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SUBPIXEL LINEAR MIXING WITHIN A CORAL REEF ENVIRONMENT BASED ON IN SITU HYPERSPECTRAL MEASUREMENTS*

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ABSTRACT

It is often necessary to assume a relatively homogeneous benthic cover within a remotely sensed pixel when attempting to identify bottom type in a coral reef environment. In reality, however, with the benthic complexity common on a coral reef, there will always be mixing within a pixel given the spatial resolution of contemporary satellite imagery. It therefore becomes important to determine how components of a pixel combine to result in one integrated pixel value. Pure endmember high spectral resolution measurements were taken in Buck Island Marine Park, off St. Croix, U.S. Virgin Islands. Linear spectral mixing was used with these endmember spectra (coral, sand, grass, bleached coral, and benthic algae) to examine the integrated pixel signals. When sand is a component of the mixed spectra, there is an increase in magnitude of reflectance, even at only 25% sand cover. Cluster analyses indicate that a sand component of a mixed spectra will have the effect of dominating the spectral reflectance to the point that it lacks spectral similarity to other endmembers present, but retains spectral characteristics specific to sand.

INTRODUCTION

At nearly any given scale of measurement or observation there will be variation occurring at a smaller scale and therefore imperceptible. This "mixel" effect is a well-known phenomenon whereby a sensor's IFOV includes more than one cover type or feature. The extent to which mixels are present, however, is a function of the spatial resolution of the imagery as well as the variation and spatial scale of the features within the scene. The mixed pixel presents a significant problem for identification and classification of benthic habitat in a coral reef environment since a pixel's spectral response is not representative of a single bottom type, but is an integrated response of multiple bottom types. Without subpixel analysis, much of the spatial variation and heterogeneity in a typical shallow coral reef ecosystem would be unidentifiable as the boundaries between features and bottom types are ambiguous. As a preliminary examination of the spectral mixing in a typical coral reef environment, a theoretical mixing of *in situ* spectral endmembers is of interest. This will provide insight on the expected degree of spectral dominance of a given endmember. The objective here is to examine the theoretical linear mixing of *in situ* endmembers to gain insight on the integrated response to expect from a pixel with multiple bottom types present. Of particular interest is investigation of the degree to which bright white sand, common in shallow, tropical coral reef ecosystems, can dominate a pixel's signal; i.e. the percent cover of sand sufficient to produce a pixel with a signal similar to that of pure white sand regardless of other bottom types present. Linear mixing of *in situ* measurements, in both equal and unequal proportions, is used as tool to investigate the nature of subpixel mixing in a coral reef environment. Cluster analysis is used as a means of examining the degree to which mixed spectra can be grouped with the pure endmember spectra.

METHODS

Data collection took place during February 1999 in Buck Island National Park, St. Croix, U.S. Virgin Islands in the Caribbean. A hyperspectral radiometer (Analytical Spectral Devices Personal Spectrometer II), which remained on board the boat, was used for data collection together with a 20m underwater optical cable, which allowed a scuba diver to carry the 22-degree field of view sensor underwater for the measurements. A Spectralon panel was used to take a reference measurement prior to each feature measurement and after the integration time was set onboard the boat to enable determination of reflectance. Weaknesses of this methodology include the inevitable shadowing influence of the diver and air bubbles from the scuba breathing apparatus, but these sources of error were minimized through careful body placement and orientation.

The *in situ* reflectance measurements were taken at nadir while the 22-degree FOV sensor was held 10cm above the surface. The radius, r, of the area measured by the 22 degree FOV sensor was found using the equation, $r = d * \tan(FOV/2)$ where d is the height above the surface. The radius of the circle measured is approximately 2cm; therefore, using πr^2, the area measured is 11.87cm^2. All features measured were larger than 12cm^2, so the chance that the surrounding substrate influenced the feature measurement was minimized. It can therefore be assumed that the measurements taken with the 22 degree FOV sensor are representative of

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the feature alone and can be considered pure end member signatures. The water present between the sensor and the feature (10cm) is considered negligible, so no correction for attenuation was performed.

