Discrimination of Coral Reefs, Seagrass Meadows, and Sand Bottom Types from Space: A Dominican Republic Case Study*

Abstract
In order to monitor changes caused by local and global human actions to a coral reef ecosystem, we "sea-truthed" a natural color Landsat Thematic Mapper (TM) image prepared for a coastal region of the northwestern Dominican Republic and recorded average water depth, precise geographical positions, and bottom types (seagrass, 15 sites; coral reef, ten sites; and sand, six sites). There were no significant differences in depth for the bottom type groups. The depths ranged from 0 to 16.1 m (0 to 52.7 ft). Sand > seagrass > coral in mean Landsat digital counts (proportional to radiance) for the three Landsat TM visible bands (TM 1, TM 2, TM 3); sand bottom sites had significantly greater digital counts than seagrass and coral sites in TM 1 only. Mean digital counts of seagrass and coral reef sites did not differ significantly in any band. A multivariate analysis of variance using all three bands gave similar results. A ratio of the green/blue bands (TM 2/TM 1) showed there was a spectral shift associated with increasing depth but not bottom type. Due to small-scale patchiness (< 30 m by 30 m), seagrass and coral areas were difficult to distinguish, but sandy areas can be distinguished using Landsat TM imagery and our methods.

Introduction
It is important for coastal planners and scientists to know the areal extent of various bottom habitats for managing and assessing tropical coastal ecosystems that are changing due to human impacts. Activities that can have a negative effect on coastal habitats include subsistence fishing, commercial fishing, recreational and tourist activities, urbanization, and nutrient and sediment pollution from agricultural activities (Grigg and Dollar, 1990; Stoffle and Halmo, 1991). In addition, global seawater warming due to excessive fossil fuel combustion has been suggested as a cause for coral reef bleaching (Glynn, 1991). Maps of tropical coral reef ecosystems showing bathymetry and bottom types prepared from remotely sensed data can greatly assist in monitoring global and local changes due to these impacts (Jupp *et al.*, 1985; Craik *et al.*, 1990). As reef ecosystems become stressed due to human impacts, areas covered by corals and seagrasses may die and become less productive and less biologically diverse sand-bottom habitats. If unvegetated sand bottom, seagrass-covered bottom, and coral-covered bottom habitats can be identified in satellite imagery, then changes in the size of these areas could be monitored over time, and management, regulation, or preservation of the resources could be implemented. The need for satellite imagery in monitoring changes in coastal resources of less developed countries is important, because these nations possess the greatest areas of undisturbed coral reef and seagrass habitats, but also lack the necessary funds and equipment to conduct extensive ground- and water-based resource inventories (Stoffle and Halmo, 1991). The first step in making satellite data useful for scientists and natural resource managers is to "sea truth" the satellite data and determine the correlation between variation in radiance and bottom habitats. In this paper, we report on the relationship between Landsat Thematic Mapper (TM) digital count values, which are proportional to radiance, and bottom type categories along the North Coast of the Dominican Republic.

Methods
We visited a region on the North Coast of the Dominican Republic for which Landsat Thematic Mapper satellite data had been prepared into a natural-color composite image as an aid to ecological and ethnographic surveys of the coastal region from 15 Feb 1991 to 04 Mar 1991 (Wagner *et al.*, 1991). Features such as a series of three fringing coral reefs, lagoons, and light and dark areas that suggested the presence of aquatic vegetation such as seagrasses and algae were visible in the image. Guided by this image and local expert fishermen, we visited 31 sites and determined the bottom type (using SCUBA observers), depth (using a ScubaPro PDS battery-powered sonar device), and precise position [using a Magellan NAV 1000 Pro GPS (Global Positioning system) Satellite Receiver]. Geo-corrected Landsat digital count values in the three visible bands [TM band 1 (blue) = 0.45 to 0.52 μm, TM band 2 (green) = 0.52 to 0.60 μm, and TM band 3 (red) = 0.63 to 0.69 μm) from a Landsat Thematic Mapper Scene (ID: 42364-14403; Scene date: 04-Jan-89; path-row: 8–46) were compared at each of these sites using analysis of variance and multivariate analysis of variance (Wilkinson, 1990). The

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Joseph J. Luczkovich
Institute for Coastal and Marine Resources, East Carolina University, Greenville, NC 27858-4353.

Thomas W. Wagner
Jeffrey L. Michalek
Environmental Research Institute of Michigan, P. O. Box 134001, Ann Arbor, MI 48113-4001.

Richard W. Stoffle
Bureau of Applied Research Anthropology, University of Arizona, Tuscon, AZ 85721.

