MAPPING NON-NATIVE PLANTS USING HYPERSPECTRAL IMAGERY

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1. INTRODUCTION

One of the significant threats to global biodiversity and ecosystem functioning is the spread of invasive plant species (Mooney and Cleland, 2001). Continuing anthropogenic related disturbances such as land conversion, grazing, and habitat fragmentation, combined with international trade and climate change indicate that these trends are likely to continue (Zedler and Scheid, 1988). In this context, the major challenge for land managers and ecologists is how to effectively manage non-native plants to preserve native biodiversity. Being able to delineate the spatial extent and ascertain the severity or intensity of the invasion is essential for resource management (Byers et al., 2001). This information provides a baseline for monitoring future expansion, the effectiveness of control efforts, and assists in identifying targets for control activities, such as satellite populations and 'invasion fronts.'

Techniques such as remote sensing offer significant opportunities for providing timely information on invasions of non-native species into native habitats. To date, there have been two divergent approaches (Everitt et al., 1996, Dewey et al., 1991). The first approach uses imagery with a high spatial, but low spectral resolution, such as black and white or color infrared aerial photographs. These photographs have the benefit of being relatively cheap, large amounts of archival data are available for many sites, and photographs are available at hyperspatial resolutions (0.1–2 m). However, the major disadvantage is that they rely on the non-native plant possessing visually detectable unique characteristics, extensive manual labor for processing and, finally, the resolution means that it is only feasible to collect data over a relatively small spatial area. The second approach uses digital images with greater spectral resolution, although coarser spatial resolution have been utilized—predominantly various airborne or spaceborne multispectral instruments. The use of digital multispectral imagery offers the opportunity for automated image processing, access to recent historical data for time series analyses, and large spatial coverage. However, the spatial resolutions of these sensors, such as TM and AVHRR imagery, mean that invasive species populations can often only be detected once, dense and widespread (Carson et al., 1995). In addition, traditional classification techniques like isodata or maximum likelihood, usually identify vulnerable land cover classes, rather than the non-native species itself. Consequently, maps have only a general applicability.

The availability of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) imagery with both increased spatial, but in particular spectral, resolution offers an enhanced potential for mapping invasive species. Because of the large number of wavebands (224) image processing is able to capitalize on both the biochemical and structural properties of the target invader. However, to date, there has been little evaluation of different processing techniques suitable for imaging spectrometry data for identifying invasive plants. The objective of this research is to investigate the use of AVIRIS imagery to detect the invasive species iceplant (*Carpobrotus edulis*) and jubata grass (*Cortaderia jubata*). More specifically, to compare three techniques for processing the imagery: Minimum Noise Fraction, Continuum Removal, and Band Ratio Indices, and to critically evaluate the relative ease of processing and repeatability of each method.

2. METHODS

2.1. Study Site and Vegetation Descriptions

The study site for this research is Vandenberg Air Force Base (VAFB) located along the central coast of California. VAFB is 39,800 ha in size and is used primarily for developing and testing missiles and satellite launches for the Department of Defense and NASA. Consequently, there are still significantly sized intact blocks of land representing one of the last undeveloped open areas of coastal California (Keil and Holland, 1998). There are 836 vascular plants documented at VAFB, of which almost a quarter are invasive species. In particular, *Carpobrotus edulis* and *Cortaderia jubata* have successfully invaded two native community types: coastal dune scrub community and maritime chaparral (Keil and Holland, 1998). The coastal scrub community forms a relatively