Underwater photographs were taken of each of the features measured to create a spectral and photographic database or library. Additionally, notes were taken on an underwater notepad describing the depth, feature type, surrounding substrate, water quality, feature size and morphology as well as any other pertinent information. Each spectral measurement has 205 contiguous waveband channels with 1.4nm bandwidths. The five feature or bottom type categories (sand, bleached coral, healthy coral, benthic algae, and seagrass) were assigned based on identification of the feature in the field and confirmed based on inspection of the underwater photographic record. In total 178 spectra were measured during this field season in water depths ranging from 1.5m to 6.6m on February 8, 9, 12 and 15, 1999.

Principal components analysis, a model in which the factors are based on the total variance, is a reliable tool for data reduction and was used here to reduce the spectral library to one representative spectrum for each of the predefined benthic categories (Griffith and Amrhein, 1997). This technique has been used previously and has proven successful (Holden and LeDrew, 1998 and 1999). Linear mixing of the representative spectra for each of the benthic categories was performed to systematically estimate the proportional contribution of the endmembers to the overall integrated pixel signal. Initially, endmembers were combined linearly with equal weightings with an increasingly large number of endmembers present. The linear mixing could therefore be assessed when it is assumed that 2 endmembers are present (50% coverage for each), 3 endmembers are present (33.3% coverage for each), 4 are present (25% coverage for each), and finally, 5 endmembers are present (20% coverage for each). The linear mixing was then assessed when the components were given disproportional weightings. With 2 endmembers present, mixing was determined for a 75-25% proportional coverage; with 3 endmembers present, mixing was determined for a 50-25-25% proportional coverage; with 4 endmembers present, mixing was determined for a 40-20-20-20% proportional coverage; and finally, with 5 endmembers present, mixing was determined for a 40-15-15-15-15% proportional coverage.

Cluster analysis was used to group the mixed pixels into categories to examine the degree to which mixing changes their ability to be grouped with the endmember spectra. Agglomerative hierarchical clustering was performed, which starts with individual samples and successively merges similar groups such that dissimilarities within groups are minimized and dissimilarities between groups are maximized. Results are summarized in a dendogram, a 2-dimensional schematic profiling the sequential grouping process with branches merging at nodes whose position along the quantitative horizontal axis define a measure of similarity. A threshold value along this horizontal axis is defined where a significant change occurs and a vertical line is drawn to indicate the number and composition of clusters (Griffith and Amrhein, 1997). The type of “linkage” of hierarchical clustering specifies the type of clustering algorithm used to amalgamate clusters (defines how distances between clusters are measured). Here, single linkage was used, which defines the distance between two objects or clusters as the distance between the two closest members of those clusters. The distance metric selected, and shown on the horizontal axis, was the R-squared metric where distances are computed using 1 minus the square of the Pearson product-moment correlation coefficient for each pair of objects.

RESULTS

Linear Mixing in Equal Proportions

Three sets of mixed spectra have nearly identical mixed spectral characteristics. First, the Coral-Sand mixture and the Algae-Sand mixture create mixed spectra which are indistinguishable, thus at a 50-50 ratio, misclassification is probable. The similarity is due to the presence of sand and dominating influence on the mixture at even 50% proportional coverage. Second, the Bleached-Algae mixture and the Coral-Bleached mixture also have very few spectral differences, apparently due to the dominating effect of the bleached coral endmember combined with the fact that the coral endmember and the algae endmember are spectrally similar.

As with the situation above with 2 endmembers, there are 3 cases where pairs of mixed spectra appear inseparable. First, the Sand-Coral-Bleached mixture and the Sand-Algae-Bleached mixture both result in nearly identical mixed spectra. Since the coral endmember and the algae endmember are very similar, it is not surprising that mixtures containing these spectra are indistinguishable. Second, the Sand-Coral-Grass mixture and the Sand-Algae-Grass mixture are nearly identical due to the same problem expressed above with the spectral similarity of coral and algae. Finally, as a result of this same coral-algae similarity issue, the Algae-Bleached-Grass mixture and the Coral-Bleached-Grass mixture have very similar mixed spectra.

