Chapter 13

MULTI-SCALE REMOTE SENSING OF CORAL REEFS

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1. Introduction

Coral reefs provide an excellent case study of the application of marine remote sensing to a shallow coastal ecosystem that is spatially limited, exhibits high diversity, high productivity, and faces severe anthropogenic and climatic threats. Coral reefs, lagoons and their associated environments exhibit a high degree of natural variability in terms of water quality, benthic patchiness, and water depth. This variability presents a significant challenge for many analytical optical algorithms.

Coral ecosystems have a high intrinsic value because of their high diversity of coral, fish, and benthic species. Often described as the marine equivalent of terrestrial rainforests in terms of species richness (Hubbell, 1997), they also have significant economic value from harvesting natural resources (e.g., food, pharmacology), coastline protection, and tourism (Costanza et al., 1997). For many tropical countries or regions, coral reefs are a major or principal source of income from fisheries, aquaculture, tourism and recreation. Several island countries in the Indian and Pacific Oceans (e.g., Maldives or Tuvalu) are entirely coral reef environments.

Unfortunately, coral reefs and associated lagoons are among the most threatened coastal ecosystems worldwide (Pandolfi et al., 2003). Coral reefs react quickly to new stressors because they thrive in a narrow range of environmental conditions and are very sensitive to small changes in temperature, light, water quality and hydrodynamics. Numerous reports have documented local consequences of pollution, overfishing, urban development or coral mining (Wilkinson, 2000). Moreover, global-scale climatic changes induce new threats, even for pristine reef systems not directly under human influence (Kleypas et al., 2001). Hence, coral-based systems may serve as a unique indicator of environmental change for diagnosing the status of tropical coastal ecosystems and global change. Since remote sensing has been applied in studies of reef systems for several decades, several multidisciplinary applications and techniques have gained enough maturity to be useful for these goals. Remote sensing can potentially be used to address many reef mega-processes (sensu Hatcher, 1997) with applications in ecology, biology, biogeochemistry, geology and management of reefs.

Recently, Andréfouët and Riegl (2004) divided remote sensing of coral reefs into two categories: direct and indirect. Direct remote sensing is when the reef itself is the
target of remote sensing while indirect remote sensing refers to studies that focus on the oceanic and atmospheric environment around the reef. Direct studies address benthic properties and status, habitat and geomorphologic structures, bathymetry, and water circulation using satellite or airborne remote sensing data, generally using one or few coverages (Mumby et al., 1997; Hochberg and Atkinson, 2000; Andréfouët et al., 2002a; Stumpf et al., 2003; Isoun et al., 2003; Brock et al. 2004). Indirect remote sensing typically aims to describe the boundary conditions of the reefs and the spatio-temporal weather context during \textit{in situ} surveys, or during events of interests such as coral spawning, benthic die-offs, algal blooms and other water quality events (Abram et al., 2003; Andréfouët et al., 2002b; Hu et al., 2003; Liu et al., 2003; Penland et al., 2004). Absolute measurements or anomalies in temperature, wave height and direction, sea level, chlorophyll and colored dissolved organic matter (CDOM) concentrations, aerosols, rain, solar insolation and cloud cover are parameters of interest that may be inferred from time-series analysis (Mumby et al., 2001a; Andréfouët et al., 2001a; Dunne and Brown, 2001; Liu et al., 2003; Abram et al., 2003; Otis et al., 2004).

In this chapter we present how both direct and indirect remote sensing can be integrated to address two major coral reef applications - coral bleaching and assessment of biodiversity. This approach reflects the current non-linear integration of remote sensing for environmental assessment of coral reefs, resulting from a rapid increase in available sensors, processing methods and interdisciplinary collaborations (Andréfouët and Riegl, 2004). Moreover, this approach has greatly benefited from recent collaborations of once independent investigations (e.g., benthic ecology, remote sensing, and numerical modeling).

