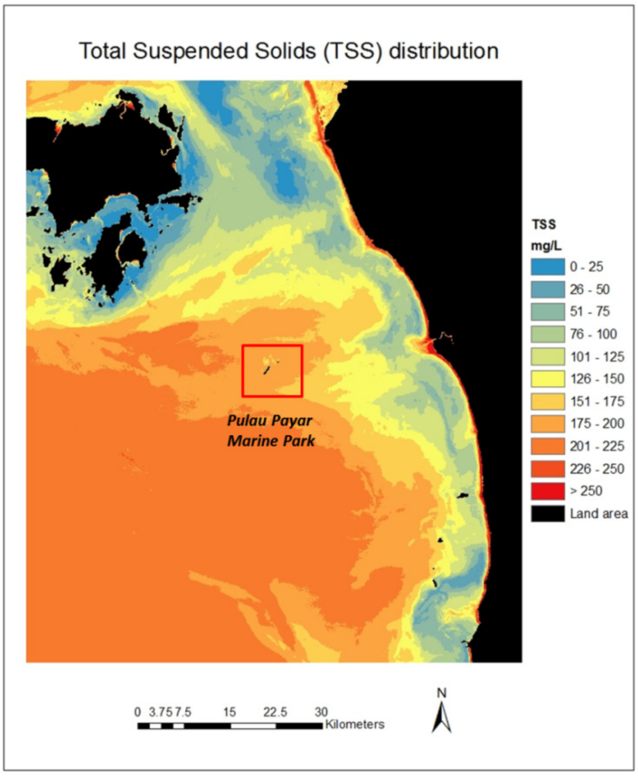

Figure 10. Distribution of total suspended solids concentrations in mg/L on surface water of northern Straits of Malacca. (source: Landsat 8 ETM+ 9 December 2013)

Surface water Chl-a distribution

Distribution of Chl-a concentrations in mg/m^3 of surface waters within the northern Straits of Malacca is shown in Figure 11. Chl-a concentrations were high ranging from 16–20 mg/m^3 to 21–25 mg/m^3 levels along the immediate coastal waters adjacent to the Kedah mainland. It is natural for Chl-a concentrations to fluctuate over time and space. Factors influencing these fluctuations are quite broad. For instance, Chl-a concentrations are often higher after rainfall, particularly if the rain had flushed nutrients into the water. Amount of light levels reaching the photic zone and the tidal regime are important controls on algal biomass. Tidal mixing and flushing rates (e.g., estuarine and river mouths) influence Chl-a concentrations because flushing dilutes nutrients and moves them away, making them less available (Brando et al. 2006). Conversely, slow moving or stagnant waters such as the case along the mainland of the coastline facing the islands which are shallow, let nutrients increase and cell numbers to grow. As a result, higher Chl-a concentrations were detected along the coastlines, and this can reflect a possible increase in nutrient loads. Nutrient runoffs such as nitrogen and phosphorus from the agricultural activities coupled with the shallow coastal features became sources of algal propagation in the seawater column resulting in higher productivity along the shallow coastlines (Anisah Lee et al. 2014). This fact is further supported with much lower Chl-a concentrations (1–5 mg/m^3) detected further out into the sea as shown in Figure 11.

Two patches of high Chl-a levels further out into the sea (as indicated by the dotted boxes in Figure 11) were clouds that could not be filtered from the raw digital data during image processing. Sensors onboard the Landsat 8 ETM platforms were not designed to penetrate thick clouds since they were based mostly on the visible and infrared range of the electronic magnetic spectrum. In order to penetrate clouds, a combination of other remote sensing techniques is required.

An enlarged area of Pulau Payar Marine Park showing distribution of Chl-a is given in Figure 12. Elevated levels of Chl-a concentrations along the northeast coast of Pulau Payar, Pulau Kaca and on the east of Pulau Kaca most likely represented the living corals within the shallow reef. This is because corals are symbiotic organisms and the zoonxanthellae present within its epidermal layer photosynthesise. Naturally, its productivity attributable to the chlorophyll pigment present in corals will be reflected in elevated Chl-a concentrations as detected in the ETM data providing invaluable clue to the presence of healthy corals. The levels of Chl-a concentration measured concurred with findings of the NASA Earth Observatory for May 2012 shown in Figure 13 (NEO 2012) and the comparison for December 2012 and December 2013 in Figure 14 (NEO 2014).