Two mixed spectra are indistinguishable: the Sand-Coral-Bleached-Grass combination and the Sand-Algae-Bleached Grass combination. As with the cases above, it is the spectral similarity of the coral and algae endmembers that results in the spectral similarity of mixtures containing either of these endmembers. The mixed spectrum that does not contain a sand component has the lowest overall magnitude of reflectance; all of the mixed spectra share a common spectral shape, which most closely resembles the bleached coral endmember. The linear mixture of all five endmembers in equal proportions results in a mixed spectrum with the sand endmember seemingly dominating the overall magnitude of reflectance and the bleached coral endmember seemingly dominating the spectral shape of the curve. As the number of endmember spectra included in the linear mixture increases, the maximum magnitude of reflectance decreases since the sand endmember's relative influence shrinks from 50% in the case of 2 endmembers to 20% in the case of 5 endmembers. Conversely, as the number of endmember spectra included in the linear mixture increases, the spectral shape appears to be increasingly dominated by the shape of the bleached coral endmember.

Linear Mixing in Unequal Proportions

The results of linear mixing of 2 endmembers in unequal proportions in a ratio of 75-25% are presented in Figure 1, where spectra are presented separately according to dominant bottom type. When the sand endmember is the dominant bottom type, the overall spectral reflectance of the mixed spectra, regardless of bottom type, is the highest of the mixed spectra. The mixed spectra have a similar shape to the pure sand endmember, but with an exaggerated absorption peak at approximately 680nm. The four mixed spectra with sand as the dominant bottom type display a similar shape and magnitude indicating that it will be difficult to detect secondary bottom types present in a pixel with 75% sand cover. When coral is the dominant bottom type, there is greater variability in magnitude of mixed reflectance as well as shape and slope of the resultant spectra than the cases above. The presence of 25% sand bottom cover results in a mixed reflectance response with higher overall reflectance than the other mixed spectra, but the presence of 75% coral cover allows for some spectral characteristics such as the reflectance peak at 610nm to remain evident. With 75% coral cover, the mixed spectra could be discriminated on the basis of magnitude of reflectance, but there would be a high probability of misclassification due to the similar spectral shapes. The overall magnitude of reflectance for the mixed spectra with benthic macroalgae as the dominant bottom type is similar to the mixed spectra with coral as the dominant bottom type. Finally, the mixed spectra resulting from 75% bleached coral cover displays similarly high overall magnitude of reflectance compared to the seagrass-dominated mixed spectra. The presence of only 25% sand cover has the effect of raising the overall magnitude of reflectance of the bleached coral dominated spectrum, which could facilitate discrimination.

The results of linear mixing of 3 endmembers in unequal proportions are presented in Figure 2, where spectra are presented separately according to dominant bottom type. The upper case letter in the legend indicates which bottom type was given the highest weighting of 50% while the lower case letter in the legend indicates which bottom types were given lower the weightings of 25%. The effect of a dominant sand cover is less significant when three endmembers are mixed since the proportional cover and therefore influence has decreased thus the sand-dominated mixed spectra have high overall reflectance, but less so than when mixed with only one other endmember. The spectral characteristics of the spectra mixed with 50% sand cover are, however, very similar to the pure sand endmember and would thus likely be misclassified as a pure sand pixel. When living coral covers 50% of a pixel, the mixed spectra vary more significantly in magnitude of reflectance, but with little spectral variability.

The results of linear mixing of 4 endmembers in unequal proportions are presented in Figure 3, where spectra are presented separately according to dominant bottom type. The upper case letter in the legend indicates which bottom type was given the highest weighting of 40% while the lower case letter in the legend indicates which bottom types were given lower the weightings of 20%. Since sand cover dominance decreases when 4 endmembers are considered, the mixed reflectance spectra display spectral variability indicative of the other bottom types when mixed with 40% sand cover, however determining the combination of other bottom types present would prove difficult. All five endmember spectra were combined linearly but in unequal proportions at a ratio of 40-15-15-15-15%. The resultant mixed spectra are compared in Figure 4. The mixed spectra are the same whether the algae or coral endmembers are given the dominant weighting of 40%. When sand is given the greatest weighting, the magnitude is greatest as the sand endmember spectrum is exerting its dominance and when the bleached coral endmember is given the greatest weighting, the spectral shape retains a slight peak at approximately 600nm as with its endmember.