2. Remote Sensing to Assess Coral Bleaching

2.1 CORAL BLEACHING

Within the tissues of healthy reef-building corals are populations of unicellular photosynthetic algae called zooxanthellae (Brown, 1997). Photosynthetic products from zooxanthellae contribute to coral growth and calcification, while respiration products from the coral contribute to zooxanthellae photosynthesis. Under conditions of stress, such as decreasing salinity or increasing water temperature, the coral host may expel the zooxanthellae. Without re-inoculation by a healthy population of endosymbionts, host mortality often occurs. Bleaching refers to the discoloration or whiter color of the host coral when pigmented zooxanthellae are removed. Coral bleaching was first documented in 1911 in the Florida Keys and became a well known phenomenon during the 1980-90’s when large-scale massive bleaching events were reported. Massive global events occurred in 1998 and 2002 (Aronson et al., 2000; Liu et al., 2003; Berkelmans et al., 2004). This outbreak is generally attributed to positive anomalies in temperature and in ultraviolet light (Brown, 1997) in the aftermath of El Niño Southern Oscillation (ENSO) periods (Hughes et al., 2003).

With rising sea surface temperatures recorded in the world’s oceans, coral bleaching is now perceived as a major threat to many reef systems (Hoegh-Guldberg, 1999; Wilkinson, 2000; Hughes et al., 2003). Some reefs impacted during the 1998 ENSO event have not recovered, potentially resulting in decreased fish abundance, phase and strategy-shifts in benthic community structures, diversity loss, and decreased overall productivity (McClanahan, 2000; Chabanet, 2002; Spalding and Jarvis, 2002). From a conservation and reef management standpoint, predicting reef vulnerability to bleaching at a scale of few tens of kilometers is important when designing monitoring programs or
networks of Marine Protected Areas (MPA) since resistance to coral bleaching is an important property of areas intended to protect biodiversity (West and Salm, 2003).

2.2 REGIONAL INDIRECT ASSESSMENT OF BLEACHING

AVHRR sensors have been used for nearly a decade to monitor sea surface temperature (SST, Fig. 1) and bleaching (Liu et al., 2003). Bleaching nowcasts and forecasts are currently based on empirical SST-derived proxies, designed through trial and error, and are continuously refined. The goal of these nowcast systems is to predict the threshold above which a coral reef will be subject to bleaching. The current methods use SST, but other relevant environmental data such as sea surface height, solar insolation, cloud cover, CDOM, etc. may be used in future models. The most recent of this SST proxy, “Max3d”, was defined by a statistical spatial analysis of the bleaching patterns that occurred in 1998-2002 along the Great Barrier Reef (Berkelmans et al. 2004). It was found that the maximum SST occurring over any 3-day period (hence, Max3d) during the bleaching season was a better predictor of bleaching than any other anomaly-based SST variable. These proxies have also been used in a conservation context. The goal is to determine conservation areas, resistant to bleaching. Thus, the spatial modeling combined with multivariate empirical reasoning and innovative computational techniques (e.g Baysian Belief Networks) make use of these proxies (Woolridge and Done, 2004).

Ultimately, it is the local and regional hydrodynamic regime that is the primary forcing factor of bleaching, since SST is affected by mixing and other thermodynamic processes in the upper water column. Topography, wind, low frequency currents and tidal regimes are critical oceanographic information needed to understand and forecast bleaching using numerical models of circulation. The next step will be to model water mixing and SST over scales of 1000’s of km at high spatial resolution (1 km). Remote sensing data such as wind velocities and direction, wave height and direction, SST, and ocean color may help improve the parameterization and calibration of ocean circulation models by assimilation or by comparing satellite observations to model solutions.

2.3 REEF-SCALE ASSESSMENT OF BLEACHING

Bleaching can occur on reefs in a variety of spatial patterns that depends on reef geomorphology and topography, previous perturbations, the type of corals (e.g. acroporids, pocilloporids, porites), possibly coral genetics, associated zooxanthellae and their adaptation to thermal stress. To understand reef-scale heterogeneity in bleaching, reef-scale hydrodynamic models with resolutions of a few 10’s of meters are required. These models will also combine physical oceanographic processes with detailed benthic community descriptions at a resolution of 10’s of meters (Done et al., 2003).