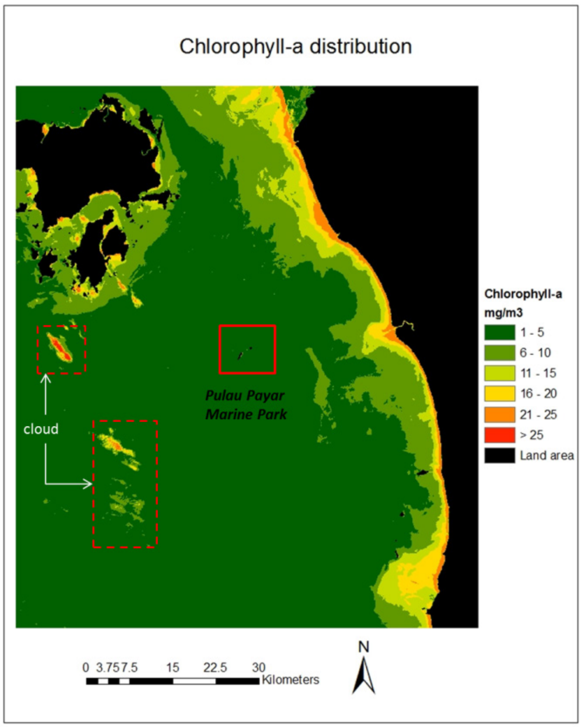

Figure 11. Distribution of chlorophyll-a concentrations in mg/m^3 on surface water of northern Straits of Malacca (source: Landsat 8 ETM+ 9 December 2013)

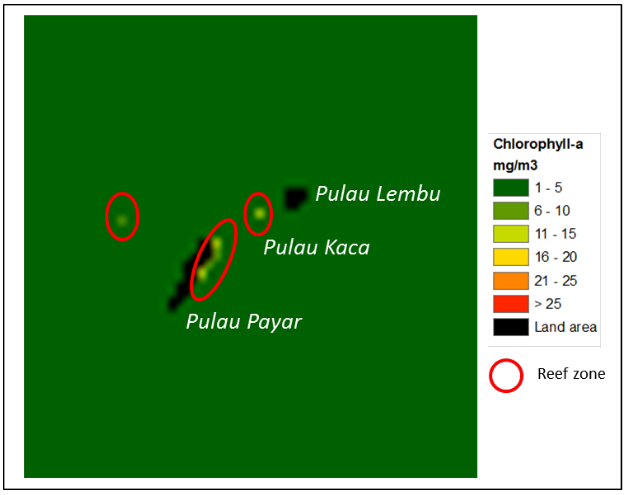

Figure 12. An enlarged area (from Figure 11) of Pulau Payar Marine Park showing elevated levels of chlorophyll-a concentration within the reef zones

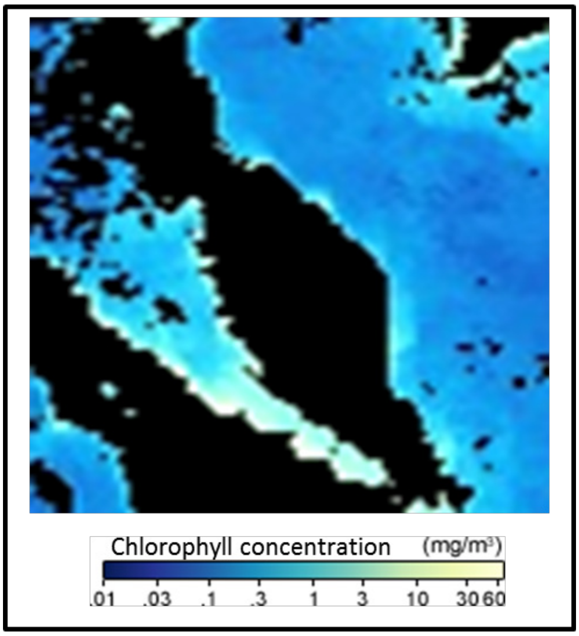

Figure 13. Chlorophyll concentration (mg/m^3) (Aqua/MODIS) for May 2012 (source: NEO 2012)