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continuous cover of low to medium shrubs (< 1m tall), subshrubs, and herbs (Keil and Holland, 1998), and is dominated by California sagebrush (*Artemisia californica*), coyote bush (*Baccharis pilularis*), and mock heather (*Ericameria ericoides*). It is one of the most threatened community types in California, being rapidly fragmented and replaced by suburban developments, which makes the extensive iceplant invasion into remaining habitats of particular concern. The second community that iceplant is encroaching on is the maritime chaparral community characterized by broad-leafed and needle-leafed sclerophyllous shrubs, such as manzanita (*Arctostaphylos purissima, A.rudis*) and chamise chaparral (*Adenostoma fasciculatum*). An extensive area of this community—the Burton Mesa chaparral—is noted as one of the rarest and most threatened chaparral types in California, harboring extraordinary biodiversity (The Nature Conservancy, 1991). Invading iceplant, jubata grass, and other invasive species such as veldt grass (*Ehrharta calycina)* form mosaics with the native species. The focus of this research is the encroachment of iceplant and jubata grass into these native communities and specifically on the ability of AVIRIS to identify pixels of different densities of these species—the premise being that lower densities at the margins of the distribution, represent invasion fronts, and thus critical areas for management attention.

Iceplant (*Carpobrotus edulis*) (Figure 1) is native to South Africa and was introduced into California in ballast sand. By the 1950s it was used extensively for stabilizing land adjacent to roads. *C. edulis* is a succulent perennial forming mats up to 20 m wide and 50 cm deep (D'Antonio, 1993). The species' success is due to its tolerance of a range of soil moisture and nutrient conditions, and utilizing a number of mammals for seed dispersal (D'Antonio, 1993). Ecological impacts of iceplant include aggressive competition with native species, such as Tidestrom's lupine (*Lupinus tidestromii*), destabilizing native dune communities, and modifying soil pH. Economic impacts stem from the time and financial costs associated with both manual and mechanical control. Jubata grass (*Cortaderia jubata*), the second species of concern, is a perennial tussock grass from the Andes Mountains, characterized by huge creamy-pink plumes and long leaves (Figure 2). Introduced as an ornamental species it now dominates much of the coastal habitat of California. Jubata grass poses a significant threat to Mediterranean ecosystems because of its prolific wind dispersed seeds, tolerance of a broad range of habitats, and its competitiveness for light, moisture, and nutrients (Cowan, 1976).

2.2. Description of Fieldwork and Global Positioning System (GPS) Data Collection

Existing Geographic Information System (GIS) data layers were acquired from VAFB, including topographic maps, vegetation maps, road layers, and land use history, which were converted into a common Universal Transverse Mercator (UTM) projection. A field sampling methodology was designed and implemented in summer 2000 to coincide with the acquisition of the AVIRIS imagery. Sampling was undertaking in five community types identified *a priori*: intact coastal dune scrub, intact maritime chaparral, invaded scrub, invaded chaparral, and chaparral invaded by jubata grass. The location of the 352 fieldwork plots was random, but consideration was given to ease of access and location within the flightline. Field data was collected at three different scales to provide information from the plot through to the community level: measurements included percent cover by species, species height, type and size of disturbances, and soil characteristics. GPS readings (Trimble Pro-XRS, Trimble Navigation, Inc.) were taken of plot centers and around pure polygons of iceplant, jubata grass, and intact community types. Fieldwork also involved the acquisition of field-based reflectance spectra of the dominant native and non-native plant species and soil types in the area. Data were acquired at the time of the overflights using a GER 2500 (Geophysical Research, Corp.) field-portable spectrometer (400–2500 nm). Owing to almost continual coastal fog during the period around the overflight, only 80 individual spectra of target species at VAFB were acquired. AVIRIS data was acquired by the NOAA Twin Otter aircraft on 9 September, 2000 at 3,810 m, providing a nominal pixel resolution of 4 m.

2.3. Data Processing Techniques

The imagery was atmospherically corrected from radiance to reflectance with ACORN (Analytical Imaging and Geophysics LLC v.4) a commercial package based on MODTRAN, using the reflectance of target features from spectrometer data acquired in the field. The AVIRIS scenes were spectrally and spatially sub-setted to allow for rapid georeferencing and noisy bands were removed (ENVI software v.3.4; Research Systems Inc.). Masks were created to limit processing to vegetated areas - identified as pixels with an NDVI > 0.2, to reduce the number of classes in the classification process. GPS points and polygons of known community types and species were differentially corrected (Pathfinder Office v.2.8; Trimble Navigation, Inc.) and used to generate regions of interest (ROIs). These ROIs then served as training polygons for conducting supervised classifications.