At reef-scale, detailed bathymetry is required as a first step to build accurate circulation models. However, such data is not available for most reefs because of the difficulty in making sounding measurements over vast expanses of shallow waters. For instance, the topography of the Great Barrier Reef shelf and lagoon is a compilation of various data sets (mostly ship sounding), interpolated and merged in the form of a 250m-resolution grid (Lewis, 1999), which is inadequate for use in most reef-scale models.

Optical bathymetric algorithms applied to multispectral/hyperspectral satellite or airborne images such as Landsat, IKONOS or Compact Airborne Spectrographic Imager CASI provide the most convenient way to overcome the limitations in acquiring bathymetric data for shallow clear waters (Lyzenga, 1978; Loubersac et al., 1991; Morel, 1996; Liceaga et al., 2002; Louchard et al., 2003; Stumpf et al., 2003). As a
result of research conducted in the 1980’s, hydrographic charts of French overseas territory (SHOM-SPT 1990) now include bathymetry derived using Satellite Pour l’Observation de la Terre (SPOT) satellite data and a multi-regression algorithm. NOAA is updating bathymetric maps of the Northwestern Hawaiian Islands using a revised ratio-algorithm applied to IKONOS data (Stumpf et al., 2003).

**Figure 1:** SST (°Celsius) monthly mean climatology obtained from AVHRR (1993-2003) for the Florida Keys. Similar time-series analysis can help detect unusually high SST values (positive anomalies) that can trigger coral bleaching events.

Active remote sensing using lasers provides an efficient alternative for detailed topography assessments of shallow coral reefs. LIDAR (LIght Detection And Ranging) altimeters such as LADS (Laser Airborne Depth Sounder) or SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) have been deployed on the Great
Barrier Reef and the Main Hawaiian Islands (Storlazzi et al., 2003). Improved systems such as the Experimental Advanced Airborne Research Lidar (EAARL), a temporal-waveform-resolving green laser altimeter constructed at NASA Wallops, was used in the northern Florida Keys during the summers of 2001 and 2002 (Brock et al., 2004). These data sets helped characterize the detailed geomorphology of a reef, such as the spur-and-grooves zone of Molokai fringing reefs (Storlazzi et al., 2003), or the rugosity of patch reef substrates in Biscayne National Park (Brock et al., 2004).

Coral bleaching has also been directly observed using aerial photographs (Andréfouët et al., 2002a), IKONOS (Elvidge et al., 2004) and Landsat data (Yamano and Tamura, 2004). The scale of interest is the community (coral assemblages) or coral colony for which sub-meter resolution is optimal (Andréfouët et al., 2002a) but beyond the current capabilities of satellite sensors. Direct sensing of bleaching is important as validation in remote sites of SST-proxy bleaching predictions (Elvidge et al., 2004), and also as a basis for planning management and monitoring activities following the bleaching event. Direct sensing is critical to surveying possible mortality or recovery that occurs within a few weeks after the peak of bleaching.

Direct remote sensing studies of bleaching have used different approaches. Change detection techniques have been applied, for example, by comparing the bleached zones detected using normalized IKONOS images acquired before and during the Great Barrier Reef 2000 event (Elvidge et al., 2004). Bleaching has been also detected using principles of radiative transfer theory applied to individual Landsat images of Ryukyus archipelago in Japan (Yamano and Tamura, 2004). Such analytical algorithms require knowledge of the reflectance of bleached corals at different depths, as well as spectral differences between bleached corals and other benthic objects (Fig. 2) (Clark et al., 2000; Holden and Ledrew, 2001; Hochberg et al., 2003).

Figure 2. Statistical differences (+/- one standard deviation) between reflectance of bleached and healthy corals.
Ultimately, spectral reflectance of coral is determined by the spectral absorption and fluorescence properties of pigments residing at various locations in a coral colony, including the zooxanthellae and ectodermal and endodermal host tissues (Dove et al., 1995; Salih et al., 2000; Mazel et al., 2003a; Hochberg et al., 2004). Variability in these pigment sources contributes to the complexity in shape and magnitude of coral spectral reflectance (including the loss of pigments during coral bleaching). One goal of ongoing research at the coral colony-scale is to explain reflectance according to variations in pigmentation, and thus indirectly describe the health of the colony.