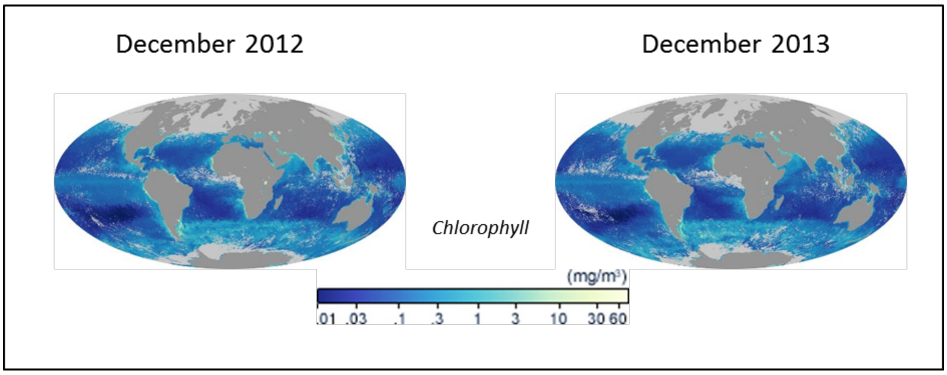

Figure 14. Comparison of Chlorophyll-a (mg/m^3) (Aqua/MODIS) between December 2012 and December 2013 on a global scale (source: NEO 2014)

Reefs are Invaluable Coastal Resources—A Natural Heritage

The most diverse and invaluable ecosystems on earth—the coral reefs, and their associated sea grass and mangrove habitats, are storehouses of immense biological wealth and provide economic and environmental services to millions of people as shoreline protection, areas of natural beauty, recreation and tourism, and sources of food, pharmaceuticals, jobs and revenues. According to one estimate, these rainforests of the sea provide services worth about US $375 billion each year—a staggering figure for an ecosystem which covers less than one percent of the earth's surface (USCRTF 2000).

Coral reefs provide a vast array of valuable services globally. Chief among these are:

Tourism. The tourism industry is one of the fastest growing sectors of the global economy. Coral reefs are a major destination for snorkelers, scuba divers, recreational fishing, boaters and sun seekers. Diving tours, fishing trips, hotels, restaurants and other businesses based near reefs provide millions of jobs and support many regional economies around the world, contributing billions of dollars in tourism-dependent revenue annually. In the Florida Keys, tourism related to the coral reef ecosystems generates over US $1.2 billion per year. Similar trends are seen internationally, where ecotourism to coral reef destinations is emerging as a major economic sector in many countries, e.g., Belize, the Carribean, Thailand, Indonesia and the Philippines.

Fishing. Over 50 percent of all federally managed fish species depend on coral reefs for part of their life cycles. The annual value of reef-dependent recreational fishing probably exceeds US $100 million per year. In developing countries, coral reefs contribute about one-quarter of the total fish catch, providing food to an estimated one billion people in Asia alone.

Coastal protection. Coral reefs buffer adjacent shorelines from wave action and prevent erosion, property damage and loss of life. Reefs also protect the highly productive mangrove fisheries and wetlands along the coast, as well as ports and harbours and the economies they support. Globally, half a billion people are estimated to live within 100 km of a coral reef and benefited from its production and protection.

Biodiversity. Reefs support at least a million species of animals and plants, including about 4,000 documented species of fish and 800 species of hard corals. Another eight million coral reef species are estimated to be as yet undiscovered. In many ways, coral reefs rival and surpass tropical rainforests in their natural wonder and biological diversity and complexity. This unparalleled biodiversity holds great promise for natural products derived from reef dwelling organisms, such as the many pharmaceuticals being developed from coral reef animals and plants as possible cures for cancer, arthritis, human bacterial infections, viruses and other diseases. In fact, reefs are often predicted to be the primary source of natural compounds for new medicines in the 21st century.

Natural heritage. Coral reefs are an important part of our natural heritage, rivalling the longevity or complexity of some treasured land-based resources like old growth forests, Joshua trees and Sequoias in the United States; and the Tualang, Meranti and Jati in Malaysia. A well-developed reef may be the manifestation of thousands of years of incremental accretion by its resident coral colonies, sometimes growing only millimetres each year. Many coral species have no known limit on colony size or age and may continue growing indefinitely in favourable habitats. As a result, some of the largest individual coral colonies found in the reefs today were almost surely alive centuries ago, long before modern times and its associated environmental pressures. The scientific, aesthetic and conservation value of such ancient animals and their complex biogenic habitats is unparalleled in the world's oceans, and indeed on land as well. These are truly living museums of the world's marine biological diversity.