Three processing techniques were compared: a supervised classification based on the results of a Minimum Noise Fraction, an unsupervised classification using the results of the Continuum Removal applied to the 932 nm water absorption feature (875 – 1032 nm), and finally a supervised classification performed on a dataset composed of selected Band Ratio Indices.

2.3.1. Minimum noise fraction classification

A Minimum Noise Fraction (MNF) was performed on each flightline to reduce and compress the data and to increase the speed of data processing. The MNF sequentially performs two Principle Component Analyses (PCA) on the data: the first separates white noise (i.e., uninformative data), the second recombines these bands into new composite bands which account for most of the variance in the original data (informative data). Based on the MNF output graph of eigenvectors and visually inspecting the new bands, a conservative noise floor was established and the first 12 bands were selected as inputs for the classification. The results of the MNF were georegistered and a maximum likelihood supervised classification performed. Twelve intact and invaded community classes were generated for VAFB, including five different densities of iceplant, three densities of jubata grass, and a class for intact scrub.

2.3.2. Continuum removal for water bands

The second technique investigated to classify specifically iceplant was a Continuum Removal of the water absorption bands, which was assumed to be particularly applicable to the fleshy succulent leaves of *C. edulis* (Figure 3). The Continuum Removal technique isolates spectral features and standardizes reflection across the liquid water absorption features so that they may be intercompared (Clark and Roush, 1984). The advantage is that values are independent of differences across the image such as illumination or shadow. The process involved spectrally subsetting 34 bands of the image; 17 around 932 nm (between the wavelengths 875–1032 nm) and 17 around 1155 nm (1070–1221 nm). Water absorption is calculated from the area under the absorption feature divided by the area under the continuum, resulting in a range of values from 0 to 1; the lower the value, the greater the absorption. This is illustrated in Figure 3, which shows a comparison of the reflectance spectra of pixels having two different densities of iceplant compared to a pixel of intact coastal scrub. The graph shows two distinctive absorptions for dense iceplant centered on the 932 nm and 1155 nm wavelengths. Visual inspection of the resulting images showed greater accuracy when using wavelengths centered around 932 nm than the 1155 nm feature due to the atmospheric water vapor absorption at 1240 nm. An unsupervised classification (K-means method) was then conducted using the derived image, classifying five community classes for VAFB.

2.3.3. Band ratios indices

Finally, use of selected vegetation indices that emphasize bands containing important biochemical and biophysical properties of the vegetation. Vegetation indices are clearly correlated with foliage chlorophyll absorption as well as Leaf Area Index, percent green cover and biomass, productivity, and photosynthetic capacity (Ustin et al., 1999). The NDVI is perhaps the most well known of these vegetation indices, while the water band index has been shown to be a good indicator of leaf and canopy water content (Peñuelas et al., 1997; Serrano et al., 2000), and the red-edge spectral parameters for chlorophyll concentration (Zarco-Tejada and Miller, 1999). Even so, using a combination of vegetation indices for a classification has received limited application for ecological studies (Fuentes et al, 2001). We seek to assess how well a land cover classification based on data from this technique compares to the results using MNF and Continuum Removal approaches. Five indices were calculated on the calibrated image, capturing NDVI, water absorption, greenness, and pigment properties (Table 1), and combined into a single image. A maximum likelihood supervised classification was performed on the results.

3. RESULTS

A visual comparison of the three classification results (Figures 4, 5, 6) shows iceplant is clearly distinguished in all analyses with a similar spatial configuration: highest densities parallel to the coastline and tapering off with increasing distance inland (in a northeast direction). Separation of different density levels of iceplant is evident in all three images. Field validation was undertaken in August 2001 to perform ocular cover estimates by species of the classification performance and also acquire GPS polygons for a formal verification of image classes.