The final aspect of investigating coral bleaching is to estimate benthic changes induced by the bleaching event, for example, quantifying the level of coral mortality (Mumby et al., 2001b). To date only one example of post-bleaching assessment (in Rangiroa atoll, French Polynesia) has been reported where extensive ground-truthing and airborne hyperspectral measurements were used to estimate the percent of dead corals with remarkable accuracy. Mumby et al. (2001b) reported classification results for dead and live corals within a 5% error range. There are several other recent satellite-based change detection case studies that describe benthic cover modifications, though not necessarily after bleaching-induced mortality (Dustan et al., 2001; Andréfouët et al., 2001b; Palandro et al., 2003a; Palandro et al., 2003b).

2.4 SYNTHESIS: MULTI-SCALE APPLICATIONS FOR BLEACHING ASSESSMENT

Figure 3 highlights the connections between the different scales (region, reef, community, colony), remote sensing domains (indirect sensing and environmental proxies, direct sensing, spectral signatures) and non-remote sensing domains (statistical analysis, computational techniques, ecology, management) that have been integrated and merged for the bleaching application over roughly the last 8 years. As a summary, remote sensing techniques are used to forecast bleaching (e.g. using SST and statistical proxies), understand bleaching causes at regional scales (proxies), to validate SST predictions and map bleaching extent (direct high resolution change detection analysis or mapping), to calibrate/validate numerical models aimed at predicting bleaching sensitivity, and to describe the spectral signatures of coral colonies for different health state (and spectral signatures of benthic objects in general) in order to design optical radiative transfer algorithms for high resolution satellite or airborne images.

Future development will likely focus on the design of regional, high-resolution (1 km or less), optimized environmental proxies that will take advantage of SST and other remotely sensed factors and climatologies. This regional approach is very similar to the local optimization of bio-optical ocean color algorithms sought for coastal Case II waters. Numerical modelling with assimilation of remote sensing data will also help in investigating local hydrodynamic and thermodynamic processes that control bleaching. Finally, better understanding of bleaching patterns will come from detailed descriptions of coral community structures. For this goal, high resolution direct remote sensing is critical to stratify detailed quantitative surveys of benthic communities.

3. Remote Sensing to Assess Coral Reef Biodiversity

3.1 WHAT IS BIODIVERSITY ASSESSMENT?

In the introduction for a series of review papers dedicated to biodiversity published by the journal *Nature* in 2000, Tilman (2000) begins with “The most striking feature of Earth is the existence of life, and the most striking feature of life is its diversity”. We could add “and coral reef ecosystems harbor the highest diversity of marine life forms
Thus, here we emphasize the application of coastal remote sensing for coral reef biodiversity assessment, a developing application with much potential.

**Figure 3.** Network of applications for coral bleaching. Text in italics and single lines refer to non-remote sensing actions; double and bold-lines refers to indirect and direct remote sensing respectively.
First used in the early 1980’s, the term "biodiversity" refers broadly to the abundance, variety, and genetic constitution of natural living communities. Purvis and Hector (2000) defined biodiversity as the sum of all biotic variation from the level of genes to an ecosystem. Practically, the field of biodiversity encompasses a vast array of scientific topics. Biodiversity science addresses the spatial and temporal patterns in biological diversity and richness, the mechanisms that control these patterns, the influence of these patterns on ecosystems functions and, conservation strategies for the preservation of these patterns. Remote sensing can help address most of these issues. Actually, the coral bleaching application previously discussed is a component of the biodiversity topic, since bleaching may result locally in a loss of biodiversity.