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TABLE 1. DATA SET USED IN THIS ANALYSIS: STATION IDENTIFIER, BOTTOM TYPES, DEPTHS IN METRES, AND LANDSAT THEMATIC MAPPER DIGITAL COUNTS (OR RADIANCE) FOR BANDS 1, 2, AND 3.

Station	Bottom Type	Depth(m)	Band 1	Band 2	Band 3
M2	SEAGRASS	00.305	82	33	36
E2	SEAGRASS	00.610	99	42	39
M1	SEAGRASS	00.219	75	29	24
A1	SEAGRASS	01.524	61	19	14
I1	SEAGRASS	01.829	90	37	29
T1	SEAGRASS	01.859	81	25	16
F2	SEAGRASS	02.499	73	23	14
B2	SEAGRASS	03.353	81	28	15
N2	SEAGRASS	03.383	77	24	14
U1	SEAGRASS	03.901	77	28	20
B1	SEAGRASS	04.115	74	22	18
G1	SEAGRASS	04.176	82	24	12
H1	SEAGRASS	05.243	72	26	19
B3	SEAGRASS	10.729	82	27	16
V1	SEAGRASS	13.655	68	19	13
E5	CORAL	00.610	65	20	14
U2	CORAL	00.610	79	32	27
X3	CORAL	00.914	86	37	31
R1	CORAL	01.097	80	28	23
AA3	CORAL	01.372	72	20	14
H2	CORAL	01.676	71	22	15
J2	CORAL	02.134	67	18	12
W1	CORAL	06.005	69	21	13
D1	CORAL	08.412	67	19	14
O1	CORAL	10.302	73	22	12
AA1	SAND	00.000	76	29	24
E1	SAND	00.457	104	44	38
AA2	SAND	01.311	77	26	16
F1	SAND	01.372	91	34	21
E6	SAND	01.524	105	45	42
X2	SAND	16.063	81	21	14

statistical fit of the data was determined by standard statistical measures: probability estimates (P) associated with statistical tests give the probability of getting a test statistic larger than the reported value by chance alone; F-ratios were used to test the hypothesis of a slope > 0 and R^2 was used to determine the percentage of total variation explained by the independent variable in all linear regression analyses and analyses of covariance; F-ratios were used to test the hypothesis of no difference in mean Landsat digital counts for analysis of variance (ANOVA) tests on individual TM bands; R^2 is used as an estimate of model adequacy in the ANOVAs; and Wilk's Lambda, a multivariate analogue of the F-ratio, was used to test the hypothesis of no difference in the Landsat digital counts for all three bands combined (Wilkinson, 1990). To determine if there was a spectral shift associated with bottom types and water depth, ratios (TM band 2 / TM band 1, TM band 3 / TM band 1, and TM band 2 / TM band 3) of digital counts in these bands were compared among bottom types using analysis of covariance with depth as the covariate (Wilkinson, 1990). In a previous study of bottom reflectance in seagrass and sand bottom habitats in the Bahamas, a depth-invariant index of bottom reflectance was developed using the ratio of light attenuation coefficients derrived from Landsat Multispectral Scanner (MSS) band 4 (green; 0.5 to 0.6 μm) and band 5 (red; 0.6 to 0.7 μm) in shallow areas of uniform bottom cover across a range of depths (Lyzenga, 1981). This approach was not used because it depends upon a training set with large areas of uniform bottom type, a situation that did not exist in our study area. Following the work of Lyzenga (1981) and Jupp *et al.* (1985) using Landsat MSS data to classify bottom cover on shallow coral reefs, we selected three bottom types that could be easily and rapidly distinguished during our field visit: seagrass meadows, coral reefs, and unvegetated sand bottom.

