DIGITAL ANALYSIS OF A PATCH REEF COMMUNITY: RAINBOW GARDENS REEF, LEE STOCKING ISLAND, EXUMA CAYS, BAHAMAS

Thesis by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABSTRACT

Rainbow Gardens Reef, a shallow water Bahamian patch reef, was used as a test site to determine if digital analyses of a low altitude, color aerial photograph can provide information appropriate for routine ecological monitoring. An aerial photograph was digitally scanned into a raster image format and rectified to known ground control points. A simple spectral correction for the water column was applied, and an unsupervised multispectral classification was performed. Geographic Information System (GIS) software was then used to compare estimates of coral cover (Scleractinia and Alcyonaria) with ground-truth data collected by three independent in-water survey techniques.

Coral cover as estimated with the digital analysis was 14.5%, which compared favorably to ground-truth linear intercept estimates of 15.0%. Patterns in distribution of coral cover examined on individual transects were not significantly different as estimated with the linear intercept survey and the digital analysis. Color aerial photographs could not be used to discriminate between stony and soft corals, nor between coral species, probably as the color of both is influenced by populations of symbiotic algae, zooxanthellae. The techniques described herein may lend themselves to routine synoptic mapping and monitoring, and to documenting changes in reef distribution patterns in a time- and cost- effective manner.

INTRODUCTION

Coral reefs are diverse, highly productive tropical ecosystems considered to be important both economically and ecologically (Dustan 1979; Wells 1988; Crosby *et al.* 1995). Their strength, size, and topographic complexity provide barriers that protect coastal regions from storms and habitat for many organisms to live and reproduce. Their biodiversity and productivity have economic importance, principally in fisheries, and their physical beauty attracts an increasing number of sports divers and tourists each year (Hawkins 1994).

Coral reefs thrive in temperatures ranging from 25 to 29° C with tolerances of 20 to 36° C (Storr 1964). Major reef formations are typically found in shallow waters where light is abundant. Light is necessary for the symbiotic zooxanthellae that are embedded within the tissues of corals to provide nutrients from photosynthesis. Because of these physical requirements, reefs of the Caribbean are found near coastal tropical regions, which are presently under pressures from urbanization due to economic development and population growth.

Reefs are subjected to stresses associated with human development. Overfishing (Rogers 1985; Bohnsack 1994), increased sedimentation, nutrient loading (Lapoint *et al.* 1994) and exploitation have resulted in coral degradation (Ogden and Gladfelter 1986; Ginsburg and Glynn 1994). There is a general concensus within the scientific community that coral cover and diversity currently are in decline on shallow coral reefs throughout the Caribbean (Rogers 1985; Dustan 1987, 1994; Dustan and Halas 1987; Wells 1988; Porter and Meir 1992; Aronson 1993; Jaap and Sargent 1994; Smith *et al.* 1994). Increased algal cover due to several factors, such as the mortality of *Diadema antillarum* (Hay 1984; Lessios *et al.* 1984), bleaching events (Brown and Ogden 1993; Lang *et al.* 1994), hurricanes (Woodley *et al.* 1981), and diseases (Gladfelter 1982; Rützler and Santovy 1983) have also contributed to a loss in live coral tissue (Porter and Meier 1992; Smith *et al.* 1994).

Coral communities are presently undergoing rapid changes, generating an immediate need to monitor and document the present status of coral reefs and measure changes in the community structure over time to support resource management efforts and education programs. For these and other reasons it is becoming increasingly important to develop non-invasive non-destructive tools for the remote sensing of shallow water coral reef systems.

The first objective of this study was to test the feasibility of using digital interpretation of a color aerial photograph to describe patterns of coral distribution and coverage on shallow patch reefs. The community structure data from the processed image of the photograph were compared to data dervied from two independent chain transect studies and a hand-drawn underwater map. Data sets acquired from a variety of sources were integrated using a Geographic Information System (GIS). The results provided a sensitivity analysis on the limits of detection and class descrimination with respect to corals and other benthic organisms. The necessity for ground-truth for the photographic interpretation required descriptions of the reef, which led to a second objective of the study, to describe the coral community structure of Rainbow Gardens Reef, Lee Stocking Island, Exumas, Bahamas. This research has established Rainbow Gardens as a monitoring site for studying changes that may occur in the future.

I. PATCH REEF COMMUNITY STRUCTURE

INTRODUCTION

Most scientific investigations on the zonation and community structure of coral reefs have focused on large-scale barrier and fringing reef complexes (Curran *et al.* 1994). Less attention has been paid to the smaller patch reefs which are frequently scattered in the lee of the principal reef tract or develop as small communities on or around shallow irregular land masses (Wells 1988). While the larger reefs are usually well-charted, there are probably no reliable estimates of the numbers of patch reefs found throughout the Western Atlantic (including the Bahamas) and the Caribbean. Patch reefs, formed with stony corals as their predominate structural component, are important ecological habitats for both adult and juvenile fish and invertebrates. One important aspect of patch reefs is that they provide habitat for the development of many species which, upon maturation, may migrate to the outer reef habitat.

Patch reefs, like islands, lend themselves well to studies of community structure because they are discrete entities and typically small enough to be explored to their boundaries, and each one represents an independent ecological experiment in the assemblage of communities (MacArthur and Wilson 1967). With the recent realization that processes of reef degradation may be accelerating, the study of patch reef communities takes on a greater priority (Brown and Dunne 1980; Fenner 1988;

Ramsey and Mason 1990; Chiappone and Sullivan 1991; Rice and Hunter 1992; Sullivan and Chiappone 1992; Curran *et al.* 1994).

The present study utilized two different survey methods (*in situ* linear intercepts and video-based point counts) to describe the benthic invertebrate community of a shallow patch reef with respect to community structure, species diversity, and apparent condition of coral colonies. Conditions assigned to individual colonies (Table 1) helped to infer the relative proportions of healthy, stressed (biologically and/or physically) and dead, as well as juvenile corals.

The principal study site was Rainbow Gardens Reef, a shallow patch reef named for its beauty, color, and vibrant appearance. For the past decade, it has been a favorite locale for recreational snorkeling and diving. Rainbow Gardens was chosen as the primary study site as it was the most extensively developed patch reef of its type found in the local area of the Caribbean Marine Research Center (CMRC). CMRC operates a NOAA/NURP field station on Lee Stocking Island (23° N, 76° W), Exuma Cays, Bahamas (Fig. 1). The Exuma Cays consist of many small islands that extend over 130 miles (209 km) along the eastern edge of Great Bahama Bank (Wells 1988). Small fringing reefs border the windward edge of Exuma Sound, and shallow patch reefs are distributed in their lee and in the tidal channels between the islands (Lang *et al.* 1988). These reefs experience minimal human impact because of their remote location from densely populated areas (Kendall *et al.* 1988; Wells 1988; Lang *et al.* 1994). Since the late 1980s, qualitative changes in the appearance of Rainbow Gardens Reef, resulting from repeated coral bleaching events and increased algal colonization, has generated concern given this site's distance from densely populated regions (Wicklund pers. comm.).

Rainbow Gardens Reef is located on the lee side of Iguana Cay approximately 3 km northwest of Lee Stocking Island (Fig. 2). The patch reef is situated near Adderley Cut, a channel that experiences a strong semidiurnal tidal exchange (up to 150 cm/s) between the waters of Great Bahama Bank and Exuma Sound. These very different water masses alternatively bathe the reef with warm, saline, turbid waters from the shallow Bank and cooler clear oceanic waters from the Sound (Kendall *et al.* 1988, Lang *et al.* 1988). Seawater temperatures range from ~21 to ~32° C annually (Wicklund *et al.* 1993).

The reef begins approximately 100 m from shore where outcrops of hard carbonate rock substrate appear on the mostly coarse carbonate sand bottom. Moving deeper, away from Iguana Cay, biomass increases rapidly as large colonies of *Montastrea annularis*, *Siderastrea sidera*, and *Diploria strigosa* become increasingly more abundant. Smaller colonies of *Porites asteroides* and *Agaricia agaricites* also increase in number and many outcrops are colonized by erect gorgonians and sponges. Such outcrops form small communities that scale into the larger mega-colony of *M. annularis* that approaches 7 m in diameter, referred to as the bommie. This extremely large knobby colony, which dominates the reefscape, comes within 60 cm of the water surface at low tide and virtually forms a patch reef within a patch reef as it has many small colonies of other species within its crevices. Southeast of the bommie, along the edge of Adderley Cut, there is a gorgonian forest comprised principally of

Pseudopterogorgia spp., *Plexura* spp., and *Gorgonia* spp. which forms in the region swept by fast moving tidal currents.

Although the original purpose of conducting this study was for ground-truth of the aerial photographic analysis, a subsequent goal was to offer a statistically valid census of the coral community at Rainbow Gardens Reef to establish a framework for long-term monitoring. The small size of the reef makes it possible to estimate coral coverage over the range of the reef and facilitated in mapping its entire extent. The community structure of Rainbow Gardens was characterized in terms of species composition, coverage, average colony size, species diversity and evenness, distribution patterns, and apparent coral conditions.

METHODS

Rainbow Gardens Reef covers an area of approximately 2800 m^2 (70 m perpendicular to shore and 40 m parallel to shore) (Fig. 3). Initial dives gave evidence for an approximate long axis of the reef extending 30° east of north, shallow to deep (3 m to 10 m). Copper clad survey stakes (12 in.) were hammered into the substrate and used in securing the ends of transect lines. Placement of transects (Loya 1972, 1978; Dustan and Halas 1987) began with positioning a starting point estimated to be near the middle of the shallow end of the axis of the reef and swimming along the axis to the deep end. The deep end of the reef was staked and a taut line was stretched between the two points. This baseline (70 m in length) was marked at each end and at 5 m intervals providing points for 15 perpendicular crosslines, one on either side of the baseline (coded L and R, respectively for the left and right sides of the baseline when facing the shoreline) for a total of 30 line transects. Six main transects were secured with permanent stakes at 0 m, 40 m, and 70 m from the shallow end of the reef (Fig. 4). Each transect extended approximately 20 m from the baseline, continuing past the reef structure into peripheral sandy areas with very few corals. A total of 615 m of transect line was established. The initial data set was acquired during the summer of 1991.

Color photographs of each transect were taken for a permanent record of the reef community at that time. Adjacent photographs directly above each transect with the line centered in the field of view (2 m from substratum) were overlapped approximately 1 m by visually locating a reference point between frames. The photographs were taken using a Nikonos-V camera with a 20-mm lens and Ektachrome ASA 200 film.

LINEAR INTERCEPT SURVEY

A chain (15 m in length) was placed directly below a taut transect line, following the curvature of the substrate (Porter 1972). Coral colonies were measured by counting the number of links (2 cm each) covering the living tissue to obtain estimates of relative coverage and size, and to calculate species diversity and evenness (Dustan and Halas 1987). Scleractinian corals and alcyonarians were identified to species level. Sponges were grouped into families or genera. Any coral colony growing independently of adjacent corals was considered to be an individual colony. An individual colony divided into two or more sections by the death of portions of the colony was still defined as one individual (Loya 1972). Branching species were measured across the colony from tip to tip of the outermost branches. Groups of branches were defined as a single colony if the branches originated from a central area (Dustan and Halas 1987).

Traditional studies with descriptions of patterns or trends in coverage and diversity regress these parameters with depth to illustrate zonation. Since there was no statistically significant increase in depth over the reef with increased distance from shore ($F = 0.002$, where $F_{0.05(1),1,13} = 4.67$, $P=0.97$), multiple regression analyses were performed using both depth and distance along transect (representing distance from shore) as independent variables and the results obtained in the linear intercept survey as the dependant variables (Hale 1990). Data were summarized for the entire reef and for individual transects. The four most abundant species were described in detail throughout the study. A total of 78,854 cm of chain was scored. Percent cover of the reef was calculated for all stony corals (Scleractinia and Milleporina), soft corals (Alcyonaria), and sponges (Porifera), for individual species of stony corals and soft corals, and for total sessile invertebrate cover (Scleractinia, Milleporina, Porifera, and Alcyonaria). Because of the fragmentation and fusion of these benthic invertebrates and the high variation in individual sizes, measurements of their area coverage may be as valuable as their number (Hughes 1984; Pitambo *et al.* 1988; Aronson 1993). Thus, Shannon's species diversity ($H' = -\Sigma\ p_i \ln p_i$) and Pielou's evenness ($J' = H'/H'max$) were calculated for both centimeter coverage (H'_{cm} and J'_{cm}) of stony coral and the number of colonies (H'_n and J'_n) (Pielou 1966, 1975). Average colony size was estimated for individual coral species encountered along the linear intercept survey by counting the number of links crossing the axis of the longest diameter across the live tissue for all encountered corals.

Describing the health of a coral reef is difficult because of the natural phenotypic variations of corals. In order to overcome some of these difficulties, Dustan (1987, 1994) has presented a list of 18 conditions that are typically observed on Caribbean corals. These conditions are easily assigned to individual corals by examining the appearance of the surface of the corals. A modified list of 25 conditions was used to describe the condition of the corals examined at Rainbow

Gardens Reef (Table 1).

The surface of reef-building corals encountered along the linear intercepts was carefully examined and assigned condition codes that are listed and defined in Table 1. The entire colony was described, thus a single colony may exhibit one or several of the conditions. For example, a juvenile colony may be labelled 23,20 (juvenile, unblemished). Since not all small colonies were considered juveniles (e.g., ***Favia fragum*** rarely, if ever, grow larger than 10 cm (Sefton and Webster 1986)), very small colonies of species that normally grow to large sizes, originated from a single polyp, and obviously not an old remnant of a larger colony, were classified as juvenile. In order to assess the effect of sediment and algal tissue necrosis (24) on the coral colony, one of two conditions was also assigned to the colony: colony decreasing in size (17) or healed with secondary algal colonization (14). A colony decreasing in size has dead areas toward the periphery of the colony and can be observed by fanning away any sediment encrusting the edges or pulling away macro algae attached to the surface. A colony healed with secondary algal colonization has dead spots or "algal islands" on the surface of the colony with live tissue surrounding the dead spot.

These conditions were grouped into 5 categories that provide a basis for quantifying the type of stress or damage within a coral population: healthy, biologically stressed, physically stressed, biologically and physically stressed, and dead (Table 2). The grouped categories presented were modified from Dustan's 1985 definitions. The category "dead" included only the recently dead, which were recognizable as corals. These data tend to underestimate the proportion of dead corals since those that have been dead for a long time are usually covered by such a thick layer of algae and sediment they are unrecognizable as corals. Conditions 14 and 17 (healed with secondary algal colonization and colony decreasing in size, respectively) were not included in the grouped categories because 1) they tend to overlap with other conditions, and 2) they were never used alone. Condition 23 (juvenile) was also excluded from the grouped categories, as this description does not indicate any form of stress. Data were summarized by the number and proportion of individual species and all species with each condition (Appendices A and B). Since a single colony may have more than one condition, total proportions were greater than 100%.

VIDEO-BASED POINT COUNT SURVEY

During the summer of 1992, a second survey of Rainbow Gardens Reef was conducted using an underwater Sony high resolution (Hi 8) color video camera. The decision to survey the reef using the video-based point count method was 1) to calculate two independent estimates of coral coverage, and 2) to determine if video point counts are suitable for coral surveys by comparing the results with the linear intercept survey. The 1992 survey differed from the linear intercept method of 1991 in two ways. Video was used to record transects, as opposed to taking notes underwater, and point counts were utilized rather than scoring every link along the chain. The permanent stakes from the previous summer were located and the transects were restrung. The chain, marked every 10 cm (5 links), was placed along the substrate under the transect line. The diver held the camera approximately 20 cm above the substrate and moved slowly along the chain. Every other transect from the previous summer was recorded (alternating between the left and right sides of the baseline), as well as both sides of the deep crossline at 70 m, for a total of 16 transects (Σ = 326 m). The transect videos were later viewed on a 13 in. color monitor, and subsequently scored by counting only the marked points.

The point was defined as the area immediately to the right of the marked link (<2 cm). If a single link was lying on both live tissue and dead substrate, the link was assigned the property of the majority coverage. After viewing the videos on the monitor it became apparent that defining a point was very subjective in areas where the chain was draped between two raised structures causing it to hang above the surface rather than lie directly on the substrate. The defined point changed depending on the angle of the camera. In this case, the point was defined when the mark first appeared in the center of the monitor.

Benthic cover and visible appearance of reef corals were identified for a total of 4,665 points. The conditions listed in Table 3 were used to describe the corals encountered along the video point count method, as they are easily distinguished while viewing the video. Results concerning conditions could not be compared between the video point count and the linear intercept surveys since the two methods were summarized differently (linear intercept Σ = 210.9% and video point count Σ = 100.0%). If the point was on a coral, the coral was identified to species and a single condition (Table 3) was assigned to the area defined as the point (4 cm^2). In order to minimize the time spent viewing, if the point was not covering a stony coral, it was labelled non-coral.

Wilcoxin's paired-sample test was used to test for significant differences between the linear intercept and the video point count surveys (Zar 1984). To achieve closer approximations to the assumptions of normality and homoscedasticity with regard to the values of coverage, the arcsine transformation of data was employed, where $Y' = \arcsin \sqrt{Y}$ (Zar 1984). The values for the left (L) and right (R) sides of the reef were combined for each transect of the linear intercept survey and for Transect 70 of the video point count survey for all statistical analyses.

RESULTS

Twenty-three species of reef corals were found at Rainbow Gardens Reef (Table 4), eighteen of which were encountered along the linear intercepts and seventeen of which were encountered along the video point count transects. The most abundant species of the 616 colonies examined in the linear intercept survey were *Porites astreoides* (24.84%), *Agaricia agaricites* (18.83%), *Montastrea annularis* (13.15%), and *Porites porites* (11.04%).

Colony diameters summarized for individual transects varied from 2 to 418 cm for *Montastrea annularis,* 2 to 218 cm for *Agaricia agaricites,* and 2 to 44 cm for *Porites astreoides* and *Porites porites.* The average diameters ranged from 2.7 cm for *Siderastrea radians* and *Favia fragum* to 55.4 cm for *S. siderea* (Table 4).

Live stony coral cover (Scleractinia and Milleporina) at Rainbow Gardens as estimated for individual transects did not differ significantly between the linear intercept (13.0%, measuring 615 m) and the video point count methods (13.3%, measuring 326 m), (Wilcoxin's $T_+ = 46$ and $T_- = 74$, where $T_{0.05(2),15} = 25$, $0.2<P<0.5$) (Tables 5 and 6).