Strategies to Conserve Coral Reefs

Efforts to conserve, protect and use our global heritage—coral reefs—had been set up and begun since the 1990s when declination and destruction of coral reefs became evident. Strategies to conserve and protect the coral reefs became the major issue around the world. For example, the USCRTF was established by President Clinton in June 1998 to lead U.S. efforts, both domestically and internationally, to protect, restore and sustainably use the coral reef ecosystems. Chaired by the Secretary of the Interior and the Secretary of Commerce, the Task Force is composed of the heads of 11 federal agencies and the Governors of seven states, territories or commonwealths with responsibilities for coral reefs. The Coral Reef Task Force identified two fundamental themes for immediate and sustained national action which can be applied globally:

- *Understand coral reef ecosystems* and the natural and anthropogenic processes that determine their health and viability; and
- *Quickly reduce the adverse impacts* of human activities on coral reefs and associated ecosystems.

The first theme on *understanding coral reef ecosystems* requires conducting comprehensive mapping, assessment and monitoring of coral reef habitats; supporting strategic research on regional threats to coral reef health and the underlying ecological processes upon which they depend; and incorporating the human dimension into conservation and management strategies. The incorporation of hydroacoustic technique to LAC framework in this study had shown that conducting comprehensive mapping, assessment and monitoring coral reef habitats and to detect changes over time is possible and viable.

The second theme on *quickly reduce the adverse impacts* requires creating an expanded and strengthened network of federal, state and territorial coral reef marine protected areas; reducing the adverse impacts of extractive uses; reducing habitat destruction; reducing pollution; restoring damaged reefs; strengthening international activities; reducing the impacts of international trade in coral reef species; improving governmental accountability and coordination; and creating an informed and engaged public for coral reef conservation. In order to achieve this through the hydroacoustic-LAC combination technique, a complete and comprehensive mapping based on the first theme and identification of key factors of environmental impacts should be conducted. The details will be invaluable to address actions to be taken to reduce adverse impacts.

Within these broad themes, integrated conservation strategies to comprehensively meet the most pressing challenges facing reefs globally were developed by the Coral Reef Task Force. In addition to these tangible field-based actions, a consensus suite of *core principles* were identified to guide the government's future actions to ensure an integrated, consistent, sustainable and inclusive approach to conserving coral reefs. The intent was not to create a static plan that would become obsolete in a few years but a dynamic *road map* instead to conserve and protect the coral reefs of the world. It is intended to be revisited, evaluated and updated regularly as conditions on the world's coral reefs change—hopefully for the better.

The core conservation principles identified are:

- To adopt a *science-based ecosystem approach* to coral reef conservation that recognises and builds upon important linkages among adjacent and remote habitats associated with coral reefs
- To employ *adaptive management* approaches that track and respond to environmental change and emerging threats
- That scientific uncertainty shall not prevent taking *precautionary measures* as appropriate to protect coral reefs
- To incorporate the *human dimension* into coral reef conservation strategies by ensuring that management measures reflect, and are sensitive to the local socioeconomic, political and cultural environment, and that they build an informed public engaged in choosing alternatives to activities that harm coral reefs
- To apply *marine zoning—including marine protected areas and no-take ecological reserves*—in order to protect and replenish coral reef ecosystems by minimising harmful human impacts and user conflicts in important habitats

- To fully and proactively use *existing management authorities and programs* at the federal, state and territorial levels, and develop, where needed, new legal mechanisms that protect, restore and enhance coral reef ecosystems
- To develop and support strong *domestic partnerships* among governmental, private and scientific interests to meet the complex cross-jurisdictional challenges of coral reef conservation
- To provide global leadership to *reduce global threats* to coral reefs through international technical and development assistance, capacity building and collaboration

The use of RoxAnn in combination with LAC framework in this study appear to be in cohesion with the global Coral Reef Task Force fundamental theme "to understand the coral ecosystem" through comprehensive mapping and its first global core conservation principle "to adopt a science-based ecosystem approach" to coral reef conservation. The integration of remote sensing modelling and its application to hydroacoustic signal classification system into LAC framework provided a more holistic approach in understanding the coral ecosystem and the adoption of science-based ecosystem approach. With advanced technology, high accuracy results, high frequency of monitoring and better future predictions of the environment and our marine resource as natural heritage may be used for a more intense prescription of actions in order to protect or achieve desired conditions for continuous sustainability.