Results

Bottom Type Classification

Ecological communities at the 31 sites we visited were very diverse and complex, but 15 sites were classified as predominantly turtlegrass (*Thalassia testudinum*) meadows, ten sites as predominantly boulder coral (*Montastrea annularis*) reefs, and six sites as unvegetated sand bottom (Table 1). These bottom classifications were based on natural groups identified in a cluster analysis of species presence-or-absence data for the ecological communities present at each site during SCUBA observations and visual estimates of predominant percentage cover made in the field (Luczkovich, 1991). However, a great deal of bottom type heterogeneity was observed at many sites. It was possible in a predominantly coral reef site, for example, to have seagrasses, macroalgae, and the underlying sand substrate present. Also, the shoot density and height of seagrasses or areal coverage of corals varied between pixels. Sand, seagrass, and coral patches occurred inside large (> 900 m²) seagrass meadows and coral reef areas. Precise quantitative assessment of the percentage cover at each sites was not possible given our time and equipment constraints and the large number of corals, macroalgal, and seagrass species observed, which numbered over 93 species at all sites (see Luczkovich, 1991). Even if precise percentage cover estimates for each species within a 28.5-m by 28.5-m area (an area equivilent to an unprocessed Landsat pixel) at each site were available, the bottom types and species present within a bottom type would have to be combined or averaged in some manner to compare with the Landsat digital count data for each pixel, because the radiance produced at each site was effectively averaged by the Landsat TM sensor at a spectral resolution of 25 m (after processing). Although many other bottom type classifications were possible, we elected to use the predominant cover estimates and cluster analysis results to classify the sites into three groups (seagrass, coral, and sand bottom types) for subsequent statistical analyses.

Effect of Depth

The sample sites occurred in water depths ranging from 0 to 16.1 m (0 to 52.7 feet), but there was no significant difference among mean depth of the bottom types (Analysis of Variance $F_{2,28} = 0.062$, $P = 0.940$; Table 2). Although less than 22 percent of the total variation in radiance was explained by depth, radiance values declined with increasing depth in two of the Landsat Thematic Mapper visible bands (Linear regression analysis, TM band 1: $F_{1,29} = 1.782$, $P = 0.192$, $R^2 = 0.058$; TM band 2: $F_{1,29} = 6.874$, $P = 0.014$, $R^2 = 0.192$; TM band 3: $F_{1,29} = 7.846$, $P = 0.009$, $R^2 = 0.213$; Figure 1). Variation in radiance seemed to decline

TABLE 2. MEAN DEPTHS AND MEAN RADIANCES FOR TM BANDS BY BOTTOM TYPE GROUPS.

Bottom type	Depth (m)	Band 1	Band 2	Band 3
Seagrass	3.893	78.2	27.1	19.9
Coral	3.313	72.9	23.9	17.5
Sand	3.454	89.0*	33.2	25.8

*Significantly different using Analysis of Variance with the Bonferroni Correction, $P < 0.05$.

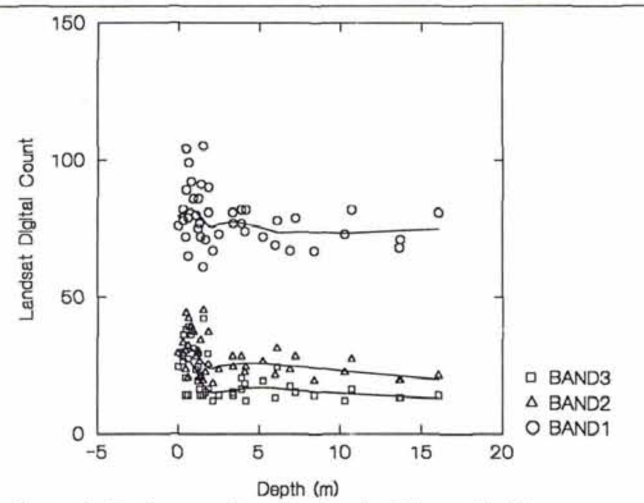

Figure 1. Radiance values for Landsat Thematic Mapper Bands 1, 2, and 3 plotted versus depth in metres.

with increasing depth for all three bands, which may reflect the turbulent nature of shallow waters, where wave action could influence radiance values greatly.

Effect of Bottom Type
Sand bottoms had greater mean Landsat digital counts than seagrass bottoms, and seagrass had greater Landsat digital counts than coral bottoms for all Thematic Mapper bands examined (Table 2). However, bottom type explained less than 30 percent of the total variation in the digital counts for all bands. Figure 2 shows the digital counts in TM band 1 versus depth by bottom types. Significant differences were found among bottom types in the mean digital counts of TM bands 1 and 2 (Analysis of Variance, TM band 1: $F_{2,28} = 5.691$, $P = 0.008$, $R^2 = 0.289$; TM band 2: $F_{2,28} = 3.245$; $P = 0.054$, $R^2 = 0.188$; TM band 3, $F_{2,28} = 1.764$, $P = 0.190$, $R^2 = 0.112$; Table 2). Mean digital counts of TM band 1 did not differ significantly between seagrass and coral sites ($F_{1,28} = 2.016$; $P = 0.167$), although both of these bottom types were significantly lower in mean Landsat digital counts than sand bottom sites (Seagrass vs. Sand: $F_{1,28} = 5.761$, $P = 0.023$; Coral vs. Sand: $F_{1,28} = 11.341$, $P = 0.002$; Seagrass and Coral vs. Sand: $F_{1,28} = 10.081$, $P = 0.004$). After applying the Bonferroni correction, a very conservative measure for judging significance used in cases where many *post-hoc contrasts are made* (Wilkinson, 1990), we conclude that sand bottoms have Landsat digital counts that are significantly greater than coral and seagrass bottoms in TM band 1. None of the *post-hoc* contrasts were significant after Bonferroni correction in TM bands 2 or TM bands 3.