Linear intercept methods estimated total soft coral cover (Alcyonaria) as 2.0%, total sponge cover (Porifera) as 5.3%, and total benthic invertebrate cover (Scleractinia, Milleporina, Alcyonaria, and Porifera) as 20.3% (Table 5).

Estimates of percent cover of the reef of individual coral species as calculated with the linear intercept and video point count methods did not differ significantly ($T_+ = 28$ and $T_- = 17$, where $T_{0.05(2),9} = 5$, $P>0.5$) for the nine most abundant stony coral species. Estimates of the proportion of the coral population for individual species did not differ significantly for the linear intercept and the video point count surveys ($T_+ = 61$ and $T_- = 75$, where $T_{0.05(2),16} = 29$, $P>0.5$).

Dominant coral coverage of the reef as estimated with the linear intercept method were the reef corals ***Montastrea annularis*, *Agaricia agaricites*, *Porites astreoides*, *Porites porites*** (Table 4), along with the gorgonian ***Pseudopterogorgia*** spp.

Diversity calculated for centimeter coverage as estimated with linear intercept and the video point count methods for individual transects did not differ significantly using the Mann-Whitney test ($U = 137.5$ and $U' = 118.5$, where $U_{0.05(2),16,16} = 181$, $P>0.2$) (Zar 1984). Estimates of diversity (H'_{cm} = cm coverage and H'_n = number of colonies) for reef corals (Table 7) were $H'_{cm} = 1.8$ (linear intercept) and $H'_{cm} = 1.9$ (video point count), and $H'_n = 2.2$ (linear intercept).

Evenness for centimeter cover was significantly different between the two methods ($U = 195.5$ and $U' = -75.5$, $0.01<P<0.02$). Evenness (J') was estimated as $J'_{cm} = 0.6$ (linear intercept) (Table 7) and $J'_{cm} = 0.7$ (video point count), and as $J'_n = 0.7$ (linear intercept).

Stony and soft coral cover increased significantly as distance from the shore increased ($F_{stony} = 16.9$, $P=0.000$ and $F_{soft} = 13.22$, $P=0.001$, where $F_{0.05(2),2,12} = 5.10$) (Fig. 5). Sponge cover remained constant with increased distance from the shore ($F_{sponge} = 1.12$, $P=0.358$).

Examination of the total benthic invertebrate community indicated that sponges dominated in the shallow portions of the reef, while stony corals were dominant in the deeper areas, or those areas more distant from the shore (Fig. 6).

Multiple regression analyses indicate that *Montastrea annularis* (F = 15.47, P = 0.000), *Porites astreoides* (F = 13.67, P = 0.001), *Agaricia agaricites* (F = 8.60, P = 0.005) and *Pseudopterogorgia* spp. (F = 6.30, P = 0.013) all increased with an increasing distance from shore, whereas *Porites porites* (F = 2.045, P = 0.172) remained constant across the reef, where $F_{0.05(2),2,12} = 5.10$ (Fig. 7).

Diversity and evenness as estimated with the linear intercept survey were examined for trends along the reef (Fig. 8). Diversity calculated for centimeter cover and number of colonies increased with distance along the transect. Evenness calculated for number of colonies decreased slightly and evenness calculated for centimeter cover remained constant over the reef.

CORAL CONDITIONS

Examination of the condition data from the grouped categories (Table 8) indicated that most (95.3%) of the corals were subjected to both physical and biological stressors. The predominant physical and biological stressor was sediment and algal induced tissue necrosis (37.3%), which affected 15 of the species examined (Appendix B). Approximately a quarter (25.3%) of the colonies were decreasing in size and 7.1% were healed with secondary algal colonization. These observations suggested that these areas of sediment and algal tissue necrosis were causing a loss of live tissue on coral colonies. Recent damage to soft tissues affected 10.7% of all corals examined, including ten species (Appendix B).

Boring sponges were another significant physical and biological stressor, affecting 10.6% of all corals examined (Appendix B). The most common boring sponge was *Cliona delitrix*, which was found in only 8 of the species, but affected 50% of all *Siderastrea siderea.*

Tissue bleaching was observed in only seven of the species examined (Appendix B). While very few corals were completely bleached (0.5%) during the summer of 1991, several exhibited slight bleaching (9.9%).

Over half (51.1%) of the colonies examined, including 16 species, were considered generally healthy (Table 8). Unblemished was the most common condition for four species: *Favia fragum* (75.8% n=62), *Siderastrea radians* (73.1% n=26), *M. alcicornis* (39.5% n=43), and *P. astreoides* (37.9% n=153) (Appendix B). More corals were unblemished (36.7%) than were almost unblemished (14.4%).

Almost 16% of the corals examined were presumed juveniles (Appendix B). Juveniles of six coral species were recorded: *Porites astreoides*, *Agaricia agaricites*, *Dichocoenia stokesii*, *Porites porites*, *Millepora alcicornis*, and *Diploria strigosa* (Appendix B). Species dominating recruitment were *P. astreoides* (41 recruits n=153), *A. agaricities* (33 recruits n=116), *D. stokesii* (12 recruits n=22, and *P. porites* (8 recruits n=68). These species are larval brooders which typically have high recruitment rates (Gittings *et al.* 1994). Although the data are not presented here, most of the juveniles observed were unblemished or almost unblemished (pers. obs.). No *Montastrea annularis*, *Montastrea cavernosa*, *Acropora cervicornis*, or *Siderastrea* *siderea* were identified as juveniles. These broadcast spawning species typically have very low recruitment rates (Gittings *et al.* 1994). A large number of *M. annularis* were both affected with sediment and algal tissue necrosis and decreasing in size (Appendix B), resulting in many isolated remnants of the previously larger colony. These remnants are sometimes difficult to distinguish from juveniles, and may contribute to the lack of juveniles recorded for this species.

About nine percent of the corals examined were only subjected to physical stress (Table 8). Excessive sediment was found on live tissue in 8.4% of the corals, including 11 species (Appendix B). This is one of the stages leading to sediment and algal tissue "necrosis". After the tissue is damaged by the sediment, colonization by an algal mat community allows the entrapment of more sediment, in turn decreasing the size of the colony. Fresh damage to the skeleton and tissue of corals was found in only 0.3% of the corals and was limited to 2 species, *M. annularis* and *D. labyrintheformis*.

Of the 616 corals examined, 6.2% exhibited only biological stress (Table 8). The most common biological stressor was dark tissue discoloration, which affected 3.6% of all corals examined (Appendix B). Dark tissue discoloration was observed in one quarter of all *D. labyrintheformis*.

Very few corals were identified as recently dead (1.1%) (Table 8). This value underestimates the true proportion of dead corals, since most of the reef rock could be classified as dead coral, although doing so would serve no purpose for this study.

A total of 4,665 points (10 cm apart) was scored at Rainbow Gardens using the video point count survey, 619 of which covered stony corals. The results were summarized by number of points rather than number of colonies since colonies larger than 10 cm were scored more than once. Each point covered an area of four square cm and because of the small area was assigned a single condition code from Table 3. Therefore the sum of all condition codes is 100% (Table 9). Of the 619 points that covered coral, 76.1% of them covered areas which were considered to be in good condition or healthy, 9.4% covered areas where algae was attached to the coral, and 7.9% covered dead areas of coral adjacent to living tissue. No tissue damage or crustose algae were recorded with the video point count survey.

DISCUSSION

This survey of Rainbow Gardens Reef was intended primarily to ground-truth a digital interpretation of an aerial photograph. Since the limits of detection for the digital analysis were not pre-determined, data were collected for the maximum expected detection level and the underwater surveys were more than sufficient in providing the requisite information. Consequently, a detailed description of the community structure of Rainbow Gardens Reef was performed, offering time-series data and information regarding the apparent condition of scleractinian corals.

The number of species found at Rainbow Gardens Reef, live coral cover, and calculated diversity are comparable to many other patch reefs in the Bahamas (Table 10) (Chiappone and Sullivan 1991; Sullivan and Chiappone 1992; Curran *et al.* 1994). *Montastrea annularis* and *Agaricia agaricites* are the dominant species in terms of cover at Rainbow Gardens, as they are on other Bahamian patch reefs (Chiappone and Sullivan 1991; Curran *et al.* 1994). *M. annularis* is considered to be the most important frame-work building species throughout the Caribbean (Goreau 1959; Dustan and Halas 1987).

Coral zonation is influenced by water depth, by modifying light penetration, wave action, and sediment run-off from land that settles on the reef (Wells 1954; Goreau 1959). Patch reefs are typically relatively level structures with minimal changes in depth; consequently, only slight zonation patterns are usually observed.

Rainbow Gardens is situated in the lee of Iguana Cay and protected from the surge of Exuma Sound; therefore, wave action is not significant in organizing the zonation patterns on the reef. Coral cover (stony and soft) and diversity increase with increased depth and distance from shore towards the periphery of the reef. This may be primarily a function of tidal exchange. In the shallow regions of the reef, further up on the terrace, bottom friction slows the water flow. The tidal current is not very strong; therefore, the food availability may be limited, resulting in smaller scleractinian corals and fewer alcyonarians. However, very strong tidal currents sweep the deeper regions of the reef. In fact, the current is so strong, it becomes very difficult to work during both flood and ebb tides. These strong tidal currents result in large masses of water flowing over the reef; thus the availability of food is increased. Coral growth is very successful (e.g., the large mega-colony of *Montastrea annularis*) in the regions more distant from shore, closer to Adderley Cut. This increased cover and diversity may driven by an edge effect (Porter 1972), where coral colonies growing near edges of escarpements or edges of the reef have increased access to available food and/or nutrients.

The condition codes, which are admittedly preliminary, are an attempt to remove some of the subjectivity in describing the conditions of corals. The categories provide information on the phenotypic condition of the corals on this reef and will be useful to document change when compared to future surveys of Rainbow Gardens Reef. No attempt was made to discern the cause and effect of the conditions, realizing that in many cases, detailed studies are needed to infer causality. Additionally, it has been shown that some species of coral undergo seasonal changes in color, presumably related to zooxanthellae populations and bleaching (Lang *et al.* 1994).

Results concerning conditions should not be compared between the video point count and the linear intercept methods since the data were summarized differently (linear intercept =210.9% and video point count =100.0%). Multiple conditions were assigned to a colony in the linear intercept survey, and only one condition was assigned to a point in the video point survey. Additionally, the entire colony was examined using the linear intercept method and only a very small area was examined using the video point count method. The linear intercept method did not take into account the proportion of individual colonies with each condition. Even if a large colony was mostly healthy (relatively unblemished over most of the surface area) and had one boring worm, it was considered physically and biologically stressed.

Data collected a year apart (summer 1991 and 1992) show almost no change in the cover even though a minor bleaching event occurred in the Fall of 1991. Several possible conclusions may be drawn from this. First, qualitative judgements tend to focus on damage and/or areas that have changed. Statistical sampling may not detect this to the same degree. Second, whatever had previously stressed the area is no longer affecting the stony corals, soft corals, and sponges. Third, the rate of change is too slow (although still operative) to detect in one year.

Multiple independent surveys provided similar statistical descriptions on the community structure of Rainbow Gardens Reef, resulting in a robust estimate of coral cover. There are advantages and disadvantages to using either the linear intercepts or the video-based point counts, and the preferred method depends on the purpose of the study, time constraints, cost, and desired resolution. The linear intercepts produce a data set with the greatest level of taxonomic accuracy as the investigator is in close contact with the corals. The advantages of video-based point counts include increased speed of acquisition in the field. No photographic processing is required, and videos may be viewed immediately after a dive; therefore, transects may easily be repeated if data are not high enough quality. Videos provide a near-permanent continuous record of the transects allowing the observer to review them multiple times, and more than one observer can view the video and discuss conditions which may be subjective. Also, videos may be reviewed for additional information during future studies (e.g., a sponge study may be conducted using the same video). Lastly, all observations are made above sea level rather than underwater where it has been shown that perception is hindered. The disadvantages of using video-based point count methods are realized when the viewer can not differentiate the coral species because of shading, focus, or improper angles of view. Also, the video camera is difficult to get into small crevices, causing an increase in the distance between the substrate and the lens of the camera. The apparent conditions may therefore be difficult to distinguish; furthermore, the frame does not allow viewing of the entire colony.

Rainbow Gardens patch reef is established as a monitoring site set up for future studies. The lack of topographic complexity makes this reef ideal for a test site for aerial photography, since colonies are visible and coral cover can be calculated.

II. DIGITAL ANALYSES OF AN AERIAL PHOTOGRAPH

INTRODUCTION

Traditional coral reef field survey methods for obtaining *in situ* estimates of coral cover and community structure (Dustan and Halas 1987; Ohlhorst *et al.* 1988) are time consuming, tedious, and expensive. Tools to partially overcome these drawbacks may be provided by digital analyses of remotely sensed images which have increased in popularity for gathering baseline data describing shallow reefs (Jupp *et al.* 1985; Maniere and Joubert 1985; Claasen 1985; Kuchler *et al.* 1986a; Kuchler *et al.* 1986b; Bainbridge and Reichalt 1988; Claasen and Pirazzoli 1988; Hopley and Catt 1988; Kuchler *et al.* 1988). Kuchler *et al.* (1988) reviewed the various platforms and sensors used in obtaining remotely sensed information for mapping and monitoring of coral reef environments. Success usually requires a multiplatform (satellite, aircraft, and/or ship) approach examining images at various spatial scales (Claasen and Kulcher 1985; Jupp 1986; Lyzenga 1987; Kuchler *et al.* 1988). Most importantly, groundtruthing is still required for accurate interpretation of data taken at any scale.

Studies utilizing remotely sensed data ideally begin with an *a priori* determination of what environmental parameters are desired and which platform and type of sensor are most appropriate. Since the purpose of this study was to estimate coral cover on a reef with dimensions of approximately 70 m x 40 m and to describe patterns of coral distribution over this reef, low altitude (1000 ft) color aerial photography was chosen for the analysis. Such photography may be electronically scanned to yield digital imagery with a spatial resolution that is greatly improved over satellite imagery (Landsat Thematic Mapper (TM) = 30 m and SPOT (Systeme Probatoire d'Observation de la Terre) = 10-20 m). In point of fact, images are limited in resolution only by the altitude, the quality of the photograph (Hopley and Catt 1988), and the resolving power of the scanning device.

This project hopes to demonstrate the utility of a digital analysis of a color aerial photograph for estimating and describing distribution patterns of live coral cover (stony and soft) on Rainbow Gardens Reef. It extends the application of remote sensing techniques for large scale morphological mapping of reefs to the small scale complexities of biotic communities of interest to ecological researchers. Ground-truth for this work was provided by the two independent studies of community cover and composition examined previously and a hand-sketched map, which included most colonies larger than approximately 10 cm.

METHODS

Data sets acquired from three sources and at three spatial scales (chain transects, underwater map, and aerial photograph) were integrated to describe the community structure of Rainbow Gardens Reef. A flow-chart was prepared to illustrate the steps involved in the digital analysis (Fig. 9).

GROUND-TRUTH

Linear intercept and video-based point count surveys were used to estimate the species composition, coral cover, and calculate stony coral species diversity and evenness at Rainbow Gardens Reef (Chapter I).

All scleractinian reef corals larger than about 10 cm were mapped. The reef was temporarily divided into 5 m x 5 m quadrats by a grid of lines based on the transect lines used in the chain transect survey. Hand-drawn sketches were prepared for each quadrat, then pieced together ashore (Fig. 10). The position of each colony was entered into a digital file by tracing the polygon shapes on a digitizing tablet with an attached handpiece using ERDAS™ software installed on the JOVE remote sensing laboratory at the College of Charleston. A file was created with each coral species occupying a unique class number, and a separate file was made to represent the actual transect lines. Each of the 30 line transects used in the chain transect survey was digitized according to the actual lengths used in the survey. The vector data set was gridded into a raster form image (Fig. 11), where 1 pixel = 5 cm (Fig. 12). These data were used for calculating estimates of coral cover over the entire reef and as ground-truthing of the scanned aerial photograph.

IMAGE PROCESSING

The optical signal recorded on film represents the reflectance of the benthic organisms modified by the optical properties of the water column. Light is attenuated in the water column through absorption and scattering by plankton, dissolved and particulate matter, and the water molecules themselves. To correct for the reduction in brightness values resulting from the attenuation of light, a simple correction was applied to the aerial image to increase the brightness value of each pixel by the amount of light estimated to be attenuated by the water column. The "water correction" procedure required two sets of information for each pixel in the image: 1) depth and 2) spectral attenuation of the water column.

Measurements of depth to the nearest foot were recorded using a digital dive computer (Edge) along each of the permanent transect lines and several other locations over the reef. Depths at low tide ranged from 2 ft. at the top of the bommi to 22 ft. near the outer edge of the reef. A contour map was generated by digitizing the depth contours using the same coordinate system as the hand-sketched base map (Fig. 13). Image processing applications allow only whole numbers as class values, making a range of 2 to 22 ft., at one-foot intervals, unrealistic of the actual relief of the reef. The scale was increased by a factor of 10, resulting in a range of 20 to 220 (0.1 ft. intervals), which more closely approximates, but does not truly represent, the gradual slope of the substrate. Spatial filters were applied to the image to smooth the changes in depth over the reef reducing the difference between the highest and lowest values of a contiguous set of pixels of the image. Low spatial frequency filters decrease the size of the digital step between pixels, spreading the change in depth over a few pixels rather than a single discrete step. Several low-frequency transformation calculations (kernels) were used to decrease the spatial frequency. Six 7 by 7 filters with a value of 1, one 12 x 12 filter with a value of 1, and three 12 x 12 filters with a value of 9 resulted in a continuously varying contour map which more appropriately represents the natural slope of the reef (Fig. 14).