Cluster Analysis

The results of the hierarchical cluster analysis performed on the pure endmember spectra in addition to the mixed spectra with 2 endmembers mixed in equal proportions are summarized in a dendogram (Figure 5). The horizontal axis contains measures of similarity indicated by R^2 value, such that when a vertical line is drawn through the dendogram at R^2=0.25, there are four clusters present. The top cluster contains the pure endmember spectra for coral, macroalgae and bleached coral as well as the coral-algae mix, the coral-bleached mix and the bleached-algae mix indicating that the mixed spectra do not change appreciably when combined since they remain spectrally similar to the pure endmember spectra. The second cluster contains the pure sand endmember as well as three mixed spectra, which all contain a sand component. This finding suggests that even with 50% cover of another bottom type, a pixel containing 50% sand cover will be identified as sand. The third cluster contains no pure endmember spectra, but is a grouping of four mixed spectra suggesting that the combination of these endmembers results in spectra, which take on their own combined spectral characteristics and will not be incorrectly identified as one of the component endmembers. The challenge remains to create an index or decision-making system capable of identifying these mixed spectra. All four of the spectra included in this third cluster contain a seagrass component, but the pure seagrass component occupies its own (the forth) cluster suggesting that the other endmember components are capable of dominating the seagrass signal at 50% coverage to the point that the characteristics are masked.

The cluster analysis, based on the pure endmember spectra and the mixed spectra created by linearly mixing in equal proportions three endmember spectra, provide an interesting comparison. When a vertical line is drawn through the dendogram at R^2=0.25, there are three clusters present, and like the cluster analysis above, the seagrass endmember spectra occupies its own cluster at the bottom. This indicates that when seagrass is mixed with other endmember spectra, the additional spectra mask the characteristics of the seagrass to the point that they are no longer spectrally similar enough to be joined in one cluster. The middle cluster contains the largest number of spectra, but only one pure endmember spectra, the sand endmember. The results of this cluster analysis indicate that when three endmembers are linearly combined in equal proportions and one of the endmembers is sand, then the resultant spectral characteristics are most similar to pure sand spectra. The top cluster contains the pure coral, algae and bleached endmember spectra as well as the mixed spectra combining these three endmembers. The dendogram summarizing the cluster analysis of the pure endmember spectra and the mixed spectra with four and five endmembers combined linearly in equal proportions. A vertical line drawn at R^2=0.25 results in 3 clusters, again with seagrass comprising its own distinct cluster. The top cluster contains only 2 spectra, both of which are endmembers, coral and macroalgae. The middle cluster contains all of the mixed spectra together with the bleached coral and the sand endmember spectra. These results indicate, as above that when a mixed cluster contains sand, it has the ability to dominate spectral reflectance to the point where other bottom types present are masked.

CONCLUSIONS

The coral and algae endmembers are spectrally similar to the degree that when either is combined with the same other endmembers, the resultant mixed spectra are very similar. At equal proportional cover, sand exerts great dominance on a mixed pixel with respect to high magnitude of reflectance and a flattening of spectral detail while the bleached coral spectra exerts dominance with respect to retaining spectral shape. As the number of endmember spectra included in the linear mixture increases, the maximum magnitude of reflectance decreases since the sand endmember's relative influence shrinks from 50% in the case of 2 endmembers to 20% in the case of 5 endmembers. Conversely, as the number of endmember spectra included in the linear mixture increases, the spectral shape appears to be increasingly dominated by the shape of the bleached coral endmember. In general, when there is a sand component, the overall magnitude of reflectance is greater, even when the presence of sand is restricted to only 25% cover. Since the living coral and benthic macroalgae endmembers are spectrally similar, when these are combined with each other or with other bottom types, discrimination is very difficult. The spectral characteristics of both seagrass and bleached coral seem to be strong enough to resist being overpowered by other spectra, such that discrimination may be possible when these bottom types are the dominant cover. The hierarchical cluster analyses performed on the pure endmember spectra and the linearly mixed spectra with endmembers combined in equal proportions indicate that, in general, if there is a sand component to the pixel, it will tend to dominate the overall reflectance signal. Mixed spectra with 2 endmembers combined tended to cluster with their component endmembers, suggesting that separating pure pixels from those with 2 bottom types present would be challenging. Mixed spectra with 3 endmembers present tended to cluster together with the pure endmember spectra excluded from that cluster, suggesting that once three bottom types are present, the spectral characteristics combine to meld semi-uniquely. Similarly, when 4 or 5 endmembers are linearly combined in equal proportions, the mixed spectra clustered together suggesting that the combination of the 4 or 5 endmembers has the effect of giving the spectra semi-unique characteristics. Of course, there are far more than 5 endmembers present in a coral reef ecosystem, and there is tremendous proven spectral variability within bottom type categories such that the endmember spectra used in this study are not representative of all study areas. The significance of this study, however, is the investigation of the manner with which these measured endmember spectra combine linearly in both equal and unequal proportions to create integrated mixed reflectance spectra.