A Multivariate Analysis of Variance (MANOVA) was used to simultaneously compare TM band 1, TM band 2, and TM band 3 among bottom types using depth as a covariate. This model explained about 33 percent to 38 percent of the variation in the three bands (TM band 1 $R^2 = 0.340$; TM band 2 $R^2 = 0.384$; TM band 3 $R^2 = 0.327$), and bottom type was a significant effect (Wilk's Lambda = 0.708, $P = 0.032$). Coral sites were significantly different from sand bottoms (Wilk's Lambda = 0.679, $P = 0.020$), but no other contrasts were significant. It would be difficult to distinguish seagrass from coral and sand bottoms based on this multivariate model. However, coral bottoms could be distinguished from sand bottoms.

Ratios of the green to blue bands (TM band 2/TM band 1), green to red (TM band 2/TM band 3), and the blue to red bands (TM band 1/TM band 3) were examined to reduce sensor noise and to detect spectral shifts that could be associated with the presence of submerged aquatic vegetation and increasing depth. No significant differences among bottom habitats were observed in this analysis, but depth explained up to 40 percent of the variation in the ratios of digital counts (Figure 3; TM band 2/TM band 1: $F_{1,27} = 14.161$, $P = 0.001$, $R^2 = 0.400$; TM band 2/TM band 3: $F_{1,27} = 4.900$, $P = 0.035$, $R^2 = 0.168$; TM band 1/TM band 3: $F_{1,27} = 12.139$, $P = 0.002$, $R^2 = 0.336$). This suggests that there is a significant spectral shift associated with increasing depth. Sandy seagrass stations (i.e., B1) had a lower TM band 2/TM band 1 ratio than dense seagrass stations (i.e., B3) (Figure 3), suggesting that density of seagrasses at a site can influence these ratios.

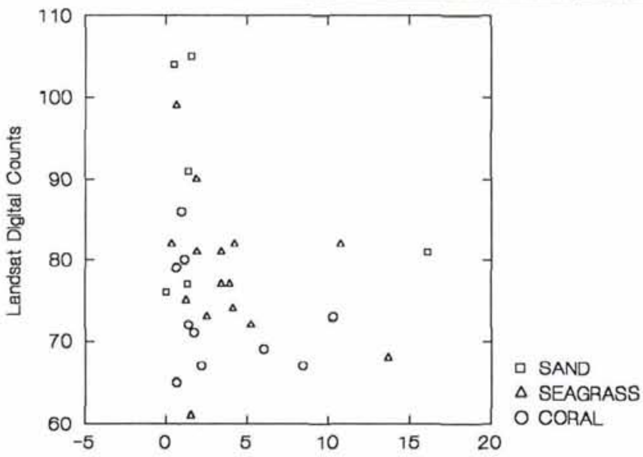

Figure 2. The radiance values of Thematic Mapper Band 1 at seagrass, coral, and sand bottom sites versus depth in metres.

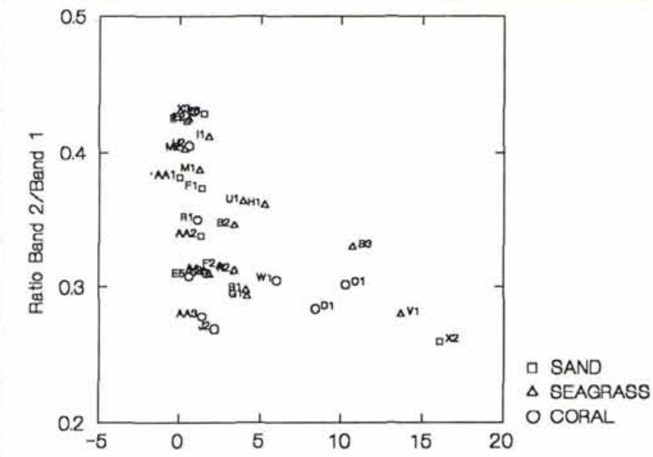

Figure 3. The ratio of green to blue (TM Band 2/TM Band 1) radiance versus depth and by bottom type.