The attenuation coefficient for photosynthetically active radiation (K_{PAR}) of the water was calculated using data collected at the time of flight for the aerial photograph using a profiling natural fluorometer (PNF300) by Biospherical Instruments. K is calculated at specific wavelengths (λ) with the equation:

$$I_{\lambda d} = I_{\lambda o} e^{-Kd}$$

where $I_{\lambda o}$ is the illumination at the surface, and $I_{\lambda d}$ is the illumination after the radiation has passed through the depth (d). The instrument calculated an average K for the water column as $K_{PAR} = 0.3$ for photosynthetically active radiation. Since the actual amount of light removed by the water column is a function of wavelength, an attenuation coefficient was estimated for each band of the image (red, green, and blue). An average wavelength for each band was calculated using the color digitization information for each of the color filters in the EIKONIX camera (Fig. 15). From Baker and Smith (1982), a value of $K_{PAR} = 0.3$ approximates the chlorophyll concentration in the water column as 1-2 mg $Chl \cdot m^{-3}$. Using the average wavelengths for each band and a plot of the spectral diffuse attenuation coefficient vs. wavelength (Fig. 16) (Baker and Smith 1982), values of K were estimated as 0.4 for the red band (608 nm), 0.2 for the green band (540 nm), and 0.27 for the blue band (445 nm).

Color aerial photographs of Rainbow Gardens Reef were taken in sunny, clear conditions at an altitude of approximately 1000 ft on July 23, 1991, from a King Air turboprop airplane, using hand-held cameras with a 60 mm f/2.8 lens and 35 mm film. The ends of each of the four major transect lines and each intersection were marked with buoys visible from the air, as well as two ground location points nearby on Iguana Cay. A photograph taken at a nearly vertical angle was selected for the digital interpretation procedure (Fig. 4).

The selected photograph was scanned with an EIKONIX 1412 Image Digitizer and a Nikon 60 mm microNikor lens using ERDAS™ software installed on a IBM clone (386/25) at the JOVE remote sensing lab at the University of Charleston. The CCD array of the red, green and blue filters of the EIKONIX color filter wheel has an effective spectral sensitivity as shown in Fig. 15. The spatial resolution of the image is defined by the user during the scanning process and should be determined according to the purpose of the study. The higher the resolution of the image, the larger the file; therefore, the resolution should result in a file of a reasonable size for the capability of the image processing workstation. Ground control points were used in determining the spatial scale of the image by calculating the number of pixels across an object of a known distance. The reef area of the photograph of Rainbow Gardens was scanned at f/5.6 in order to allow the proper exposure to discern the reef features while also increasing the depth of field of the image for increased focal ability. A multispectral RGB (red, green and blue) color image of 2048 X 2048 pixels was produced at an estimated resolution of 1 pixel = 5 cm (Fig. 4).

A pixel by pixel comparison of separate images of one scene collected from different sources (or at different scales) requires that each image must conform to the same coordinate system. The hand-drawn map was used as a base map for image-to-image registration of the aerial photograph. Twenty-one ground control points were used to compute and test a transformation matrix which converts source coordinates to rectified coordinates. The matrix consists of coefficients which are used in polynomial equations to convert the coordinates. A second order transformation was preferred over a first order linear transformation since a second order can correct for nonlinear surface distortions such as changes in depth over the reef. The root-mean-square error (RMSE), which is the distance between the input (source) location of a GCP and the retransformed location for the same GCP, was less than ±10 pixels (±0.5 m). The output image file (Fig. 17) with the new coordinate information in the header was created by non-linear rectification using nearest-neighbor resampling where the value of the closest pixel is used to assign to the output pixel value. Nearest-neighbor resampling transfers original data values without averaging them; therefore, the extremes and subtleties of the data values are not lost.

Algebraic equations were applied to the aerial image to correct for the reduction in the brightness values from the attenuation of light by the water column using the estimated values of K for each band and the depth contour map. The purpose of the water correction was to provide an estimate of the optical signal the benthic community would produce in the absence of water. The algorithm takes each band of the aerial image separately and adds back the amount of light removed by the water column. The general algorithm is as follows:

$$\frac{\text{brightness value}}{\text{exponent}^{-K} \circ \text{depth} / 33}$$

Depth is divided by 33 since the equation was developed using meters and the scale was increased from 2-22 ft to 20-220 ft. Three equations were used in the algebraic processing, one for each band:

Red band: $$\frac{x1}{(\exp^{-0.4} \circ x4 / 33)}$$

Green band: $$\frac{x2}{(\exp^{-0.2} \circ x4 / 33)}$$

Blue band: $$\frac{x3}{(\exp^{-0.27} \circ x4 / 33)}$$

where x1 = the red band; x2 = the green band; x3 = the blue band, and x4 = the depth from the contour map. The purpose of applying algebra to the aerial image was to replace the light removed by the water column, producing Fig. 18. Fifty points were haphazardly selected from both the shallow and the deep sandy areas of each image before and after the water correction to determine the accuracy of the procedure. The brightness values for each of the three bands (red, green and blue) were compared individually between the shallow and deep areas using a t-Test. Since the t-Test assumes equal variances, the variance ratio test was performed for the red band of the image.

Classification of a multispectral RGB image groups similar spectral signals from each band into clusters of a specified size producing a GIS file (a single band data set). The rectified multispectral RGB image corrected for water attenuation was classified using an unsupervised cluster of 28 classes to produce a single band false color image (Fig. 19).

The scanning and rectification processes produced several classes containing information known to be "noise" in the image, such as the edges of the image, foamlines across the image, and flaring from the sun's reflection produced by small waves at the surface of the water (Fig. 19). Each of the 28 classes was examined separately to determine which ones were relevant (classes containing reef information) and which ones to "mask" out (classes containing "noise"). The "noise" classes were masked and the resulting image was classified and reexamined for any "noise". This procedure was repeated until no classes contained any "noise". The final image is considered to be the image most suitable for estimating coral coverage (Fig. 20).

The reef area was subset out of the final image using the digitized map boundaries to calculate estimates of percent coral cover over the reef. Classes were labelled as coral (including both stony and soft coral) and non-coral by visual inspection of the image and personal knowledge of the reef. It should be noted that this type of reasoning may be considered circular, as personal knowledge of this reef was far greater than it would be with minimum ground-truthing (i.e., ground control points and optical properties of the water). A true test of the ability to correctly identify corals and non-corals would be to apply these techniques to another reef in similar waters, which would be another study in itself. A statistical summary of the proportion of the image that each of the 28 classes represented provided an estimate of coral cover over the entire reef. These data were compared to the underwater chain transect data and the digitized map to determine the accuracy of the digital analysis.

Attempts were made to differentiate between species of corals using the clusters of classes produced by the classification process. All "non-coral" classes in the final image were masked leaving only what was considered live coral to be classified into 28 classes (Fig. 21). Each of the 28 classes was examined individually using the map as a reference, to look for similarities among coral colonies known to be of the same species.

GEOGRAPHIC INFORMATION SYSTEM

In an attempt to survey the reef using similar sample methods as the linear intercept method, the GIS transect line coverage was overlain with the hand-digitized map and final subset image. Because of errors resulting from the digitizing and rectification processes, exact replication of alignment of the underwater chain transects was not possible, but the same proportion of the reef was sampled in approximately the same areas. The statistical distribution of pixels was used to calculate estimates of coral cover where transect lines intersect coral. The left and right sides of the baseline were combined as in the linear intercept method for comparisons. Individual transects of the aerial image were compared with the underwater linear intercept data to examine the possibility of inferring patterns of coral distribution from the aerial image.

In order to decrease the amount of error resulting from small sample sizes (i.e., line transects), the image was subset into zones by digitizing a GIS coverage with 9 belt transects, measuring 10 m in width, perpendicular to the main transect. The 9 zones were defined by drawing polygons around the transects meeting half-way between each transect. The 9 zones include Transects 0 and 5, 10 and 15, 20 and 25, 30 and 35, 40 and 45, 50 and 55, 60, 65, and 70. Coral cover (including both stony and soft coral) was estimated for each of the 9 belts. GIS belt estimates were compared to GIS line estimates and *in situ* estimates of coral cover to determine if patterns of coverage can be more closely approximated by examining the image for wide belts rather that single pixel lines.

RESULTS

The linear intercept survey estimated coral cover (stony and soft) at Rainbow Gardens Reef as 15.0% (Chapter I). Eleven stony coral taxa were large enough to be included on the digitized map based on the underwater sketches (Table 11). Total live coral cover was estimated as 10.9% on the digitized map, and as 14.0% when the transects were overlain on the digitized map. The map was considered to produce the least accurate estimate of the surveys presented in this study, as it was based on a hand-sketched map using 5 m grids. Only the larger species were included, and no data for individual colonies are available regarding the amount of live tissue verses dead skeletal material. Hence, smaller species were underestimated and larger species are overestimated with 5 m drawings.

Initially 25 ground control points (GCPs) were established using the buoys visible on the image and the major reef structures referenced on the map. A total RMSE (Root-Mean-Square-Error) of 10 pixels (50 cm) was defined as the maximum acceptable error. Using all 25 GCPs in the second-order transformation process resulted in a total RMSE of 13.43 pixels. Deleting the three GCPs with the highest error resulted in a total RMSE of 9.95 pixels (49.75 cm), which was deemed within acceptance. The three GCPs that were deleted were located in the deeper regions of the reef. The most likely source of error for these particular GCPs was increased distance in the water column for light penetration. Because a second order transformation was used, the resulting image had curved edges. A visual inspection of the transects on the rectified image, as compared to the unrectified image, illustrated how the rectification process modified the shape of the two-dimensional image to more closely approximate the actual three-dimensional layout of the reef as it is underwater.

The variance ratio test of the points collected in the deep and shallow sandy areas (Table 12) indicated that variances may be assumed to be equal before the water correction ($F = 0.45$, where $F_{0.05,2,49,49} = 1.88$, $P>0.5$) (Zar 1984). Therefore a t-Test for two samples assuming equal variances was used to test for significant differences between the brightness values for the shallow and deep areas of sand. Before the process of water-correcting the image, the deep and the shallow were significantly different for each band ($t_{red} = 37.29$ $P<0.001$, $t_{green} = 32.27$ $P<0.001$, $t_{blue} = 32.37$ $P<0.001$, where $t_{0.05,(2),98} = 1.98$). After the process of water-correcting the image, there were no differences for the blue band ($t_{blue} = 0.09$ $P>0.5$). The red and green bands still exhibited significant differences between deep and shallow ($t_{red} = 11.58$ and $t_{green} = 14.39$ $P<0.001$); however, the ratio of shallow to deep was closer to one (Red ratio = 0.44_{before} to 0.89_{after} and Green ratio = 0.60_{before} to 0.84_{after}), suggesting that this process shifted the color composition closer to how the benthos might appear without a covering of water.

The iterative masking/cluster analysis process was carried out through 4 cycles to produce an image of the reef containing 28 relevant classes. Of the 28 classes resulting from the first unsupervised classification, 10 classes contained reef information and 18 classes were considered "noise". These 18 classes were masked out of the original multispectral image, which was then reclustered to 28 classes. The resulting image contained 20 classes of reef information and 8 "noise" classes, which were masked from the original image. Classification of this image to 28 classes produced an image with 27 classes of reef information and 1 "noise" class. The masking of this class and a final classification resulted in a final image containing 28 reef information classes (Fig. 20).

The intermediate images in this procedure were considered unsuitable for accurate estimates of coral cover since some classes contained "noise", e.g., pixels scattered throughout the edges of the image. Nevertheless, coral cover estimates were calculated for the second and third images (at 11.6% and 11.5% respectively) to determine to what extent the masking process alters the results. The final image yielded an estimate of coral cover over the entire reef as 14.5%. This estimate increased to 19.6% when the GIS transect layer was overlain on the reef (Table 13).

Coral cover distribution patterns were inferred by examining either single pixel line transects overlain on the aerial image (Fig. 22) or hand-digitized belts along the reef (Fig. 23). Wilcoxin's paired sample test was used to compare the arcsine transformed values of coral coverage from the image to the combined stony and soft coral values from the underwater linear intercept survey. Neither the line transect overlay nor the belts were significantly different from the linear intercept data (T_{+line} = 52 and T_{-line} = 68, where $T_{0.05(2),15}$ = 25, $P>0.5$; and T_{+belt} = 26 and T_{-belt} = 19, where $T_{0.05(2),9}$ = 5, $P>0.5$). Both digital overlays slightly underestimated coral cover in the shallow regions and slightly overestimated coral cover in the deeper regions, as compared to the linear intercept survey. Although statistically the two methods of examining patterns did not differ, it seems likely that the belt method would provide more accurate estimates of coverage since a larger area was sampled.

There was no correspondence between class and coral species. The classes seemed to more closely correspond to changes in depth with individual coral colonies, resulting in concentric "rings" of classes around each colony.

DISCUSSION

Digital analyses of an aerial photograph provide a useful form of remote sensing to estimate coral (stony and soft) cover on small Bahamian patch reefs. Aerial photographs are currently the most common source of remotely-sensed information available for coral reefs (Jupp 1986; Kulcher *et al.* 1988). Most of these images are used in regional scale morphological studies and very few are examined for biological patterns on the scale of an individual coral reef. For the purpose of examining patterns of coral distribution on a small reef, aerial photos are chosen over satellite imagery because of increased resolution and accessibility. Although Landsat TM and SPOT images are less expensive and can cover remote regions more frequently than aerial photographs, the resolution is not sufficient to monitor changes in distribution patterns of small patch reefs, which are prominent elements of modern reef complexes (Curran *et al.* 1994). Also, no satellite-based sensor is spectrally and spatially customized for the specific coral reef mapping tasks (Kulcher *et al.* 1988).

The increasing trend to digitize existing or new aerial photographs (Maniere and Jaubert 1985; Kulcher *et al.* 1988) allows researchers to process large amounts of information very quickly, perform geometrical rectifications to the image, and produce accurate maps (Maniere and Joubert 1985). Image processing is required for accurate interpretation. The water correction process appears to improve the spectral resolution of classification; however, this process only approximates the spectral alteration of the light field by water. Colors are relative and scanner responsivity is broad; therefore, this is an extremely difficult correction to apply at the next level of precision. Better results could undoubtly be obtained with newly developing techniques, which include high resolution imaging spectroradiometers and in-water measurements of spectral optical properties.

Estimates of coral cover from a digitally processed aerial photograph of a shallow water patch reef, taken with a hand-held 35 mm camera, compared favorably with results using *in situ* linear intercepts, there being only a 0.5 percent difference between these two meethods. The underestimates of coral cover in the shallow regions of the reef, using the digital overlays, were possibly a function of the digital interpretation not detecting the small individual colonies growing independently from other colonies. The overestimates of coral cover in the deeper regions of the reef, using the digital overlays, were likely a result of the gorgonian forest canopy. Linear intercepts tend to measure only the base or a branch of a gorgonian, as the digital interpretation of the aerial photograph measured the entire canopy. The digital interpretation was not able to differentiate between species of coral, nor between stony and soft coral, as these organisms all contain populations of zooxanthellae embedded within their tissues. Also, the remotely sensed data did not provide information on the condition of corals; therefore, it remains for future development to perfect methods to remotely sense coral condition. Aerial photography may not be useful for monitoring fringing reefs in deeper waters, as the water attenuation is more pronounced and the typical steep slopes do not allow the shaded colonies to be photographed.

GIS allows photo-interpreters to integrate and compare data from different sources (aerial photograph, *in situ* transects, and hand-drawn underwater map). Rectified images of particular areas can be analyzed individually as layers or combined for multiple comparisons. Perhaps the most significant aspect of this project was the use of remote sensing for describing distribution patterns of live coral cover on a small patch reef. This development expands the present applications of using remote sensing techniques from large scale morphological mapping of reefs to the small scale complexities of biotic communities of interest to ecological researchers.

CONCLUSIONS

One of the goals of the present study was to understand how the information gathered at different spatial resolutions can be used to monitor coral reef communities. Coral coverage was compared between four different spatial scales (underwater linear intercepts [2 cm], underwater video-based point counts [10 cm], underwater map [10 cm^2], and aerial photograph [5 cm]) to determine if these four survey methods yield similar results. The work presented demonstrates that underwater surveys carried out with various techniques at different spatial scales yield similar results with respect to the overall coverage of scleractinian and alcyonarian corals on a shallow patch reef. Comparisons with aerial photographic results provided a linkage with data that presents new challenges. Aerial photography provided information at a spatial resolution appropriate for the routine landscape scale monitoring of coral reefs.

The reward of using these techniques is recognized when routine surveys of a particular reef are performed. Once a monitoring site has been established with the appropriate ground control points and the depth contour map, follow-up flights over the same areas at approximately the same altitude provide a simple way for routine monitoring. Such a survey only requires some measurement of K (light attenuation coefficient) for the water column at the time of flight.

The strengths of the digital analysis lie in the ability to assess the full view of the reef. Aerial photography is inexpensive in comparison to time-consuming field studies, and photographs are easy to obtain. A large amount of archived aerial photography exists that has not been well utilized as an investigatory tool. New data on "local reefs" is easily acquired using small airplanes. Aerial photography offers the ability to survey changes over many reefs in a short time, and provides an excellent tool for separating reef ecosystems into major habitats (such as sand, grassbeds, reef, etc). The limitations of digital interpretation lie in the inability to monitor individual colonies and the inability to distinguish species. For studies interested in examining individual coral species or determining estimates of diversity, ground-based methods are necessary.

The results suggest that if one is interested in a synoptic view, monitoring gross changes of live coral cover over many reefs covering a large area, aerial photography is appropriate. However, if one is interested in monitoring changes in individual corals or interactions of organisms, traditional in-water survey methods may be more appropriate. Remote sensing does not replace underwater observations; however, it extends the limits of underwater observations through image processing and GIS interpretation of properly ground-truthed images.

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Table 1.