Several reviews of remote sensing applied to biodiversity issues have been compiled, mostly for terrestrial ecosystems (e.g. Stoms and Estes, 1993; Nagendra, 2001; Turner et al., 2003). The application of coastal remote sensing for coral reef biodiversity assessment has much potential. Turner et al. (2003) classified remote sensing applications as “direct” and “indirect”. Direct applications utilize imagery with spatial and spectral resolutions adequate to describe the distributions of species or species assemblages present in a target area, thereby creating inventories of those biological units. In a coral reef context, the closest related fields are the spectral discrimination and mapping of reef habitats, communities and species. This single application has been the primary focus of coral reef remote sensing studies from the 1980’s through the present. Conversely, indirect approaches, sensu Turner et al. (2003), seek to obtain information about diversity patterns, and patterns of ecosystems functions. Two categories emerge: 1) the definition of relevant environmental proxies that will indirectly reflect species richness patterns and will help explain processes that shape these patterns, and 2) the up-scaling of ecosystem functions and processes using habitat/community maps combined with comprehensive field data.

3.2 REEF-SCALE GEOMORPHOLOGY, HABITAT AND COMMUNITY MAPPING

The first applications of remote sensing data for reef assessment consisted of identification and mapping of reef geomorphology or habitat (Fig. 4), using aerial photographs, satellites for Earth observation, and airborne digital systems (see for instance, for recent applications, Isoun et al., 2003; Andréfouët et al., 2003, Garza-Perez et al. 2004). From these studies, there is now a good appreciation of the limits of each sensor based on their spatial and spectral resolutions. The range of map accuracies that can be expected for various complexities of habitat classification schemes has been described for representative sites where extensive ground-truthing and multi-sensor coverages exist (Mumby and Edwards, 2002; Hochberg and Atkinson, 2003; Hochberg et al., 2003a; Capolsini et al., 2003; Andréfouët et al., 2003). For instance, a compilation of results suggests that the overall accuracy (%) is related to the number of habitat classes such that overall accuracy = -3.90*number of habitat classes + 86.38 (r²=0.63) for Landsat ETM+, and overall accuracy = -2.78*number of habitat classes + 91.69 (r²=0.82) for IKONOS (Andréfouët et al., 2003).

Most investigations using images with limited spectral (2-5 bands) and spatial resolution (10-80 meters) have used the statistically-oriented “sensor down” approach (sensu Hochberg et al., 2003a) where local knowledge of reef communities or structure and image-specific statistics drive the (generally) supervised classification of the data (Green et al., 2000). Processing image data prior to classification may be useful, if not imperative. Atmospheric, sea-surface roughness, and water column corrections have been applied to imagery of reef environments (Zhang et al., 1999; Green et al., 2000; Hu
et al., 2001; Palandro et al., 2003, Hochberg et al., 2003b), though not necessarily in a consistent fashion (Andréfouët et al., 2003).

With the increasing interest in hyperspectral sensors better knowledge of spectral signatures of biotic and abiotic end-members has been achieved (Hedley and Mumby, 2002; Minghelli-Roman et al., 2002; Hochberg et al., 2003a; Kutser et al., 2003; Louchard et al., 2003). There has also been progress in understanding spectral mixing (Hedley et al., 2004), radiative transfer processes (Maritorena et al., 1994) and optimization techniques (Lee et al., 2001). These advances help justify an analytical “reef up” approach to map reef communities (Hochberg and Atkinson, 2000; Hochberg et al., 2003a). This “reef up” approach is desirable because it is physics-based, and its application is independent of site- and image-specific statistics. However, calibration accuracy, lack of adequate models, complexity of the radiative transfer processes, heterogeneity of the coral reef world, and absence of spaceborne sensors designed specifically for reef studies make this approach difficult to apply routinely.