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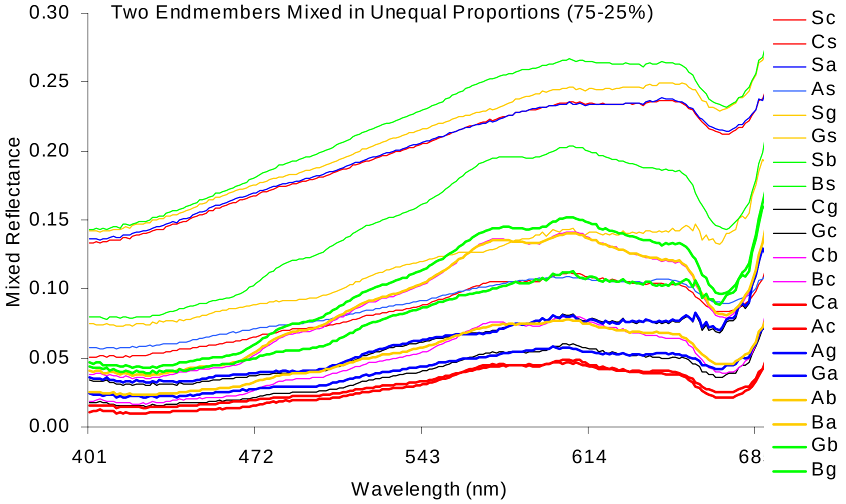

Figure 1. Mixed spectra resulting from disproportional mixing of 2 endmembers at a ratio of 75% (upper case letters in legend) to 25% (lower case letters) bottom type

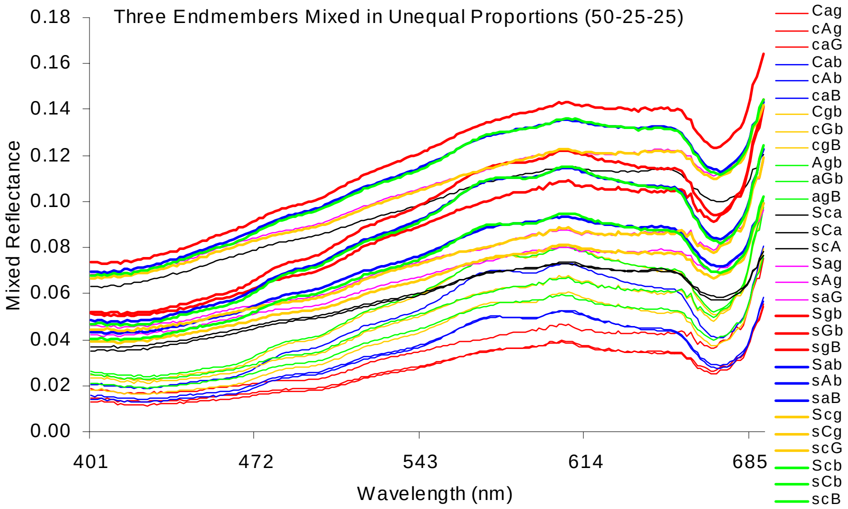

Figure 2. Mixed spectra resulting from disproportional mixing of 3 endmembers at a ratio of 50-25-25% where the upper case letter in the legend indicates 50% coverage of that bottom type and the lower case letter indicates 25% coverage of that bottom type