Condition codes and definitions assigned to coral colonies encountered along the linear intercept survey at Rainbow Gardens Reef. Condition list was modified from Dustan's 1985 coding system (some code numbers were omitted with the modifications):

Code	Condition	Definition
5	Fresh damage to skeleton and tissue	physical damage (fish bites, human impacts)
6	Excessive sediment on live tissue	build up of sediment with no tissue damage
7	Recent damage to soft tissues	tissue damage with no skeletal abrasion (e.g. snail carnivory)
8	Tissue bleaching	areas where tissue color is uneven and light
9	Excess mucous	noticable amount of mucous on surface
11	Obvious algal mat smothering	algae overgrowing periphery (not attached to live surface)
12	Sediment damage with tissue necrosis	ongterm sediment abrasion causing death to those areas
13	White plague (putative bacteria)	definite area of solid white skeleton (white band)
14	Healed with secondary algal colonization	dead area with algae adjacent to living tissue (not peripheral)
15	Recently dead	bare skeleton with no algae (may have thin diatom layer)
16	Algal tufts on surface	algae attached to living surface
17	Colony decreasing in size	decrease in live surface area (dead skeleton towards periphery)
18	Colony almost unblemished	most of colony unblemished (only very small area damaged)
20	Unblemished (healthy)	no obvious damage to tissue or skeleton
23	Juvenile	new recruit to very young (approximated by number of polyps)
24	Sed/alg tissue necrosis	sediment embedded within an algal turf causing tissue damage
25	Bleached	tissue bleached white from loss of zooxanthellae
26	Overgrowth by green tunicate	green tunicate overgrowing live tissue causing death
27	Overgrowth by encrusting sponge	various mat-like sponges overgrowing live tissue causing death
28	Dead area from soft coral/sponge	abrasion from neighboring soft coral or sponge
29	Dark tissue discoloration	dark area on living tissue (resembles bruise)
31	Boring sponge	boring sponge within the skeleton visible from the surface
32	Boring worm	visible worm or tunnel (Sabellidae/Serpulidae)
33	Encrusting red algae	red algae encrusting live tissue surface
35	Competition with other organism	any physical interaction occurring with other organisms

Table 2.

Grouped categories of conditions into physical and biological stressors for summary of linear intercept condition data. Conditions were grouped following a modification of Dustan's 1985 and 1994 definitions:

Code	Condition
5	Fresh damage to skeleton and tissue
6	Excessive sediment on live tissue
7	Recent damage to soft tissues
8	Tissue bleaching
9	Excess mucous
11	Obvious algal mat smothering
12	Sediment damage with tissue necrosis
13	White plague (putative bacteria)
14	Healed with secondary algal colonization
15	Recently dead
16	Algal tufts on surface
17	Colony decreasing in size
18	Colony almost unblemished
20	Unblemished (healthy)
23	Juvenile
24	Sed/alg tissue necrosis
25	Bleached
26	Overgrowth by green tunicate
27	Overgrowth by encrusting sponge
28	Dead area from soft coral/sponge
29	Dark tissue discoloration
31	Boring sponge
32	Boring worm
33	Encrusting red algae
35	Competition with other organism

Grouped Categories	Codes
HEALTHY	18, 20
BIOLOGICAL STRESS	9, 13, 29
PHYSICAL STRESS	5, 6
PHYSICAL/BIOLOGICAL STRESS	7, 8, 11, 12, 16, 24, 25, 26, 27, 28, 31, 32, 33, 35
DEAD	15

Table 3.

Condition codes and definitions assigned to coral points encountered along the video point count survey at Rainbow Gardens Reef:

Code	**Condition**	**Definition**
1	Good	no obvious damage
2	Uneven tissue color	tissue color is light (bleaching)
3	Other animal	interaction with another organism (boring worms/sponges, overgrowth by other corals/sponges)
4	Tissue damage	damage to tissue only (no skeletal abrasion)
5	Dead among alive	dead area adjacent to living tissue
6	Algae	any algal colonization on coral
7	Crustose algae	red crustose algae encrusted on surface
8	Sediment	excessive sediment on surface with or without algal colonization

Table 4.

Species list, average colony size, and cover for stony corals at Rainbow Gardens Reef. A total of 78,854 cm were scored with the linear intercept survey (linear) and 4,665 points were scored with the video point count survey (video). Twenty-three species were found (a '*' indicates where each species was encountered). Four species were present, but not encountered with either survey method. Average colony size was estimated using the linear intercept data only. Percent coral cover was calculated for the entire reef area and for proportion of coral population (popn):

Species	Linear	Video	# indiv	cm coral (linear)	# coral points (video)	Avg. colony diameter (cm)	% cover (linear)	% cover (video)	% coral popn (linear)	% coral popn (video)
Acropora cervicornis	*	*	2	14	11	7.0	0.02	0.24	0.14	1.78
Mycetophyllia lamarckiana			–	–	–	–	–	–	–	–
Agaricia agaricites	*	*	116	1812	78	15.6	2.37	1.67	17.74	12.6
Agaricia lamarcki	*		1	6	–	6.0	0.01	–	0.06	–
Colpophyllia natans			–	–	–	–	–	–	–	–
Montastrea annularis	*	*	81	4220	259	52.1	5.52	5.56	41.32	41.84
Montastrea cavernosa	*	*	3	100	10	33.3	0.13	0.21	0.98	1.62
Favia fragum	*	*	62	170	13	2.7	0.22	0.28	1.66	2.1
Siderastrea radians	*	*	26	70	8	2.7	0.09	0.17	0.69	1.29
Siderastrea siderea	*	*	10	554	17	55.4	0.72	0.36	5.42	2.75
Dichocoenia stokesii	*	*	22	208	9	9.5	0.27	0.19	2.04	1.45
Stephanocoenia michelini		*	–	–	1	–	–	0.02	–	0.16
Diploria strigosa	*	*	3	18	3	6.0	0.02	0.06	0.18	0.48
Diploria labyrinthiformis	*	*	8	260	12	32.5	0.34	0.26	2.55	1.94
Isophyllastrea rigida	*	*	4	24	1	6.0	0.03	0.02	0.23	0.16
Porites porites	*	*	68	720	46	10.6	0.94	0.99	7.05	7.43
Porites astreoides	*	*	153	1426	77	9.3	1.86	1.65	13.96	12.44
Porites furcata			–	–	–	–	–	–	–	–
Madracis pharensis	*		2	16	–	8.0	0.02	–	0.16	–
Madracis decactis	*	*	1	36	1	36.0	0.05	0.02	0.35	0.16
Millepora alcicornis	*	*	43	318	68	7.4	0.42	1.46	3.11	10.99
Eusmilia fastigiata	*	*	11	86	6	7.8	0.11	0.13	0.84	0.97
Meandrina meandrites			–	–	–	–	–	–	–	–
Total	**18**	**17**	**616**	**10214**	**619**	–	**13.0**	**13.3**	–	–

Table 5.

Transect and reef coverage for stony corals (Scleractinia and Milleporina), soft corals (Alcyonaria), sponges (Porifera), and total living Scleractinia, Milleporina, Alcyonaria, and Porifera at Rainbow Gardens Reef as estimated with the linear intercept method:

	Stony Coral Cover		**Soft Coral Cover**		**Sponge Cover**		**Total Live Cover**		**Transect Length (cm)**	
Transect	cm	% cover	cm	% cover	cm	% cover	cm	% cover	chain	linear
0-L	62	3.3	4	0.2	114	6.0	180	9.5	1894	1720
0-R	14	0.7	18	1.2	70	4.5	102	5.3	1942	1690
5-L	48	3.2	32	2.2	74	5.0	154	10.3	1490	1720
5-R	30	1.6	16	0.9	48	2.6	94	4.9	1938	1690
10-L	186	9.2	22	1.1	124	6.3	332	16.5	2012	1720
10-R	102	5.4	0	0	74	4.4	176	9.3	1892	1690
15-L	102	5.5	8	0.4	86	4.7	196	10.6	1852	1720
15-R	472	13.3	54	1.6	216	6.3	742	20.9	3546	2345
20-L	238	8.9	40	1.5	150	5.7	428	15.9	2686	2049
20-R	62	2.3	22	0.9	32	1.3	116	4.3	2698	2520
25-L	402	14.8	34	1.3	136	5.0	572	21.0	2724	2049
25-R	318	14.3	34	1.5	136	6.2	488	21.9	2228	1700
30-L	236	8.9	76	3.0	132	5.1	444	16.7	2658	2049
30-R	232	9.1	70	2.8	132	5.3	434	17.1	2540	1940
35-L	298	11.8	30	1.2	130	5.3	458	18.1	2528	2049
35-R	228	7.3	50	1.6	110	3.6	388	12.5	3110	2610
40-L	482	16.8	36	1.3	220	7.8	738	25.7	2876	2049
40-R	144	6.0	14	0.6	70	3.0	228	9.6	2388	1940
45-L	710	22.8	150	4.9	286	9.3	1146	36.9	3110	2049
45-R	456	16.1	38	1.4	160	5.7	654	23.1	2834	1940
50-L	342	13.9	88	3.9	94	4.2	524	21.3	2456	2049
50-R	1128	24.3	76	1.7	160	3.6	1364	29.4	4642	3220
55-L	1242	34.3	88	2.5	220	6.2	1550	42.8	3618	2144
55-R	288	9.7	62	2.1	86	2.9	436	14.7	2968	2160
60-L	1194	33.9	120	3.4	326	9.3	1640	46.6	3518	2144
60-R	218	8.7	82	3.3	214	8.7	514	20.6	2500	2090
65-L	358	13.6	48	1.9	112	4.4	518	19.6	2638	2144
65-R	188	7.4	138	5.6	154	6.2	480	18.8	2548	2090
70-L	164	6.6	86	3.5	186	7.5	436	17.5	2492	2144
70-R	270	10.7	76	3.2	102	4.3	448	17.7	2528	2090
REEF	**10214**	**13.0**	**1612**	**2.0**	**4154**	**5.3**	**15980**	**20.3**	**78854**	**61514**

Table 6.

Transect and reef coverage for stony corals (Scleractinia and Milleporina) at Rainbow Gardens Reef as estimated with the video point count method:

	Coral Cover		
Transect	**# coral pts**	**total # pts**	**% cover**
0-L	4	186	2.2
5-R	9	180	5.0
10-L	25	185	13.5
15-R	57	360	15.5
20-L	29	277	10.5
25-R	55	459	12.0
30-L	74	442	16.7
35-R	25	319	7.8
40-L	42	278	15.1
45-R	72	434	16.6
50-L	50	254	19.7
55-R	24	228	10.5
60-L	106	316	33.8
65-R	14	259	5.4
70-L	16	250	6.4
70-R	17	238	7.1
REEF	**619**	**4665**	**13.3**

Table 7.

Estimates of Shannon's diversity and Pielou's evenness for each transect and the entire reef calculated for centimeter coverage (H'cm and J'cm) of stony corals and the number of colonies (H'n and J'n) as estimated with the linear intercept method (linear) and the video point count method (video):

	DIVERSITY (H')			EVENNESS (J')		
	H'cm		H'n	J'cm		J'n
Transect	linear	video	linear	linear	video	linear
0-L	0.76	1.04	1.04	0.69	0.95	0.95
0-R	1.08	--	1.10	0.98	–	0.61
5-L	1.14	--	1.33	0.83	–	0.58
5-R	1.20	1.15	1.61	0.75	0.83	0.59
10-L	1.09	1.46	1.70	0.61	0.81	0.56
10-R	0.32	--	1.10	0.29	–	0.35
15-L	1.25	--	1.56	0.78	–	0.46
15-R	1.26	1.86	1.86	0.57	0.85	0.51
20-L	1.29	1.10	1.67	0.72	0.68	0.44
20-R	1.45	--	1.52	0.90	–	0.93
25-L	1.29	--	2.07	0.59	–	0.51
25-R	1.70	1.50	1.96	0.82	0.77	0.47
30-L	1.60	1.15	1.79	0.82	0.59	0.42
30-R	1.43	--	1.78	0.73	–	0.41
35-L	1.17	--	1.93	0.56	–	0.43
35-R	1.71	1.47	1.79	0.82	0.91	0.39
40-L	1.56	1.57	1.71	0.80	0.81	0.37
40-R	1.80	--	1.81	0.93	–	0.38
45-L	1.68	--	1.89	0.76	–	0.40
45-R	1.07	1.80	1.51	0.60	0.78	0.31
50-L	1.21	1.64	1.78	0.58	0.79	0.36
50-R	1.63	--	2.12	0.64	–	0.43
55-L	1.27	--	1.80	0.61	–	0.36
55-R	1.48	1.20	1.98	0.71	0.75	0.39
60-L	1.29	1.51	1.83	0.59	0.73	0.36
60-R	1.49	--	1.66	0.72	–	0.32
65-L	1.34	--	2.00	0.61	–	0.38
65-R	1.46	1.33	1.76	0.75	0.83	0.33
70-L	1.15	1.24	1.44	0.71	0.77	0.27
70-R	1.30	1.07	1.62	0.67	0.77	0.30
REEF	**1.80**	**1.90**	**2.20**	**0.60**	**0.70**	**0.70**

Table 8.

Summary of the number and proportion of the 616 coral colonies with conditions as grouped into physical and biological stressors from Table 2:

General Condition	# Observations	% All Colonies
Healthy (18, 20)	315	51.1
Bio. Stress (9, 13, 29)	38	6.2
Phys. Stress (5, 6)	54	8.8
Phys./Bio. Stress (7, 8, 11, 12, 16, 24, 25, 26, 27, 28, 31, 32, 33, 35)	587	95.3
Dead (15)	7	1.1
Total	**1001**	**162.5**

Table 9.

Number of observations of each condition from Table 3 scored in the video point count survey:

Code	Condition	*A. cerv*	*A. agar*	*M. ann*	*M. cav*	*F. frag*	*S. rad*	*S. sid*	*D. stok*	*S. mich*	*D. strig*	*D. lab*	*I. rig*	*P. por*	*P. ast*	*M. dec*	*M. alc*	*E. fast*	Total
1	Good	10	61	172	6	11	5	15	8		3	12	1	34	65	1	63	5	**471**
2	Uneven color	1		12	1	1									1				**16**
3	Other animal							1											**1**
5	Dead among alive		5	40	2			1		1									**49**
6	Algae		12	33	1									9			3		**58**
8	Sediment			2		1	3		1					3	11		2	1	**24**
	Total	**11**	**78**	**259**	**10**	**13**	**8**	**17**	**9**	**1**	**3**	**12**	**1**	**46**	**77**	**1**	**68**	**6**	**619**

Proportion of observations of each condition from Table 3 scored in the video point count survey:

Code	Condition	*A. cerv*	*A. agar*	*M. ann*	*M. cav*	*F. frag*	*S. rad*	*S. sid*	*D. stok*	*S. mich*	*D. strig*	*D. lab*	*I. rig*	*P. por*	*P. ast*	*M. dec*	*M. alc*	*E. fast*	%
1	Good	90.9	78.2	66.4	60.0	84.6	62.5	88.2	88.9		100.0	100.0	100.0	73.9	84.4	100.0	92.6	83.3	**76.1**
2	Uneven color	9.1		4.6	10.0	7.7									1.3				**2.6**
3	Other animal							5.9											**0.2**
5	Dead among alive		6.4	1.5	20.0			5.9		100.0									**7.9**
6	Algae		15.4	12.7	10.0									19.6			4.4		**9.4**
8	Sediment			0.8		7.7	37.5		11.1					6.5	14.3		2.9	16.7	**3.9**
	Total	**11**	**78**	**259**	**10**	**13**	**8**	**17**	**9**	**1**	**3**	**12**	**1**	**46**	**77**	**1**	**68**	**6**	**100.0**

Table 10.

Summary of reviewed Bahamian patch reef communities (Chiappone and Sullivan 1991; Sullivan and Chiappone 1992; Curran *et al.* 1994). *M. ann.* = *Montastrea annularis* and *A. agar.* = *Agaricia agaricites*:

	# species	**H'**	**dominant spp.**	**coral cover**
Rainbow Gardens	23	1.8 - 1.9	*M. ann.* *A. agar.*	13 - 13.3
Chiappone and Sullivan	30	1.14 - 1.84	*M. ann.* *A. agar.*	3.7 - 29.8
Sullivan and Chiappone	21	1.52 - 2.16		
Curran *et al.*	2-16		*M. ann.*	

Table 11.

Number of points and proportion of the total points of each species drawn on the underwater map:

Class number	Species	# Pixels	Percent Cover of Reef	Proportion of Corals
0	background	1,378,332		
1	*A .cerv*	252	0.02	0.15
2	*Ag.* spp.	27,374	1.77	16.18
3	*M. ann*	103,300	6.68	61.07
4	*M. cav*	5,049	0.33	2.99
5	*D. stok*	1	0.00	0.00
6	*P. por*	2,013	0.13	1.19
7	*P. ast*	5,471	0.35	3.23
8	*M. mean*	132	0.01	0.08
9	*Dip.* spp.	14,936	0.97	8.83
10	*Sid.* spp.	9,820	0.63	5.81
11	*Colpo.* spp.	789	0.05	0.47
Total		**1,547,469**	**10.9**	**100.0**

Table 12.

Summary of the brightness values for sandy areas of the color aerial image of Rainbow Gardens Reef. The individual bands of the deep and shallow areas were compared before and after the water correction to test for significant differences in the signals:

Before Water Correction							After Water Correction					
Red		Green		Blue			Red		Green		Blue	
deep	shallow	deep	shallow	deep	shallow		deep	shallow	deep	shallow	deep	shallow
30	90	106	221	70	107		135	170	166	219	180	178
29	89	104	204	69	104		138	171	163	217	179	179
29	83	102	198	69	104		131	162	168	208	172	171
28	79	107	197	71	106		136	161	170	200	177	172
32	83	111	204	71	109		134	155	172	208	178	174
31	87	113	209	74	109		136	161	178	207	184	184
30	89	108	223	70	113		136	158	172	200	178	176
29	100	107	221	71	109		139	157	182	205	179	172
29	90	105	218	70	104		132	150	173	199	179	174
30	86	104	206	70	106		135	153	182	210	184	184
30	93	110	214	74	114		133	149	169	199	176	176
30	80	109	210	69	103		134	152	160	205	171	170
32	87	114	213	71	104		139	155	157	208	165	174
31	88	112	224	74	109		129	149	151	197	165	167
34	86	118	210	76	109		130	149	153	200	162	172
34	78	121	202	75	107		130	144	169	191	171	166
34	78	107	195	71	101		131	152	172	200	170	164
31	79	102	213	69	107		137	152	183	199	176	166
31	81	115	206	71	104		137	152	180	210	176	167
34	74	124	203	78	106		139	146	179	189	176	164
34	84	122	206	78	107		135	144	177	193	173	165
36	88	128	214	76	112		138	151	179	193	178	170
36	83	132	200	80	103		141	159	180	212	173	178
33	84	127	215	76	107		134	156	176	206	172	172
37	77	132	204	79	99		130	156	169	209	171	177
33	75	125	206	79	102		131	163	167	202	165	178
36	86	128	213	79	104		129	157	157	206	161	180
35	73	126	193	76	99		122	146	139	190	152	167
39	80	135	209	81	106		129	149	149	201	162	172
39	79	140	200	81	107		131	151	146	206	158	174
42	75	140	201	81	104		128	139	144	181	154	166
36	77	132	202	79	106		130	141	156	193	159	160
40	80	139	209	83	104		127	144	161	188	161	164
43	77	142	210	80	103		135	144	176	186	171	158
45	76	146	199	81	103		139	149	185	190	176	160
42	91	147	213	84	103		144	141	189	188	179	162
43	79	146	198	85	99		144	138	177	179	176	159
46	82	157	200	86	104		136	139	185	182	172	158
40	73	140	200	81	103		135	151	169	201	164	168
45	75	158	200	83	101		135	134	175	178	168	157
40	83	146	213	81	102		131	145	166	200	166	173
36	76	126	205	74	104		126	144	155	192	155	167
34	67	124	192	76	101		123	151	151	195	157	162
36	72	113	197	75	108		123	148	156	195	149	165
36	73	127	193	76	104		130	151	163	201	157	174
36	70	120	192	73	101		128	142	159	185	155	166
33	81	119	196	73	101		145	148	168	199	174	167
32	67	120	195	76	99		145	161	172	211	178	180
32	69	104	196	68	106		156	148	173	192	180	168
29	69	97	181	65	94		143	155	161	209	174	178

Table 13.