In the nine-step process of LAC framework mentioned earlier in Figure 1, direct and potential contributions of remote sensing through application of optical modelling and the utilisation of hydroacoustic signal classification system is summarised in Table 1. Direct contributions refer to known levels of contribution and measurable, and carry impact to the LAC framework. Potential contribution refers to possible involvement of the specified technique in the near future which may have not been tested on the LAC framework. Alternatively, the unknown contribution naturally implied the unknown possibility of applying the techniques in order to achieve the LAC framework. It does not imply unattainable or unfeasible solutions or contributions except that perhaps future advanced technique may offer a better option than at present.

Table 1. Summary of direct and potential contributions of remote sensing and hydroacoustic signal classification system techniques in achieving LAC framework for coastal and marine areas

Steps in LAC framework	Application of water quality optical models in coastal marine waters	Application of hydroacoustic signal classification system in benthic studies
Step 1: Identify issues and concerns	Direct and potential	Direct and potential
Step 2: Define and describe opportunity zones	Direct and potential	Direct and potential
Step 3: Select indicators of resource and social conditions	Direct and potential	Direct and potential
Step 4: Inventory of existing resource and social conditions	Unknown	Direct and potential
Step 5: Specify measurable standards for resource and social indicators selected for each opportunity zone	Direct and potential	Direct
Step 6: Identify alternative opportunity zone allocations	Direct and potential	Direct
Step 7: Identify management actions for each alternative	Unknown	Direct and potential
Step 8: Evaluation and selection of a preferred alternative	Direct and potential	Direct and potential
Step 9: Implement actions and monitor conditions	Direct and potential	Direct

Summary

As an initiative towards the conservation and preservation of our natural heritage, and in this study with emphasis on the coral reef, conventional or traditional method alone is no longer an option. With the coastal resource declination at an alarming rate, new technique or combination of techniques is necessary to provide faster, accurate and broad-scale applications to keep us more prepared and at par if not ahead of unsustainable living. The integrated conservation strategy to conserve the coral reefs is a dynamic approach requiring long term monitoring and endless efforts to ensure all measures taken reflect its fundamental issue. It is only when we understand the ecosystem can we move forward towards achieving the core or goal of the initiatives. In this study, a combination of two approaches—LAC framework and hydroacoustic technique—was applied to a coral reef area in adopting a science-based ecosystem approach to understanding a coral ecosystem as a natural heritage conservation measure.

The RoxAnn, a hydroacoustic signal processing technique was incorporated to the LAC framework as this system has been proven to be a successful large scale survey tool capable of mapping a wide variety of sea-bed types. The use of hydroacoustic signals as a remote sensing tool is capable of determining the distribution of coral habitats and categories by measuring different hardness and roughness of the substrates. The system stores, categorises and manipulates data received, and produces maps of the sea-bed types especially corals. This technique helps to determine the percentage of coral reef cover types (e.g., live and dead coral) and helps in resource identification and inventory process for the application of LAC in a large scale survey. The main advantage of the system was its ability to cover large area within a limited time. In addition, it was able to map deeper areas beyond the access of normal diving. Other advantages included its ability to map out reefs occurring in turbid waters and mapping even during rough sea conditions.

This study has shown that with two runs of surveys in a limited time frame, the authors are able to determine the dominant bottom types or substrates and produced a 3D view of the bathymetry of a large reef area such as that of Pulau Payar using interpolation technique. This survey could be further improved by using both satellite-based remote sensing in addition to sonar-based reef mapping. Survey runs should be increased to enable proper coverage, i.e., track running parallel and at perpendicular to the island.

The application of optically-derived water quality models on satellite imagery (ETM data) to map the distribution of total suspended solids and chlorophyll-a concentrations is imperative in preserving the corals. This is because one of the life-depending elements surrounding the coral communities is the seawater around them. Just like the air we breathe, the corals "breathe" the seawater. The more polluted and the longer the duration of exposure to pollutants the more it will endanger the coral health resulting in low productivity which will affect the very source of food chain all other lives on earth depend on. Continuous and intensive monitoring of the corals' environment is fundamental in order to achieve sustainability that will eventually fulfil the possibility of identifying the actual limits of acceptable change and the designing of implementation actions for our exhausting resource.

This study has proven that the combination of techniques i.e., the application of LAC framework, hydroacoustic signal processing and remote sensing, is a viable, cost-effective and time-saving to conduct a science-based ecosystem approach to understand the coral reefs as our natural heritage conservation strategy.

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