Future work will likely exhibit a combination of the “reef up” and “sensor down” approaches depending on the application and available data. Analytical physics-based methods will certainly be effective for mapping and creating inventories of key communities with biogeographically invariant spectral properties like those described by Hochberg et al. (2003a). This likely requires very high spatial resolution imagery, at few meters resolution at most, so that the level of spectral mixing is manageable, with communities composed by few end-members (Hedley et al., 2004). Conversely, at the end of the spatial spectrum or at a geomorphological scale, “sensor down” methods will still be of interest, since the discriminating information depends on both color and topology (position and shape of the classes). While the last 10 years have seen a significant increase in papers presenting the spectral reflectance of reef objects (reviewed in Hochberg et al., 2003a), to date, there has been little focus on formalizing the spatial contextual rules that help improve spectral classification (Mumby et al., 1998; Andréfouët et al., 2000; Andréfouët et al., 2003). Spatial rules are critical, but at present are empirical. Contextual rules are currently best formalized using soft-computing techniques such as fuzzy logic (Andréfouët et al., 2000; Matsakis et al., 2002) but there are still very few specific coral reef examples (Suzuki et al., 2001).

Optical data have been successfully used to assess reef communities worldwide, but always in shallow (0-30 meters at best) and relatively clear waters. There is a great deal of evidence that many deeper reef frameworks exist, along with extensive carpets of coral communities. In the Caribbean Sea, for example, the richest communities are often along deep walls and escarpments out of reach of optical data, while shallow reef flats dominate Indo-Pacific reefs. In a global warming context, medium depth coral carpets and reefs could be the only future refuge and reservoir of diversity (Riegl and Piller, 2003). Investigations of these systems will be the next frontier of direct remote sensing work for reefs.

In turbid, deep waters, shipborne acoustic remote sensing techniques are now used to complement airborne or spaceborne optical surveys. Side-scan sonars, single beam echo-sounders and multi-beam swath systems are currently under evaluation in several regions of the world. Common single-beam Acoustic Ground Discrimination Systems (AGDS) are RoxAnn®, Quester Tangent Corp. (QTC)-View™ (Collins et al., 1996; Collins and Lacroix, 1997; Tsembali and Collins, 1997) and, more recently, ECHOplus™ (Bates and Whitehead, 2001). The respective benefits of these AGDS are compared in the context of marine habitat classification by Kenny et al. (2003). There is still a paucity of coral reef and lagoon work, but recent surveys in the Philippines (White
et al., 2003), Florida (Walter et al., 2002; Moyer et al., 2002) and New Caledonia are promising. Thus far, the focus has been predominantly on geologic and sedimentologic characterization, but the biological diversity of deep habitats is also clearly of interest. Classification results, coupled with extensive ground-truthing, have provided results compatible with optical multispectral methods obtained in shallower waters (White et al., 2003).

The difficulty in acoustic mapping consists in translating the roughness and hardness signals acquired using a variety of frequencies into meaningful biological information. In New Caledonia, the potential of RoxAnn® for mapping complex coral reef lagoon bottoms has been tested. Acoustic responses were recorded in a wide area of the Nouméa lagoon (ca. 2 750 km²), from coastal embayment to barrier reef, in order to classify a large range of bottom types with terrestrial and carbonate sediments (Fig. 5). 267 ground-truthing sites were sampled to collect sedimentological data and habitat information to validate the acoustic classification. An example of the final AGDS product between 20 and 40 meters is presented Fig. 6. Future work will explore the coupling between the shallow optical classification with the deep acoustic classification.

Of the several multispectral imaging systems that have been deployed on reefs, only one active system provides results at centimeter scale. Mazel et al. (2003b) deployed a narrow-beam in-water line-scanning multispectral fluorescence imaging system at night on Florida and Bahamas reefs. A statistical classification exploited differences in 3 fluorescence bands and allowed a good determination of the main benthic functional groups. The Mazel et al. pilot study is successful but the required logistical support is still too cumbersome to make this technique widely available.

Figure 4. Geomorphological map of Wallis, a volcanic island of the South Pacific Ocean, derived from a Landsat 7 ETM+ image (left). Processing included a supervised classification and spatial contextual editing (right), thus a mix between spectral and spatial information.
Figure 5. Acoustic AGDS (Roxann) scatter-plot signatures for a variety of bottoms of New Caledonia lagoon.

Figure 6. 3D mapping of 4 broad sedimentological classes (simplified bottom types presented in Fig. 5) near the lagoonal submarine valley of Dumbea river, New Caledonia.