Summary of results from each survey method: linear intercept (Linear), video point count (Video), hand-drawn map (Map), and digital aerial photograph (GIS). A '--' indicates data that was not collected, and a '?' indicates data that could not be calculated:

	Linear	**Video**	**Map**	**GIS**
Resolution	2 cm	2 cm	10 cm	5 cm
# spp	18	17	11	?
Stony coral cover (%)	13.0	13.3	10.9	?
Soft coral cover (%)	2.0	--	--	?
Stony and soft cover (%)	15.0	--	--	14.5
Sponge cover (%)	5.3	--	--	?
Benthic invertebrate cover (%)	20.3	--	--	?
$H'_{(cm)}$	1.8	1.9	?	?
$H'_{(n)}$	2.2	--	?	?
$J'_{(cm)}$	0.6	0.7	?	?
$J'_{(n)}$	0.7	--	?	?
Coral cover (%) with GIS transects	--	--	14.0 (stony)	19.6 (stony and soft)

Figure 1. Map showing the position of Lee Stocking Island, Exumas, Bahamas, where the Caribbean Marine Research Center is located.

THE COMMONWEALTH OF THE BAHAMAS

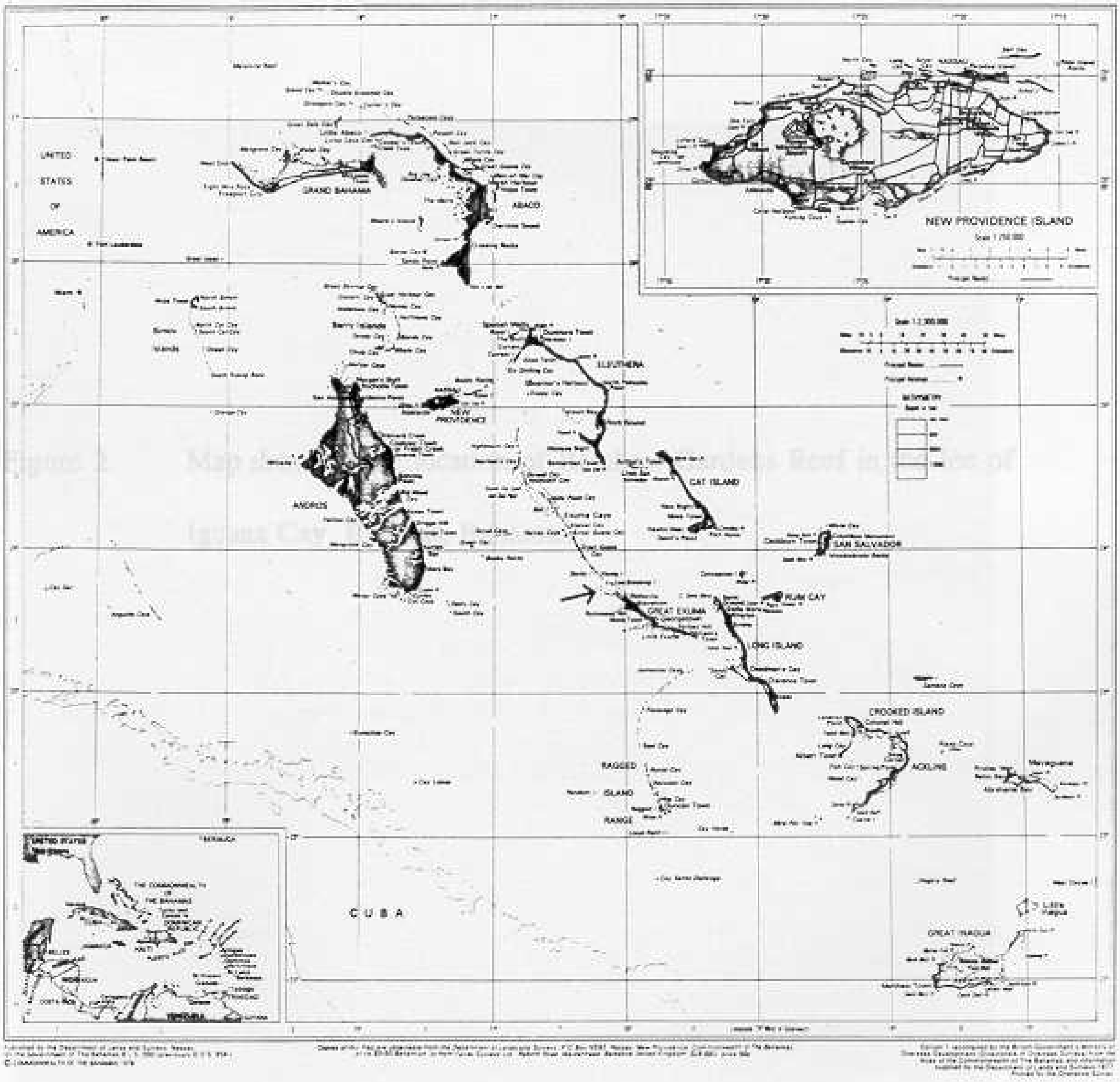


Figure 2. Map showing the location of Rainbow Gardens Reef in the lee of Iguana Cay, Exumas, Bahamas.

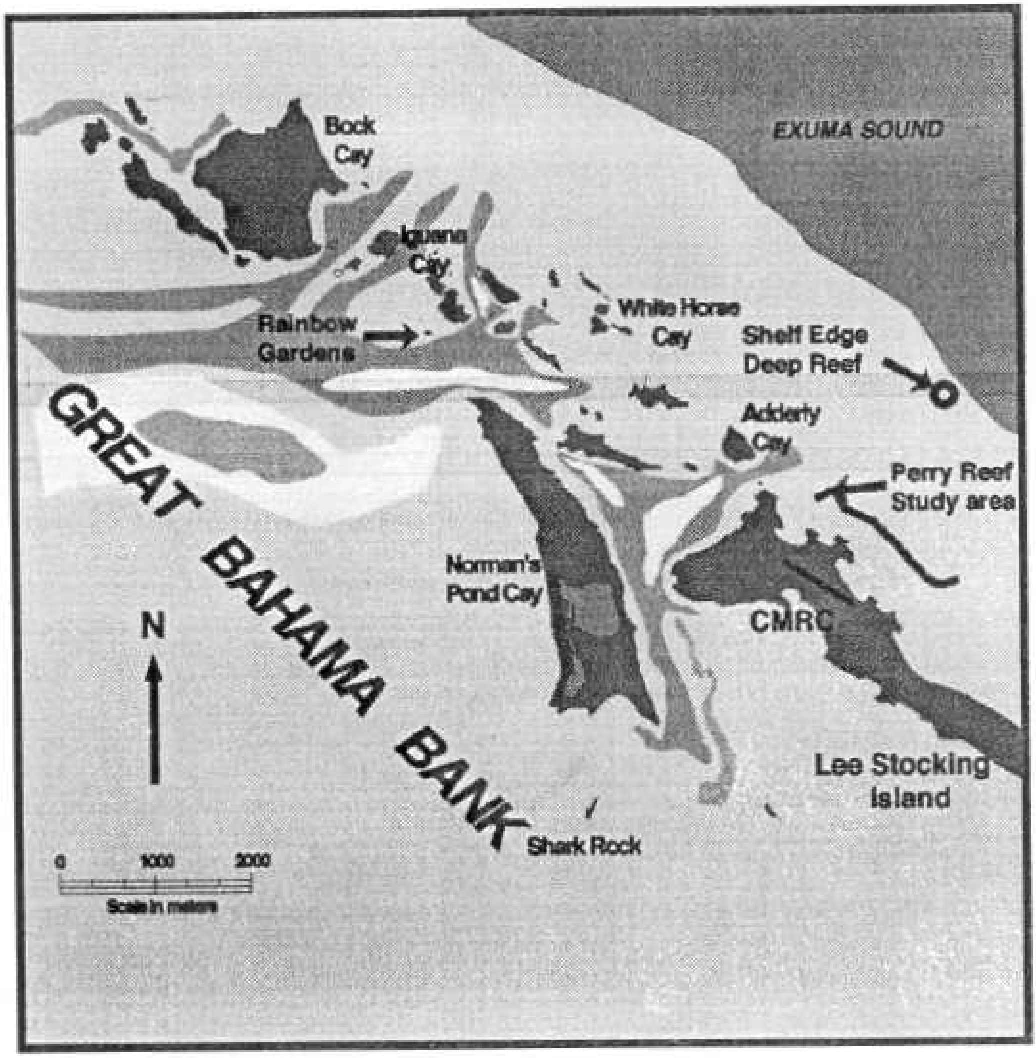

EXUMA SOUND
Bock Cay
Iguana Cay
White Horse Cay
Rainbow Gardens
Shelf Edge Deep Reef
Adderly Cay
Perry Reef Study area
GREAT BAHAMA BANK
Norman's Pond Cay
N
CMRC
Lee Stocking Island
Shark Rock
0
1000
2000
Scale in meters

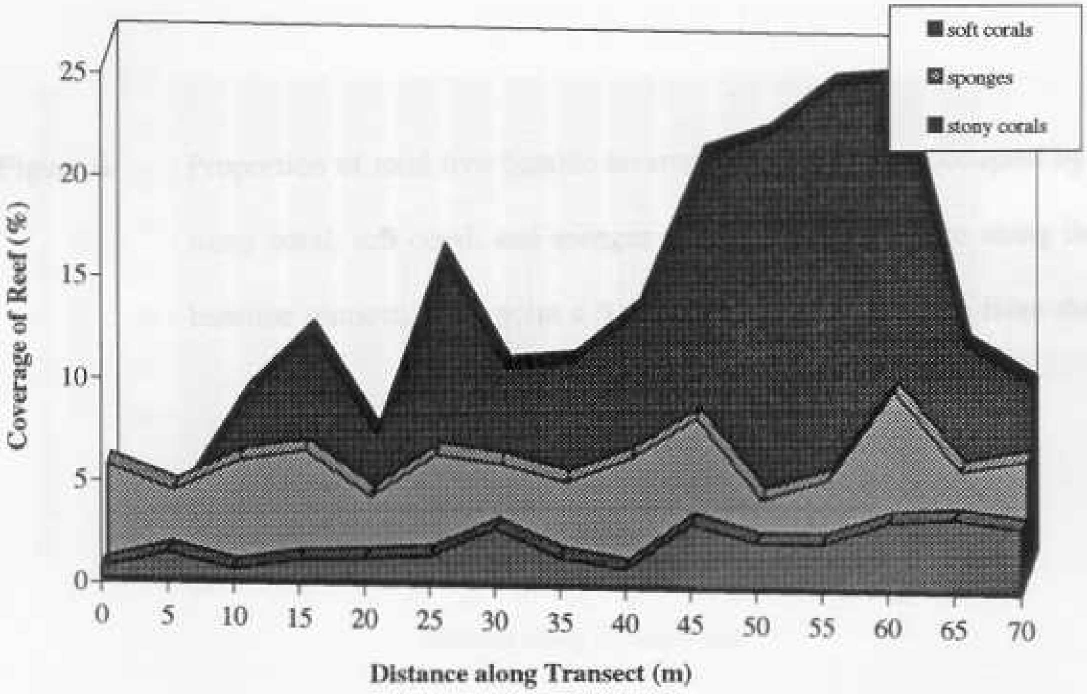
Figure 3. Aerial photograph of Rainbow Gardens Reef off Iguana Cay, Exumas, Bahamas. Buoys mark ends of main transect lines.

N

Figure 4. Multispectral RGB (red, green, blue) photograph of Rainbow Gardens Reef showing placement of main transect lines (1 in = 50 ft).


0

Figure 5. Coverage of stony coral, soft coral, and sponges plotted against distance along the baseline transect. The point at 0 m is approximately 100 m from shore.



soft corals
sponges
stony corals
Coverage of Reef (%)
0
5
10
15
20
25
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Distance along Transect (m)

Figure 6. Proportion of total live benthic invertebrate community occupied by stony coral, soft coral, and sponges plotted against distance along the baseline transect. The point a 0 m is approximately 100 m from shore.

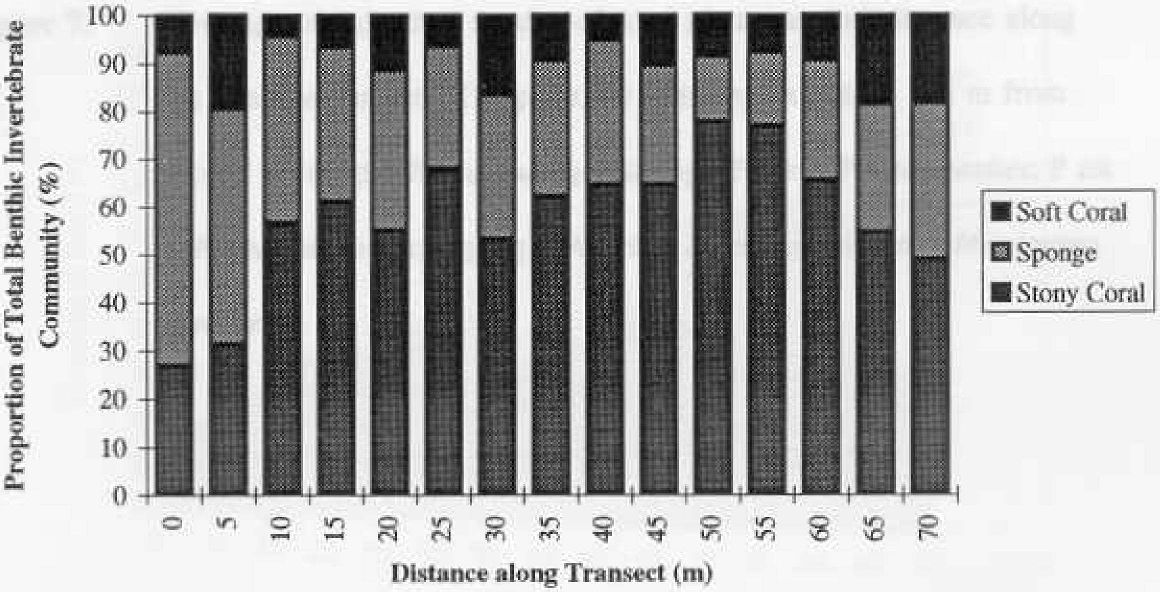

Proportion of Total Benthic Invertebrate Community (%)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Distance along Transect (m)
Soft Coral
Sponge
Stony Coral

Figure 7. Coverage of individual species of coral plotted against distance along the baseline transect. The point a 0 m is approximately 100 m from shore. Pseudop = *Pseudopterogorgia* spp.; P por = *Porites porites*; P ast = *Porites astreoides*; Ag Ag = *Agaricia agaricites*; M ann = *Montastrea annularis*.

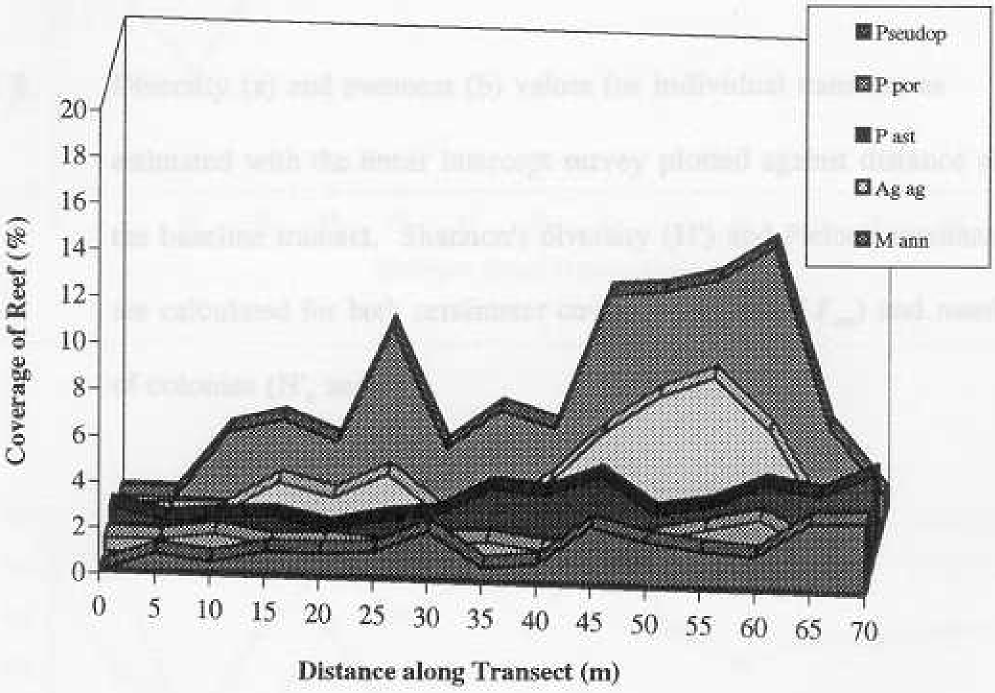

Pseudop
P por
P ast
Ag ag
M ann
Coverage of Reef (%)
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Distance along Transect (m)

Figure 8. Diversity (a) and evenness (b) values for individual transects as estimated with the linear intercept survey plotted against distance along the baseline transect. Shannon's diversity (H') and Pielou's evenness (J') are calculated for both centimeter coverage (H'_{cm} and J'_{cm}) and number of colonies (H'_{n} and J'_{n}).