Discussion

There are several possible reasons for the failure of sites visited in this study to fall into distinct bottom type groups with characteristic Landsat digital counts. First, categorizing the sites into three groups (sand, seagrass, and coral bottoms) was a rough approximation used only for convenience: many of these categories may have over-lapped in mean Landsat digital counts because several bottom types were present in the 812 m^2 area that comprised a single Landsat pixel. Features within each pixel or in nearby pixels may have affected the Landsat digital counts. For example, sand patches inside seagrass and coral reef habitats may influence pixel brightness. The sites that we sampled were very heterogeneous at a spatial scale of less than 30 m. Second, the sea-truthing was made over two years after the satellite data were collected. We may have been sea-truthing a much different ecosystem. For instance, if some sites categorized as sand bottom had in fact been covered with seagrass or coral two years earlier, then we would have grouped such sites that had low Landsat digital counts with other truly sandy sites that had high digital counts. Such changes are very likely, because we have detected significant changes over a four-year period (1985 to 1989) that suggest a brightening of certain pixels in this same Landsat scene using multispectral change vector analysis imagery (Wagner *et al.*, 1991; Michalek *et al.*, 1993). Sensor noise, wave action, atmospheric state, and water clarity may have contributed additional sources of error in the satellite data. We suspect that the first two sources of variation, i.e., bottom type heterogeneity and changes that occurred between image acquisition and sea-truth visit date, are the most significant, due to our *in situ* SCUBA observations and discussions with local fishermen. "Sea-truthing" a tropical reef ecosystem such as the one on the north coast of the Dominican Republic may take much more surveying effort than we first anticipated. Perhaps multiple areas as large as 90 m by 90 m (8100 m^2 or nine pixels) may have to be categorized to adequately "sea-truth" a pixel of interest and the surrounding pixels that might influence its Landsat digital count and radiance.

The ecological complexity and diversity present at the sites visited in this study made the spectral reflectance properties of the bottom complex, in all likelihood. For example, in addition to the dominant species of seagrass (*Thalassia testudinum*) and coral (*Montastrea annularis*), there were many other species of plants (56 species of macroalgae and two other seagrass species) and corals (37 species) present in both seagrass meadows and coral reef bottom type categories (see Luczkovich, 1991). These other species may have unique spectral reflectance patterns, and the relative proportion of these species at a given site may determine the radiance associated with that pixel. In the future, we recommend that further "sea-truthing" be conducted using Landsat TM data and a greater number of "sea-truth" sites be included in each category. We also recommend that new and existing sensors, which may be used aboard aircraft and that can target specific areas of interest with improved spatial and spectral resolution, be considered for constructing bottom type maps in the future (Lyzenga *et al.*, 1979; Lyzenga, 1981; Lyzenga, 1985). However, we would like to emphasize potential importance of the historical database collected over almost 20 years with Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) sensors, which can prove useful to monitor changes that have already occurred in the areal coverage of seagrasses and coral reef ecosystems and may be continuing to occur (Michalek *et al.*, 1993). It is now possible to monitor changes to tropical coastal ecosystems that can occur over wide temporal and spatial scales with Landsat data, and we recommend that this work continue, especially along the coastal zones of less-developed tropical nations.

Conclusions

It is clear that sand bottoms have significantly greater bottom reflectance patterns than seagrass meadows and coral reefs. Landsat Thematic Mapper (TM) band 1, and perhaps TM band 2, can be used to detect such sandy bottom areas. Seagrass tends to have greater Landsat digital counts (and hence radiance) than coral bottoms at all TM bands examined, perhaps due to the increased reflectance of the underlying sandy substrata in low-shoot density seagrass areas, but these two bottom habitats will be much more difficult to distinguish with Landsat imagery and our current sample size of "sea-truth" sites. With a larger number of sample sites and better estimates of percentage cover and seagrass density measured over a large 8100 m^2 area at the sites, it might be possible to distinguish changes in these bottom types with Landsat pixel resolution (28.5 m by 28.5 m). Other remotely sensed data (such as high-spatial resolution SPOT data, aerial photography, high-spectral-and-spatial resolution airborne scanners, and new satellite sensors to be deployed in the future) will also prove useful in categorizing the heterogenous mix of these bottom types. However, Landsat imagery may be very useful in detecting expanding patches of unvegetated sand bottom, which can occur as humans impact coral reef ecosystems and their associated seagrass meadows. Landsat TM data does extend backwards in time to 1982, and so may prove to be extremely useful in measuring changes through time indicative of death of productive seagrasses and corals that are replaced by less productive sand bottom habitats.

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