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Geomorphology, habitat and community mapping provides explicitly the distribution and richness of species if adequate ground-truthing (species inventory) has been conducted and is then explicitly integrated into the classification scheme. In most studies, benthic classes are defined by statistical methods and result from a compromise between thematic complexity and classification accuracy (Andréfouët and Claereboudt, 2000). The inclusion of rare species or specific assemblages significantly complicates the classification scheme and most likely makes the mapping exercise statistically intractable. As a result, classification schemes are generally made of a few spectrally distinct broad classes (generally 4 to 20 at best) that explicitly include only conspicuous and dominant species or assemblages. It is difficult to reconcile this simplification with the goal of biodiversity assessment. Perhaps the solution is to consider habitat assemblages as indirect proxies for biodiversity indicators.

It has been suggested that spatial analysis of geomorphology and habitat maps could be used as predictors of benthic or fish diversity under the assumption that diversity of critical habitats will be mirrored by biodiversity patterns (Ward et al., 1999; Purvis and Hector, 2000; Mumby, 2001; Beger et al., 2003; Andréfouët and Guzman, 2004). Mumby (2001) has proposed promising theoretical methods to analyze high-resolution habitat maps, yet to be applied in the real world. Andréfouët and Guzman (2004) have opportunistically measured in the San Blas archipelago, Panama, if diversity in reef geomorphology detected with Landsat imagery could predict diversity in corals, octocorals and sponges, but the results were not totally convincing. Unfortunately, despite its strong potential, using remote sensing as an indirect way to characterize biodiversity patterns is in its infancy and more work is needed.

3.3 THE FUTURE: INDIRECT CHARACTERIZATION OF BIODIVERSITY

The natural processes that shaped modern reef biodiversity have received considerable attention. Indeed, coral reef research is driven by practical conservation goals in order to design the best possible management strategies to maintain biodiversity and ecosystem functions, services and (economic) value (Gaston, 2000; Turner et al., 2003). Gaston (2000) reviews the main ecological areas of inquiry that drive current research exploring biodiversity spatial patterns. Related to reef research, there are four domains to consider: species-energy relationships, latitudinal/longitudinal gradients in species richness, relationships between local and regional richness and taxonomic covariance in species richness. Remote sensing capabilities could be useful for most of these topics beyond providing species lists.

Species richness-energy relationships have long been emphasized since reefs thrive in nutrient poor oligotrophic oceanic environment, which seemed a paradox until relatively recently when nutrient uptake processes began to be elucidated (Atkinson and Bilger, 1992; Atkinson et al., 2001). At community scale, the metabolic standards established by Kinsey (1985) confirm that generally highly diverse coral communities have higher gross production, even if net production within the coral ecosystem is close to zero. Reef-scale productivity patterns have been up-scaled from in situ community metabolism measurements using remotely sensed benthic habitat maps (Atkinson and Grigg, 1984; Ahmad and Neil, 1993; Andréfouët and Payri, 2001). However, remote sensing products have not yet been used over large reef areas for inter-regional comparisons of productivity and richness.
Latitudinal/longitudinal gradients in species richness have been the focus of many regional studies (e.g. Connolly et al., 2003). The concept of distance to the center of diversity (DCD, located in the Coral Triangle, between Papua New Guinea, Indonesia and Philippines) has been key for explaining marine richness patterns in the Indo-Pacific areas (Mora et al., 2003 for fish communities). Closely linked to the influence of geographic positional variables (latitude, longitude, DCD), the question of the relationships between local and regional richness for remarkable (or well-known) groups of species, and therefore the influence of local vs regional/global factors, has engendered complex statistical multivariate analysis (e.g. Karlson and Cornell, 1998; Bellwood and Hughes, 2001). However, the numerous approaches, heteroclite data sets and intuitive heuristics used in coral reef biogeography analysis of biodiversity patterns are confounding and unification of the data sets would be certainly very useful.