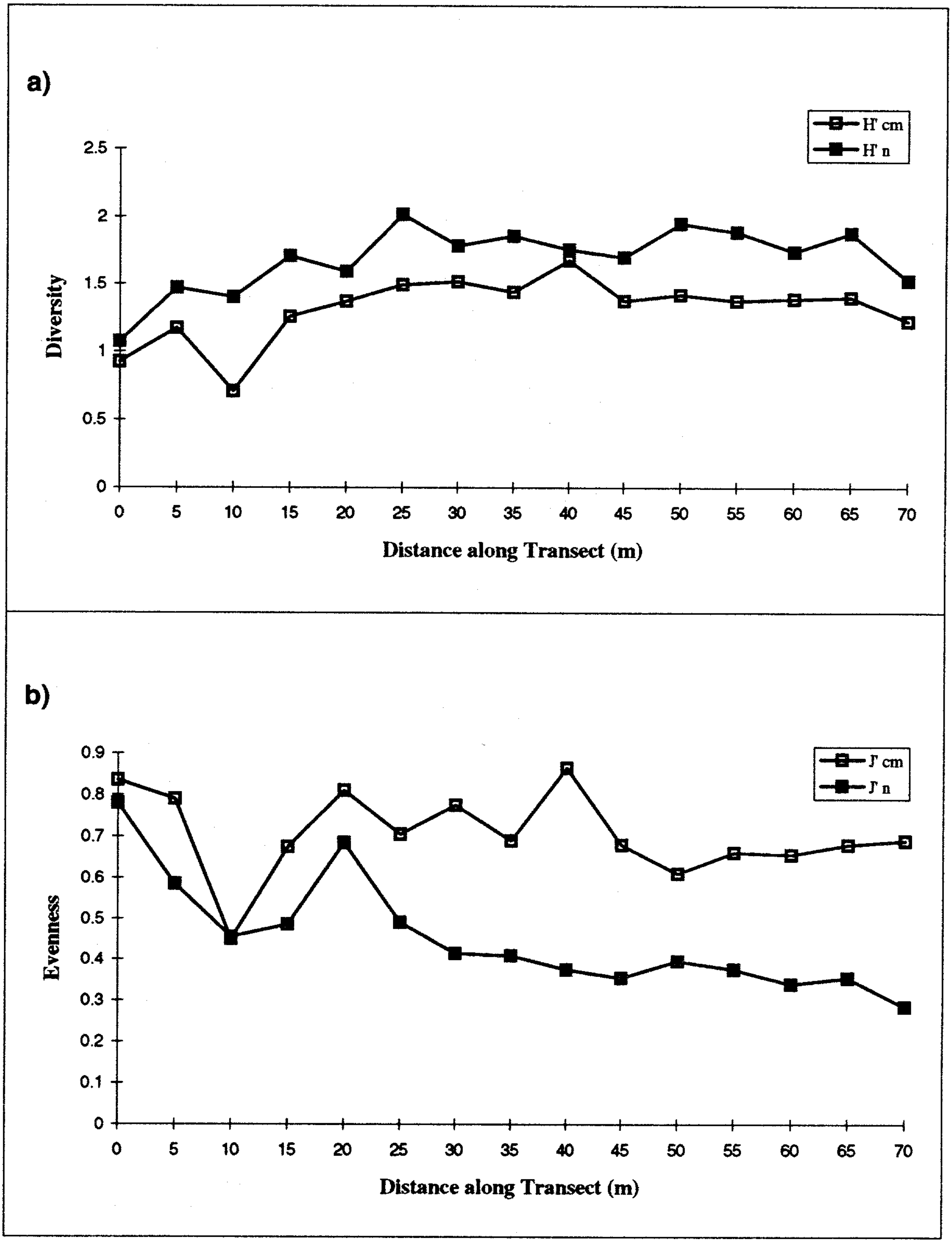

a)
H' cm
H' n
Diversity
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Distance along Transect (m)
b)
J' cm
J' n
Evenness
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Distance along Transect (m)

Figure 9. Flow chart illustrating the steps in the digital analysis of the aerial photograph.

DIGITAL ANALYSIS OF AERIAL PHOTOGRAPH

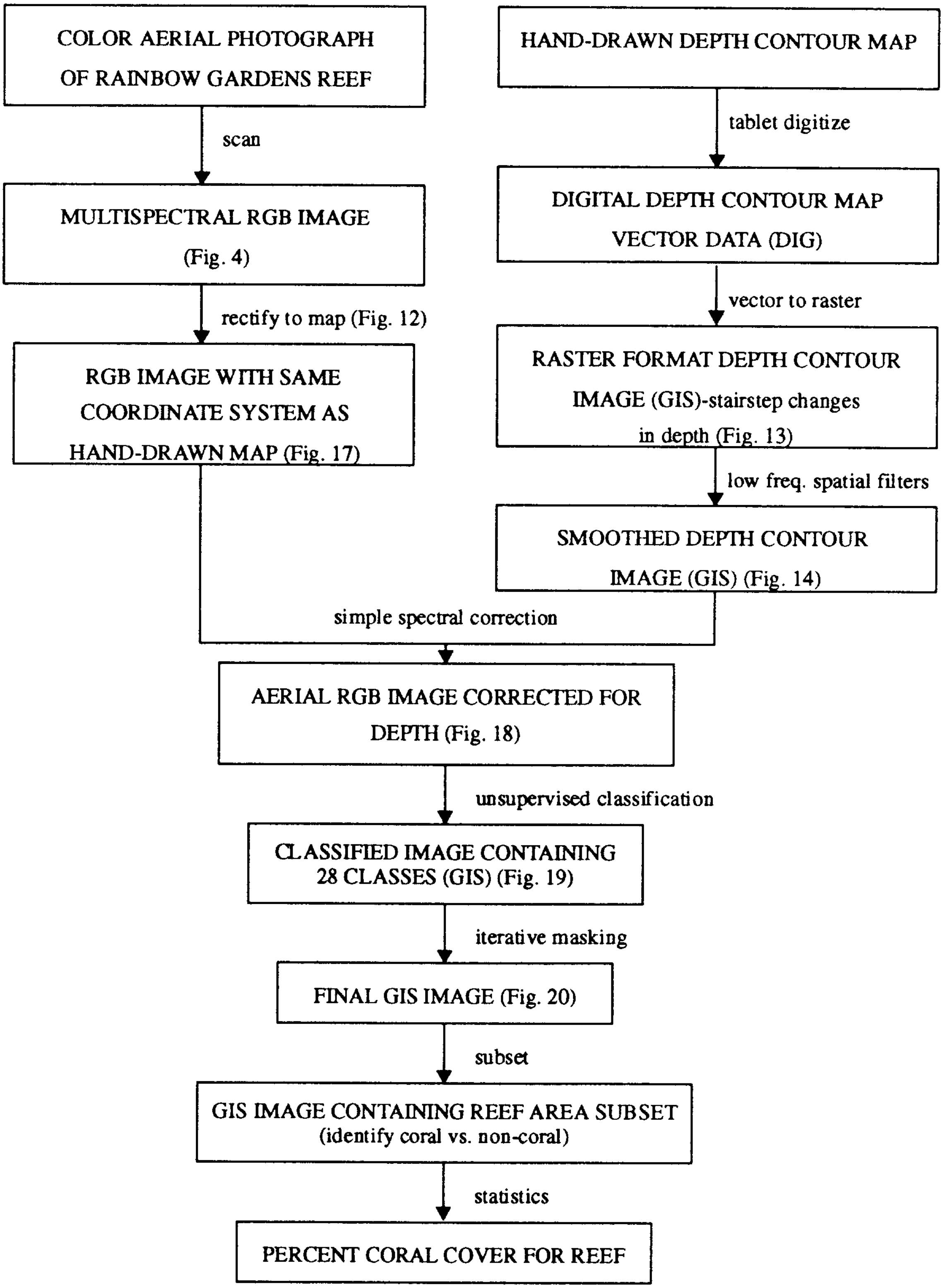


Figure 10. Reduced copy of the hand-sketched map of Rainbow Gardens Reef. Circles designate coral colonies.

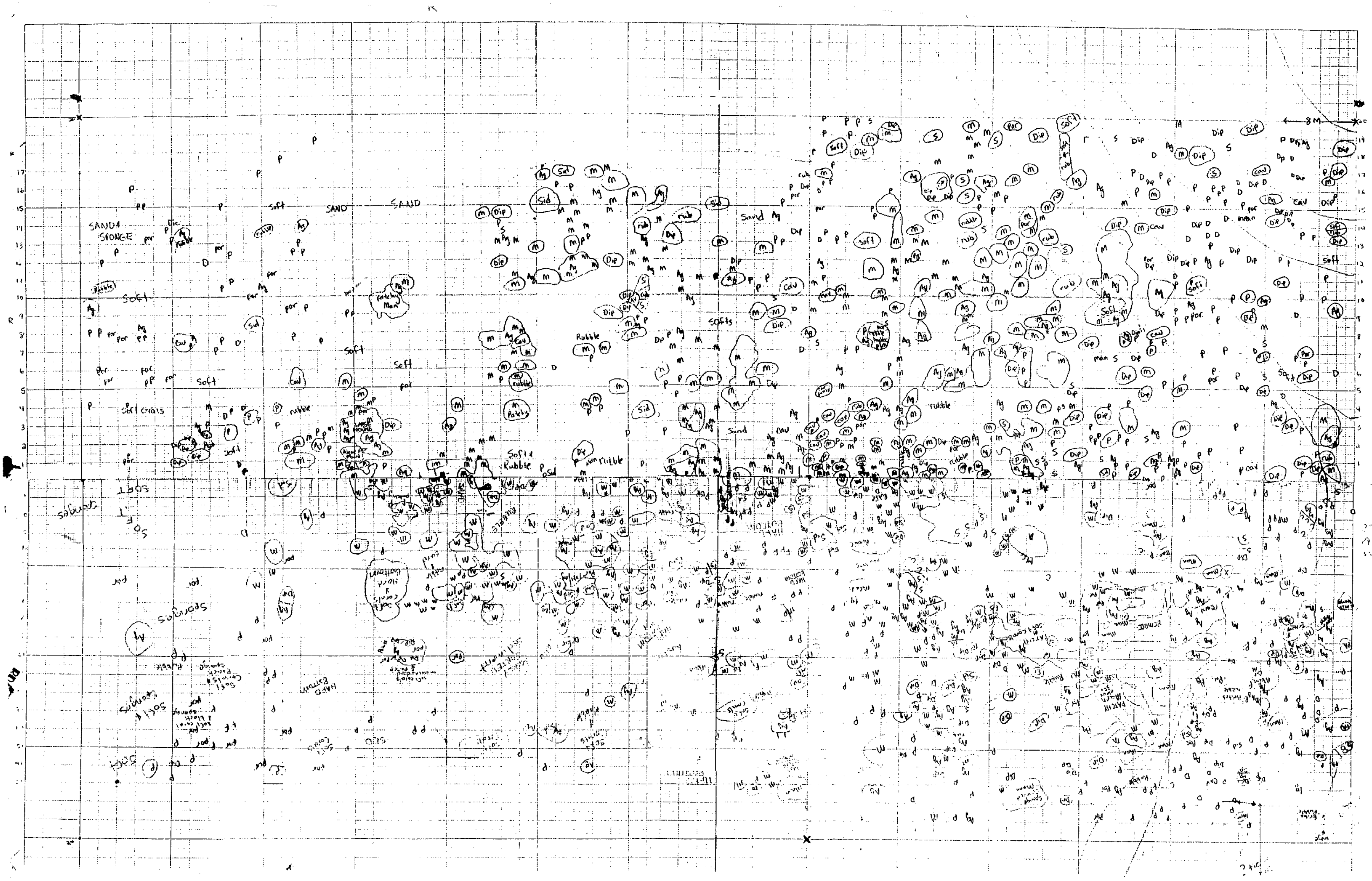
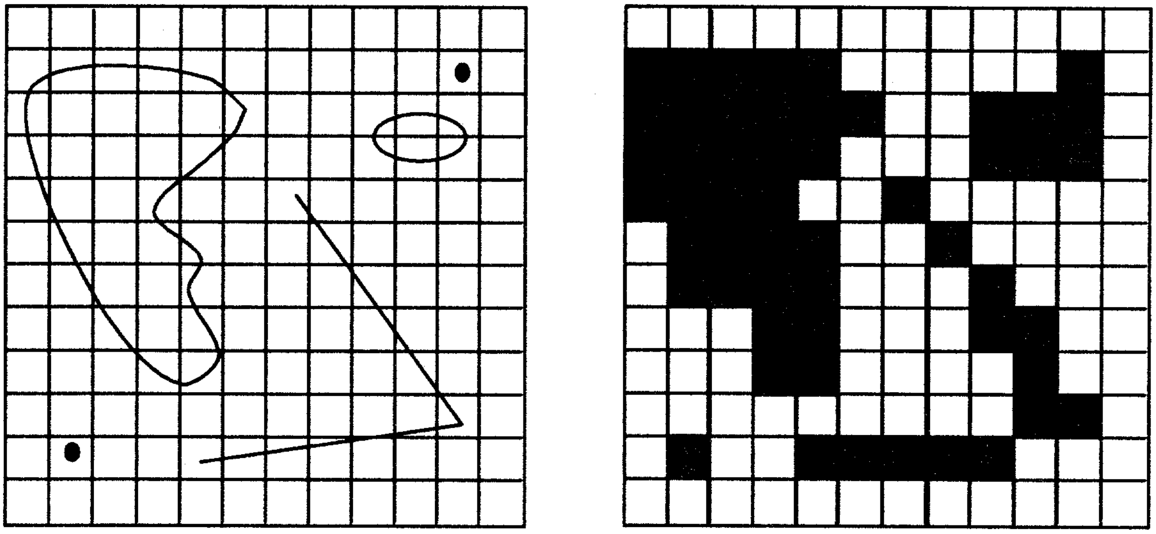

SAND4 SPONGE
SAND
SAND
Soft
Soft crats
Soft & Rubble
Rubble
Sand
Softs
8M

Figure 11. Transformation of vector data into raster format.

Vector vs. Raster Data



Vectors superimposed
on raster grid

Vectors converted to
raster data

Figure 12. Digitized output from hand-sketched map with transects overlain on the image.

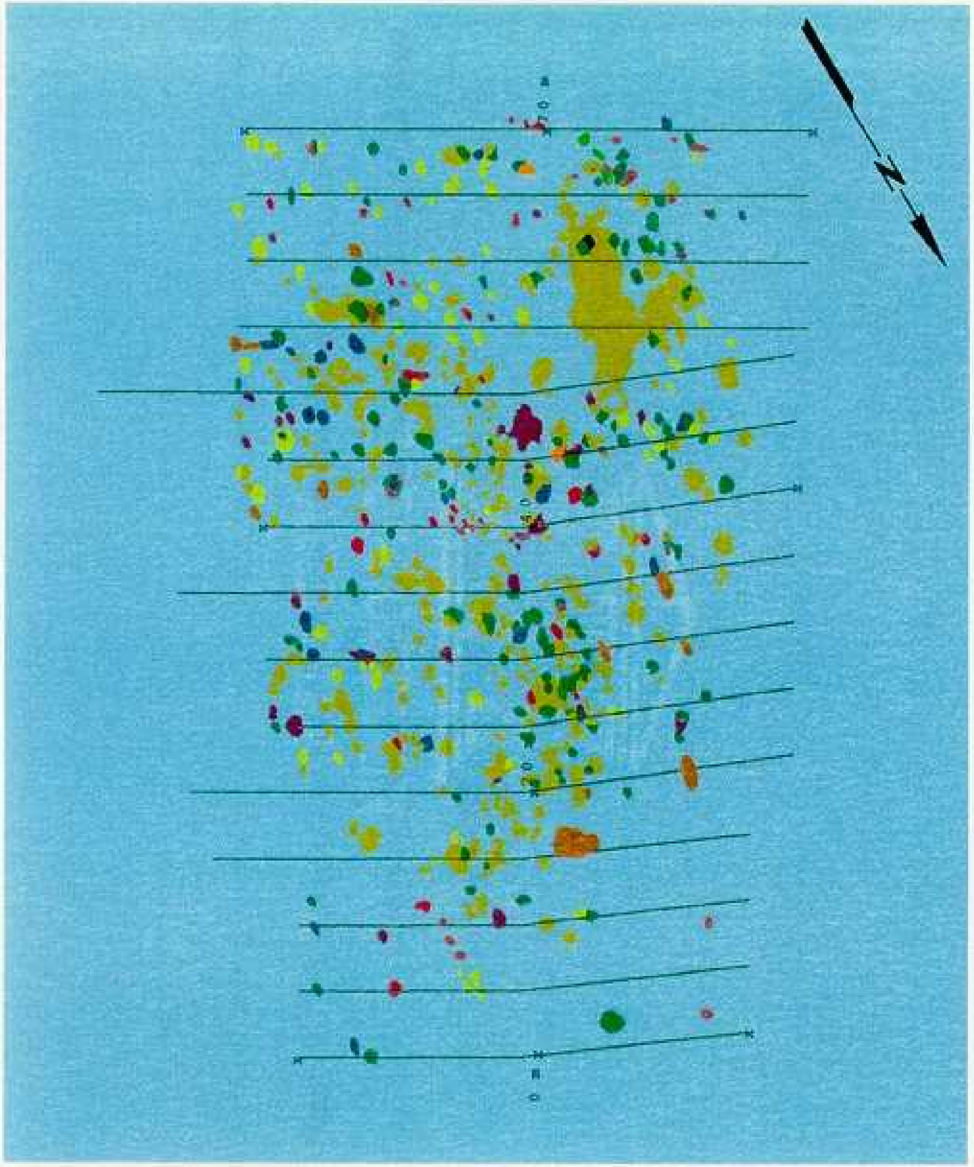

A
B
N

Figure 13. Depth contour map of Rainbow Gardens Reef with grey scale representing discrete depth changes unrealistic of natural gradual slope of reef (black = 22 ft and white = 2 ft).