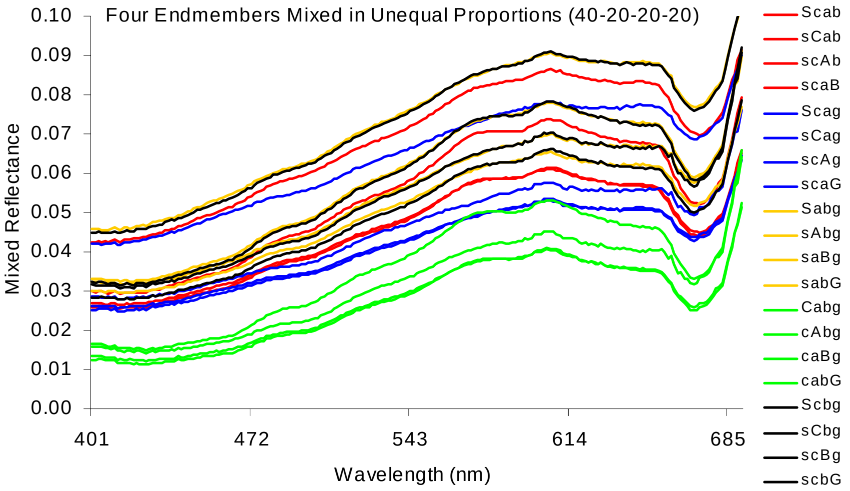

Figure 3. Mixed spectra resulting from unequal mixing of 4 endmembers at a ratio of 40-20-20-20% where the upper case letter in the legend indicates 40% coverage of that bottom type and the lower case letter indicates 15% coverage of that bottom type

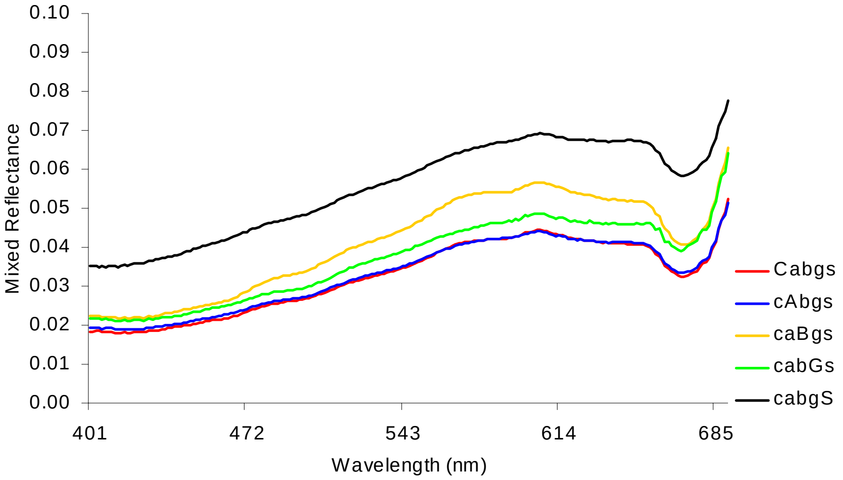

Figure 4. Mixed spectra resulting from disproportional mixing of 5 endmembers at a ratio of 40% to 15% where the upper case letter in the legend indicates 40% coverage of that bottom type and the lower case letter indicates 15% coverage of that bottom type

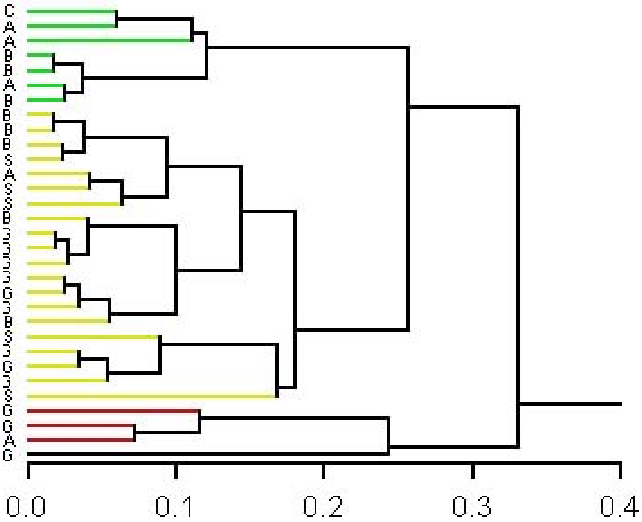

Figure 5. Cluster analysis dendogram with all pure endmembers plus all spectra mixed in equal proportions