Remote sensing will help make more comparable the different theoretical approaches by providing consistent data sets (Myers et al., 2000; Gaston 2000; Nagendra, 2001; Turner, 2003; McLaughlin et al., 2003; Guinotte et al., 2003). Today, with the wide variety of available remote sensing products (Mumby et al., 2004), there is no justification to use inaccurate, vague or arbitrary proxies of environmental factors for regional or global analyses, which has been common practice in previous studies to compensate for the lack of adequate environmental data (e.g. Bellwood and Hughes, 2001; Roberts et al., 2002). However, this implies that ecologists must master these products and collaborate with remote sensing practitioners beginning with the conceptual designs of their studies.

Geological history, eustatic variations in sea level, genetic and physical connectivity, distance to the center of diversity, temperature, turbidity, geomorphology, habitat structures, natural perturbations and human pressures are examples of factors that have influenced speciation and richness patterns in different reef regions (Galzin et al., 1994; Veron, 1995; Tomascik et al., 1997; Shulman and Bermingham 1995; Done, 1999; Fabricius and De'ath, 2001). As a result, among the standard remote sensing oceanographic products, climatologies of SST, solar insolation, water clarity, chlorophyll and suspended sediments concentrations, exposure to wind and swell, and land masses are clearly of interest. Recently, McLaughlin et al. (2003) reported on a global statistical relationship between reef occurrence and potential terrigeneous sediment sources. The methods of the analysis (k-means clustering, correlation statistics and Geographical Information System analysis) match closely the biodiversity analysis that can be now conceived.

3.4 SYNTHESIS: MULTI-SCALE BIODIVERSITY ASSESSMENTS

On one hand, biodiversity assessment includes one of the most developed and utilized remote sensing techniques, namely habitat mapping using high resolution sensors. On the other hand, it also includes one of the least developed, but equally promising techniques, namely the indirect characterization of biodiversity patterns. The efforts that have been made in a relatively short amount of time specifically for bleaching assessment have yet to be applied for these biodiversity assessments. However, we suggest that the urgency of conservation issues will challenge both the remote sensing and ecology communities and interdisciplinary work will likely improve the situation in the short term.

To establish a network of existing or potential remote sensing applications for biodiversity assessment (Fig. 7), we have considered the two domains where remote sensing will likely be considered first, namely the search for patterns (and explanations
Figure 7. Network of applications for biodiversity assessment. Italicized text refers to non-remote sensing actions.
of these patterns) in gradients in species richness, and the relationships between local and regional richness. Methodologically, this translates into environmental characterization of reef regions (indirect remote sensing of reefs), mapping of reef locations, geomorphology and habitats (direct remote sensing, but indirect biodiversity assessment), and species mapping (direct remote sensing and direct biodiversity assessment). Activities non-specific to remote sensing include \textit{in situ} surveys and spatial statistical analysis, and downstream the data flow, we added methods to design marine protected areas (soft computing) for management purposes.

4. Conclusions and Perspectives: Multi-scale, Multi-sensor, and Multi-method Approach

In this chapter, we used coral bleaching and assessing coral reef biodiversity to illustrate the integration of various remote sensing tools and techniques at several scales. This approach could be presented for other topics of coral reefs as well as other issues in coastal systems. The application of remote sensing to coral bleaching is well established while developments in the use of remote sensing to assess biodiversity are needed. These topics are representative of what can be done to describe the reef structures and their environments in order to better understand the consequences of natural or human forcing on the functioning of these ecosystems.

An analysis of coral bleaching and biodiversity suggests that no single scale (organism or reef or region or global), single method (statistical or analytical) or single sensor (airborne or satellite, multispectral or hyperspectral, active or passive) may be best for all studies. Addressing reef processes requires the capacity to streamline each component in a multi-scale, multi-sensor, multi-method approach, and take advantage of each technique. This also implies combining effectively with parallel domains such as spatial analysis or field survey designs. It is a two-way process. Remote sensing practices should be optimized according to coral reef specificities, and as a feed back, remote sensing should be used more efficiently to observe reefs and their environments.

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6. References