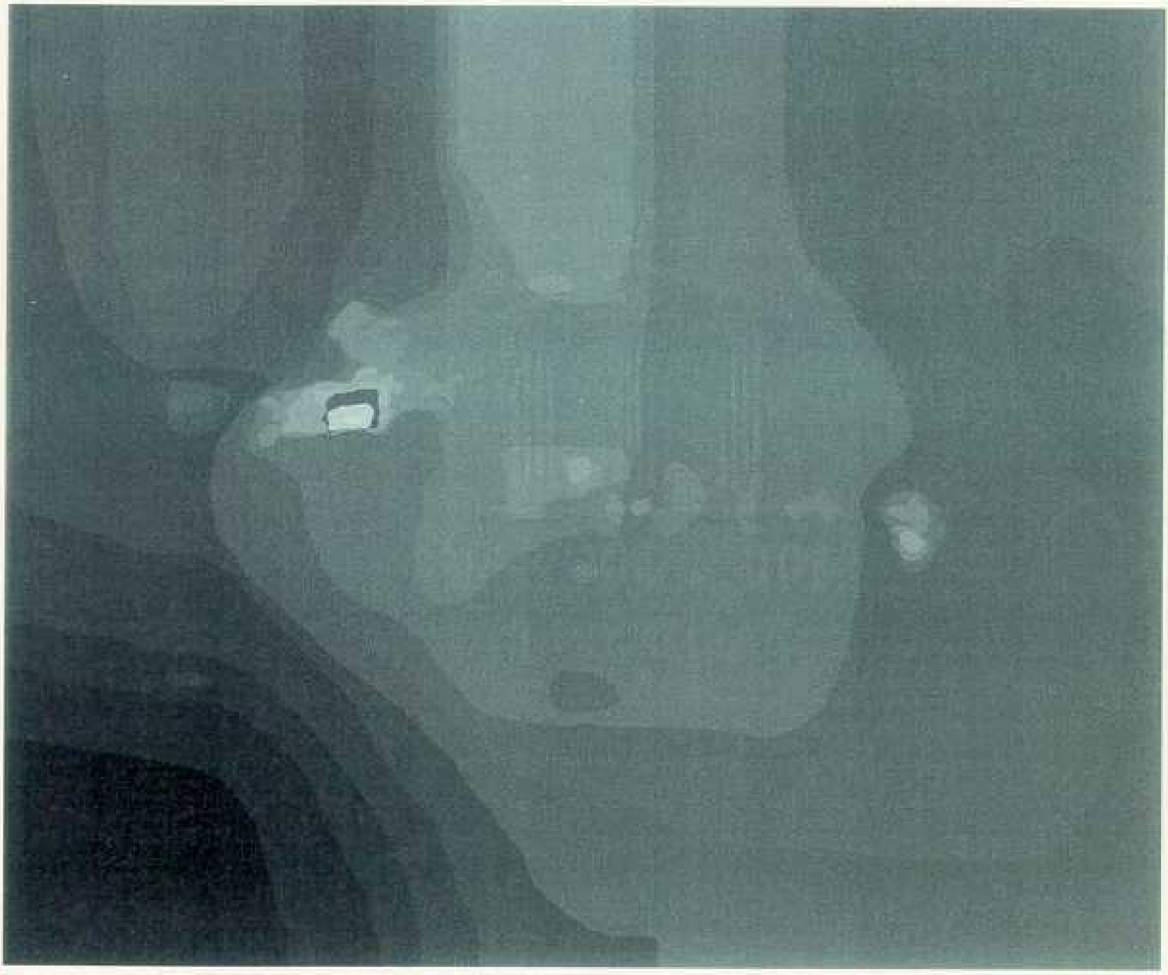


Figure 14. Filtered depth contour map of Rainbow Gardens Reef with grey scale representing a closer approximation of the natural slope of the reef (black = 22 ft and white = 2 ft).

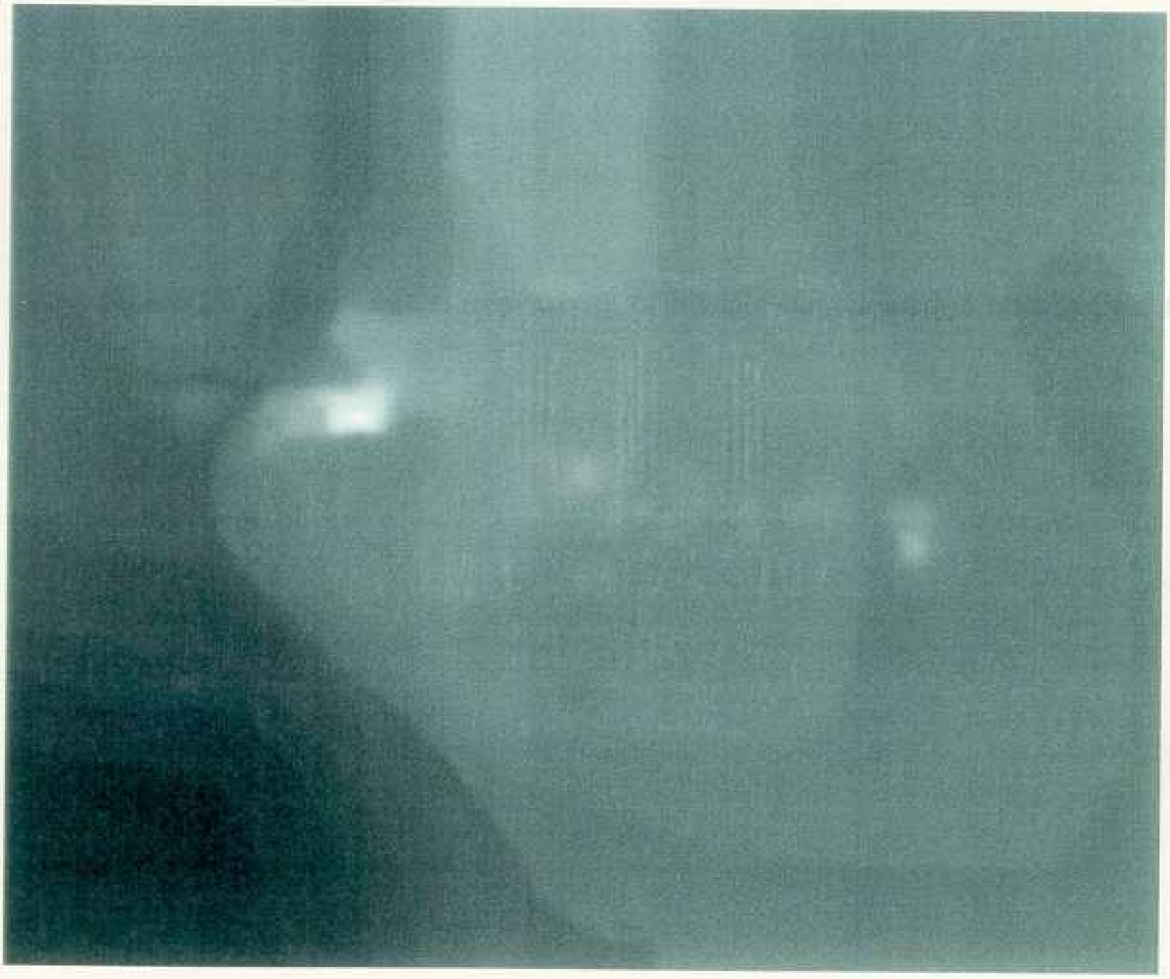
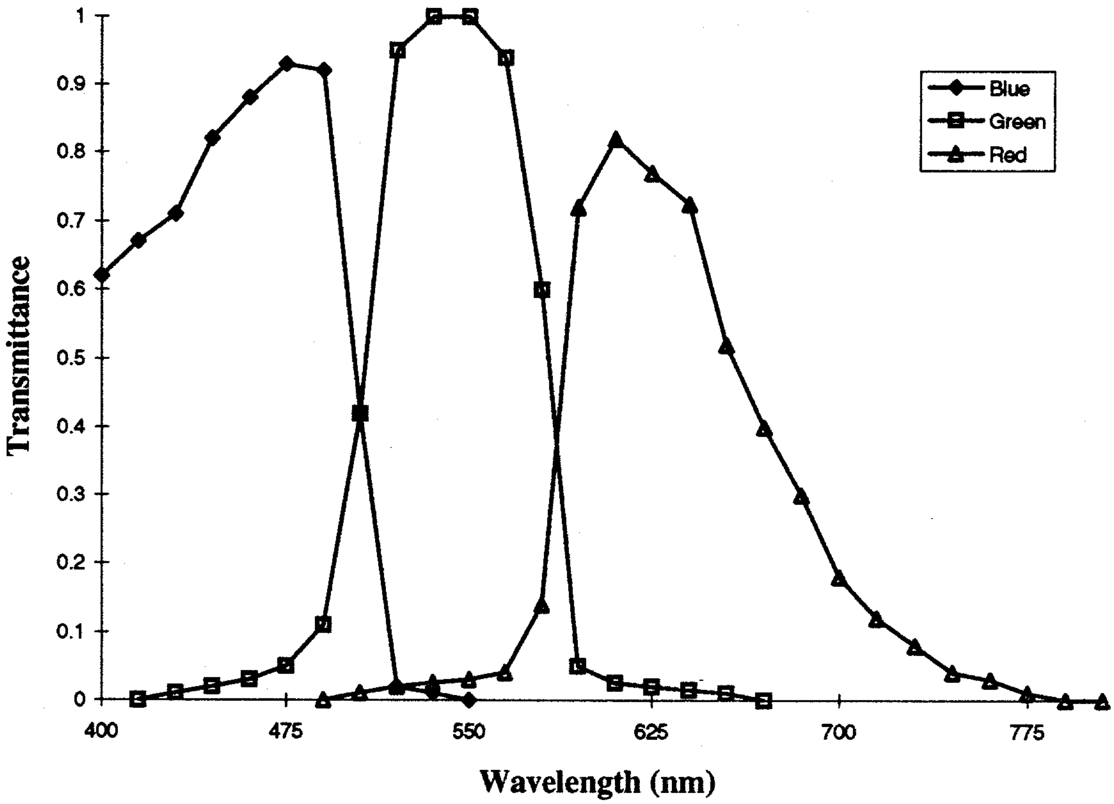
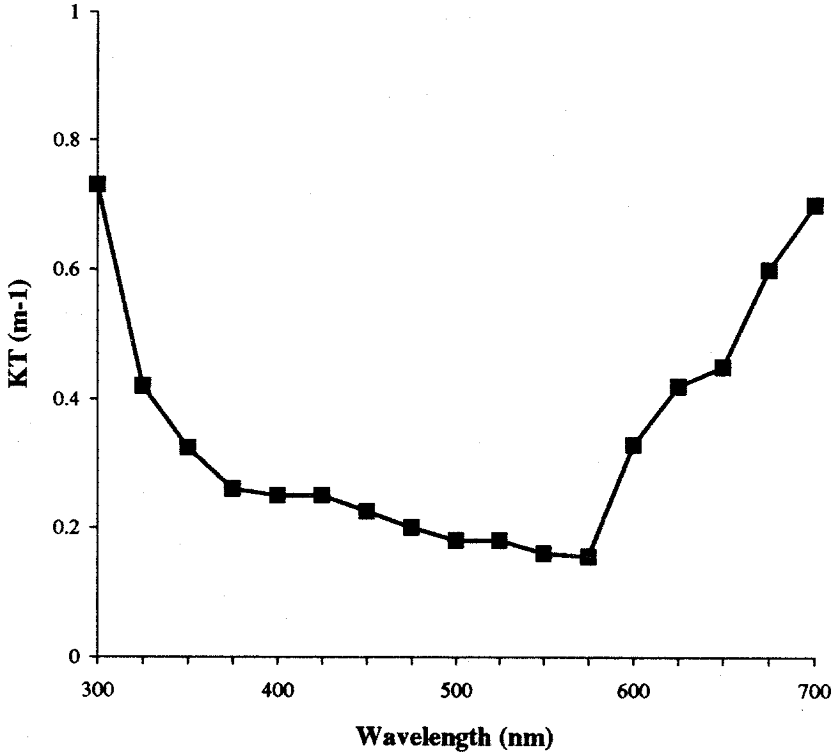


Figure 15. The spectral responsivity of Eikonix camera used in scanning the aerial image.



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Transmittance
400
475
550
625
700
775
Wavelength (nm)
Blue
Green
Red

Figure 16. Spectral diffuse attenuation coefficient for seawater with a chlorophyll concentration of 1.4 (mg chl m^{-3}) used to estimate values of K for each band of the aerial image (Baker and Smith 1982).



1
0.8
0.6
0.4
0.2
0
KT (m-1)
300
400
500
600
700
Wavelength (nm)

Figure 17. Rectified multispectral RBG image of Rainbow Gardens Reef.

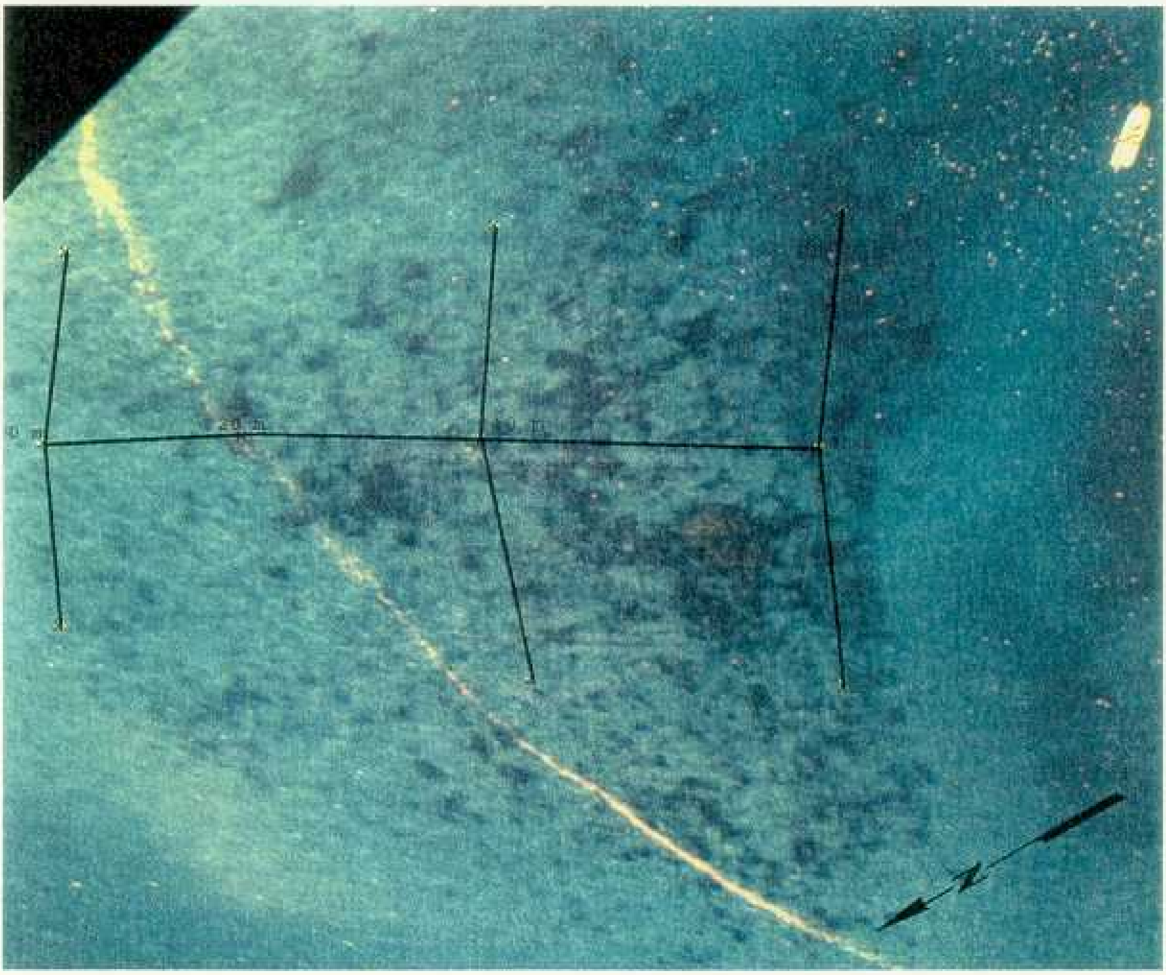

0 m
20 m
40 m
N

Figure 18. Water corrected multispectral RGB image of Rainbow Gardens Reef after application of algebraic equations that correct for the attenuation of light by the water column.


N

Figure 19. Classified GIS image of Rainbow Gardens Reef containing 28 clusters from the multispectral RGB aerial image.

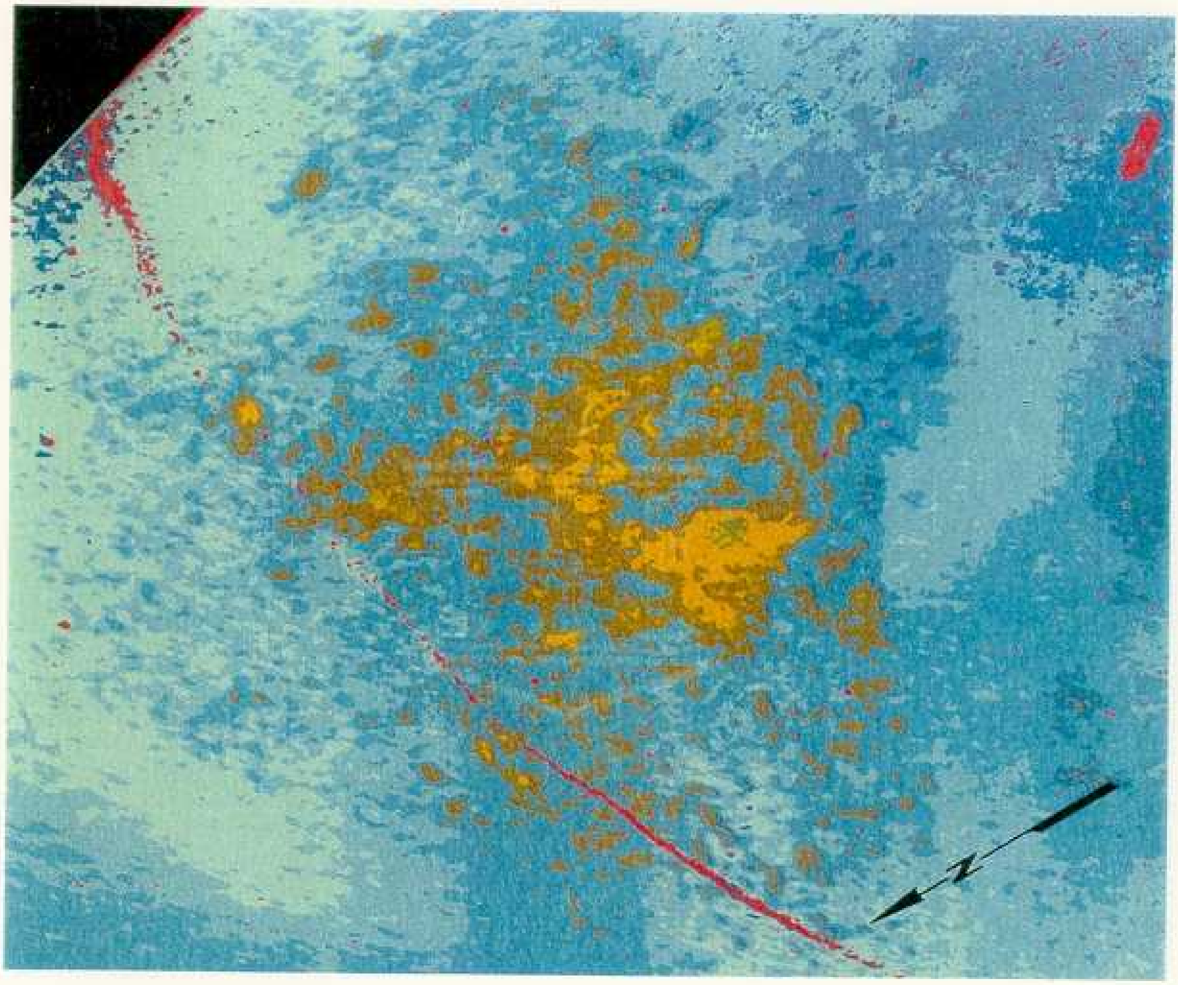

N

Figure 20. Final classified GIS image with all noise "masked" out containing 28 clusters.

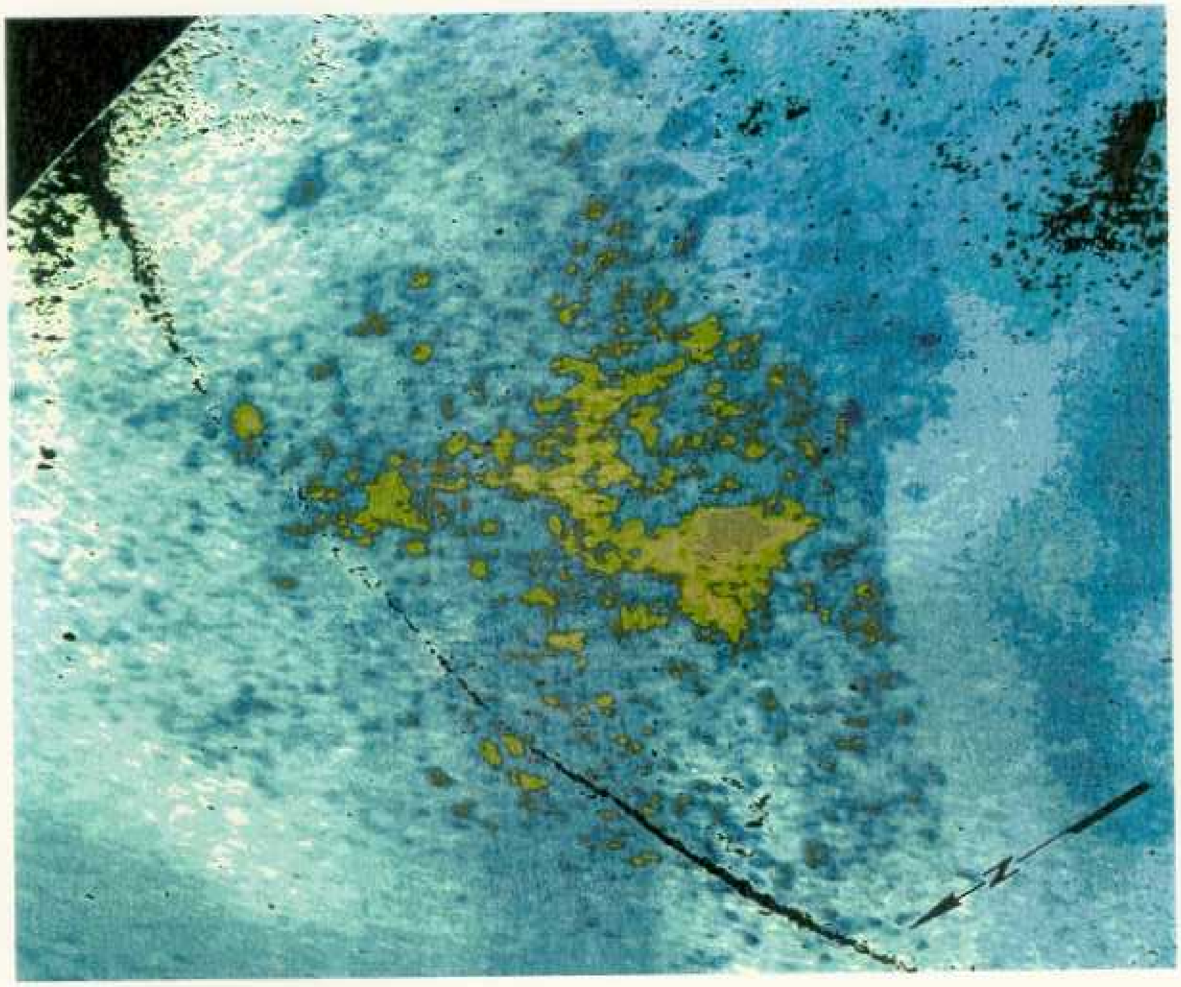

N

Figure 21. Concentric "rings" of classes resulting from a classification of only the coral colonies into 28 clusters. Classes are not representative of species, but of the bio-optical properties of the corals and the depth of the water column.

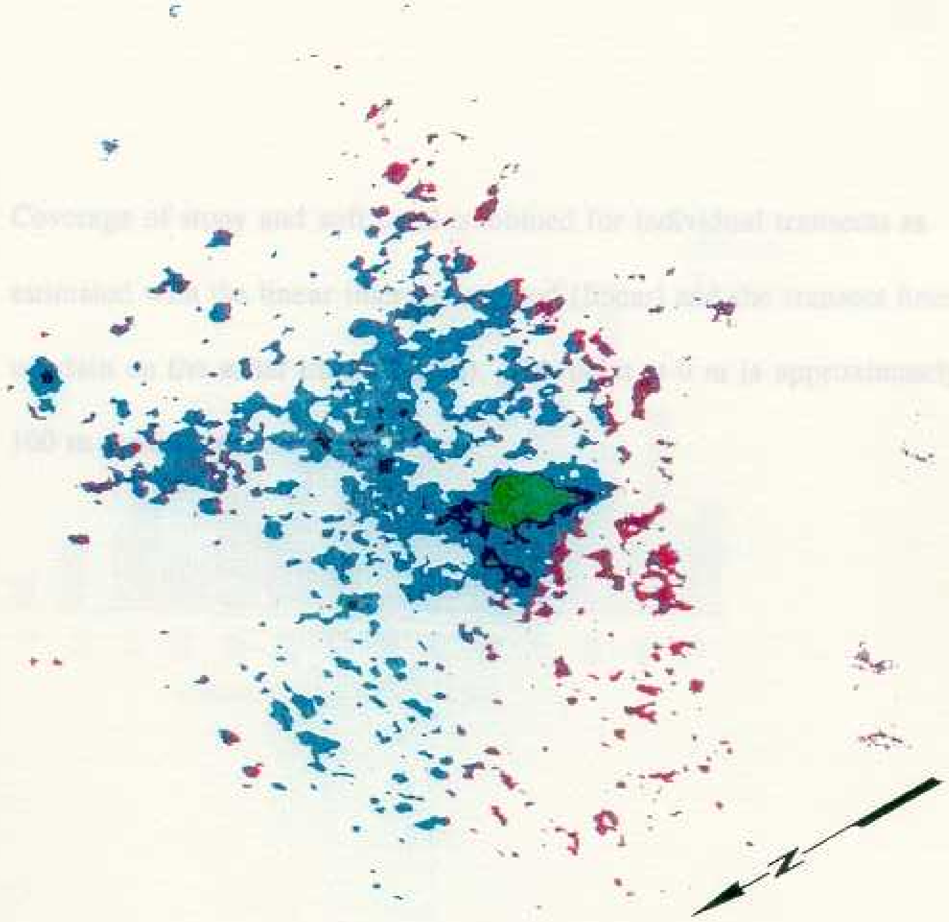

N

Figure 22. Coverage of stony and soft coral combined for individual transects as estimated with the linear intercept method (linear) and the transect lines overlain on the aerial image (aerial). The point at 0 m is approximately 100 m from shore.

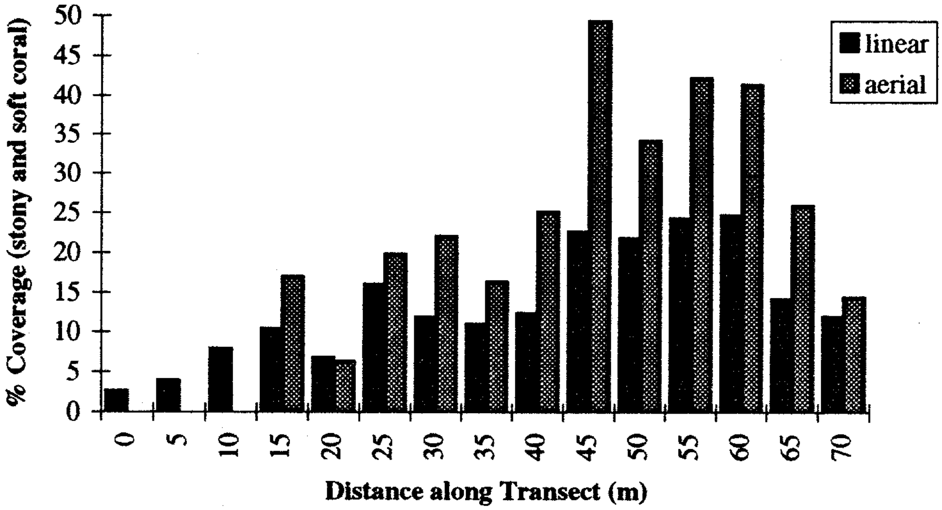
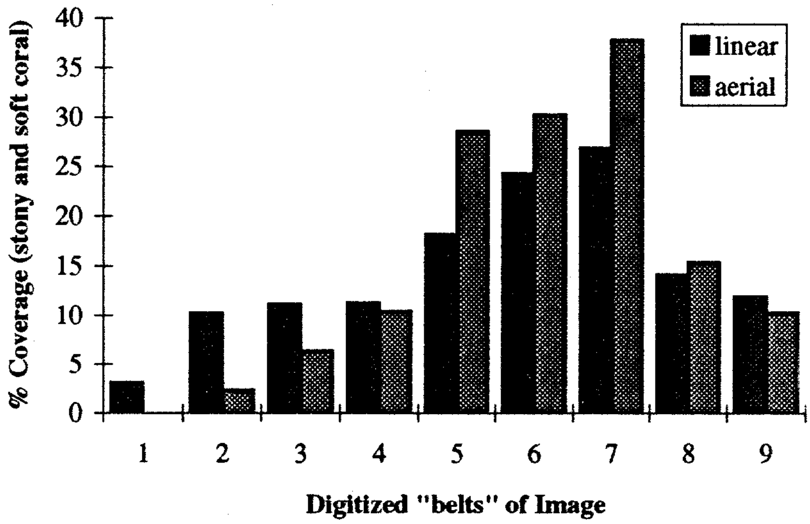

% Coverage (stony and soft coral)
50
45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Distance along Transect (m)
■ linear
▨ aerial

Figure 23. Coverage of stony and soft coral combined for groups of transects as estimated with the linear intercept method (linear) and the digitized belts overlain on the aerial image (aerial). The point at 0 m is approximately 100 m from shore.


% Coverage (stony and soft coral)
40
35
30
25
20
15
10
5
0
linear
aerial
1
2
3
4
5
6
7
8
9
Digitized "belts" of Image

Appendix A. Numbers of colonies (by species) with each condition summarized from all the transects in the linear intercept survey.

Appendix A.

Number of colonies of individual coral species with each condition encountered along the linear intercept survey (616 coral colonies examined):

Code	**Condition**	***A. cerv***	***A. agar***	***A. lam***	***M. ann***	***M. cav***	***F. frag***	***S. rad***	***S. sid***	***D. stok***	***D. strig***	***D. lab***	***I. rig***	***P. por***	***P. ast***	***M. phar***	***M. dec***	***M. alc***	***E. fast***	**Total**
5	Fresh damage to skeleton and tissue				1							1								**2**
6	Excessive sediment on live tissue		1		10		2	6	1			2	2	8	18			1	1	**52**
7	Recent damage to soft tissues		13	1	21		1			2		1	1	17	8			1		**66**
8	Tissue bleaching	1	1		50		1			1		1			6					**61**
9	Excess mucous on surface				7									2	5					**14**
11	Obvious algal mat smothering		1											1	2					**4**
12	Sediment damage with tissue necrosis		1		2					2		1			3			1		**10**
13	White plague (putative bacteria)		1		1															**2**
14	Healed with secondary algal colonization		5		24	1			5	2		1		1	5					**44**
15	Recently dead		1		6															**7**
16	Algal tufts on surface		9		9		1							3	3			1		**26**
17	Colony decreasing in size		43		55	1	4		1	5	1	6	1	23	15			1		**156**
18	Colony almost unblemished		11		9	2	1		4					13	37	1	1	7	3	**89**
20	Unblemished (healthy)	1	39		4	1	47	19	3	9	2		1	19	58	1		17	5	**226**
23	Juvenile		33							12	1			8	41			3		**98**
24	Sed/alg tissue necrosis		60		63	2	9	1	5	11	1	7	1	29	32		1	6	2	**230**
25	Bleached				1		1			1										**3**
26	Overgrowth by green tunicate		1		2															**3**
27	Overgrowth by encrusting sponge		8		8					1		3		7	2			5		**34**
28	Dead area from soft coral/sponge		3		3				1			1		1	2					**11**
29	Dark tissue discoloration		6		12							2			2					**22**
31	Boring sponge		2		7				5	2		1		3	9				1	**65**
32	Boring worm		5		15				2			1		1	11					**35**
33	Encrusting red algae		6		6			1							4			1		**18**
35	Competition		4		3							1	1	1				11		**21**
	Total number colonies (n)	**2**	**116**	**1**	**81**	**3**	**62**	**26**	**10**	**22**	**3**	**8**	**4**	**68**	**153**	**2**	**1**	**43**	**11**	**1299**

Appendix B. Proportion of colonies (by species) with each condition summarized from all the transects in the linear intercept survey.

Appendix B.

Proportion of colonies of each coral species with each condition encountered along the linear intercept survey (616 coral colonies examined):

Code	Condition	*A. cerv*	*A. agar*	*A. lam*	*M. ann*	*M. cav*	*F. frag*	*S. rad*	*S. sid*	*D. stok*	*D. strig*	*D. lab*	*I. rig*	*P. por*	*P. ast*	*M. phar*	*M. dec*	*M. alc*	*E. fast*	Total
5	Fresh damage to skeleton and tissue				1.2							12.5								**0.3**
6	Excessive sediment on live tissue		0.9		12.3		3.2	23.1	10.0			25.0	50.0	11.8	11.8			2.3	9.1	**8.4**
7	Recent damage to soft tissues		11.2	100.0	25.9		1.6			9.1		12.5	25.0	25.0	5.2			2.3		**10.7**
8	Tissue bleaching	50.0	0.9		61.7		1.6			4.5		12.5			3.9					**9.9**
9	Excess mucous on surface				8.6									2.9	3.3					**2.3**
11	Obvious algal mat smothering		0.9											1.5	1.3					**0.6**
12	Sediment damage with tissue necrosis		0.9		2.5					9.1		12.5			2.0			2.3		**1.6**
13	White plague (putative bacteria)		0.9		1.2															**0.3**
14	Healed with secondary algal colonization		4.3		29.6	33.3			50.0	9.1		12.5		1.5	3.3					**7.1**
15	Recently dead		0.9		7.4															**1.1**
16	Algal tufts on surface		7.8		11.1		1.6							4.4	2.0			2.3		**4.2**
17	Colony decreasing in size		37.1		67.9	33.3	6.5		10.0	22.7	33.3	75.0	25.0	33.8	9.8			2.3		**25.3**
18	Colony almost unblemished		9.5		11.1	66.7	1.6		40.0					19.1	24.2	50.0	100.0	16.3	27.3	**14.4**
20	Unblemished (healthy)	50.0	33.6		4.9	33.3	75.8	73.1	30.0	40.9	66.7		25.0	27.9	37.9	50.0		39.5	45.5	**36.7**
23	Juvenile		28.4							54.5	33.3			11.8	26.8			7.0		**15.9**
24	Sed/alg tissue necrosis		51.7		77.8	66.7	14.5	3.8	50.0	50.0	33.3	87.5	25.0	42.6	20.9		100.0	14.0	18.2	**37.3**
25	Bleached				1.2		1.6			4.5										**0.5**
26	Overgrowth by green tunicate		0.9		2.5															**0.5**
27	Overgrowth by encrusting sponge		6.9		9.9					4.5		37.5		10.3	1.3			11.6		**5.5**
28	Dead area from soft coral/sponge		2.6		3.7				10.0			12.5		1.5	1.3					**1.8**
29	Dark tissue discoloration		5.2		14.8							25.0			1.3					**3.6**
31	Boring sponge		1.7		8.6				50.0	9.1		12.5		4.4	5.9				9.1	**10.6**
32	Boring worm		4.3		18.5				20.0			12.5		1.5	7.2					**5.7**
33	Encrusting red algae		5.2		7.4			3.8							2.6			2.3		**2.9**
35	Competition		3.4		3.7							12.5	25.0	1.5				25.6		**3.4**
	Total number colonies (n)	**2**	**116**	**1**	**81**	**3**	**62**	**26**	**10**	**22**	**3**	**8**	**4**	**68**	**153**	**2**	**1**	**43**	**11**	**210.9**