A total of twenty-three regions of interest were acquired during the second period of fieldwork across intact scrub and iceplant at four different densities (≤ 50%, 51-75%, 76-90%, 91-100%) to provide the reference data for validation (Table 2). An evaluation of the three images for simply classifying presence/absence of iceplant of any density had very high success: 99% for the MNF, and 98% for the Continuum Removal and Band Ratio techniques—indicating that the distinctive succulent characteristics of iceplant are being identified in each method. It is more informative; however, to compare the accuracy assessment for the intact scrub class and each of the different densities of iceplant classes in turn using a confusion matrix (Congalton, 1991). For intact scrub and any density of iceplant the Band Ratios and MNF results achieved comparable levels of accuracy: 92% and 91% respectively. When this assessment was limited to intact scrub and iceplant with densities > 50% and then further refined to intact scrub and iceplant density > 75% the Band Ratios technique performed marginally better in both cases: 90% v. 88% and 90% v. 86%. The Continuum Removal approach also performed well - achieving 89% and 84% respectively. But in a comparison of intact scrub and the densest class of iceplant (> 90%) the MNF approach performed best.

Significant differences between the three approaches were only revealed by looking at the overall accuracy across all four density classes: intact scrub, iceplant 51%-75%, 76%-90%, and 91%-100%. In this case, the MNF result was superior, achieving a 55.2% overall accuracy and a kappa value of 0.36, compared to Band Ratios with 44% accuracy (kappa = 0.26), and finally Continuum Removal with a 39% accuracy (kappa = 0.20%). It is interesting to note the percent of iceplant pixels that were confused as scrub pixels is relatively low for all methods, on average 8% and 4%, and 13% for MNF, Band Ratios, and Continuum Removal respectively. This illustrates that the primary source of confusion is in classifying different densities of iceplant, rather than confusing iceplant with scrub pixels.

Although no formal accuracy assessment was performed for the results of the jubata grass classification, fieldwork verification indicated that the results from the MNF and Band Ratio Indices performed similarly. The MNF method did distinguish three density classes although it overestimated the total extent, in some cases confusing jubata grass with areas of eucalyptus trees (Figure 5). The Band Ratio technique provided a more realistic estimate of extent of jubata grass (Figure 6), identifying the major infestations in the northeast corner of the image where jubata grass has rapidly invaded areas of disturbed chaparral.

4. DISCUSSION

Effective management of invasive species requires accurate knowledge of their spatial distribution and density, which all three processing methods succeeded in capturing, producing some encouraging results. The following discussion evaluates the three methods in terms of accuracy, logistics of processing, and ease of interpretation.

The techniques were extremely successful in detecting the presence of iceplant and jubata grass. However, the MNF and Band Ratio techniques were better able to distinguish different densities of iceplant. This is because these two techniques utilize significantly more information from the image. The MNF classification utilized the 12 most informative transformed bands while the Band Ratios used five key indices capitalizing on the physiological properties of the species. In contrast, the Continuum Removal method relies solely on the seventeen bands around the 932 nm water absorption feature, which explains why it performed relatively well for classifying areas of dense iceplant, but poorly when the iceplant forms more complex mosaics with the scrub species. The confusion matrices demonstrate that the MNF and Band Ratio methods performed equally as well, one disadvantage of the Band Ratio classification is that it produced a speckled image with single and double pixels scattered throughout. Even after a sieving and clumping of the image was performed to generalize the spatial patterns, the accuracy only increased by 1.8%. This improvement in accuracy is not significant and not warranted at the expense of losing information, particularly along critical invasion boundary areas. Also, a proportion of the inaccuracies occurring in the classification are most likely attributable to a combination of errors in both the georegistration of the image and the accuracy of the GPS polygons despite differentially correcting the acquired positions.

Interpretation of the different techniques varied markedly. The MNF method was the most difficult to interpret. Although values from each of the eigenvectors generated by the PCA can be graphed, interpreting the basis of spectral variation was difficult. Even in wavelengths of water absorption there were no consistently high eigenvalues. Alternatively, using the Band Ratios has the advantage of being more intuitive, highlighting ecophysiological information about the vegetation that can be readily related to the data collected in fieldwork.

From a processing perspective, the Continuum Removal method was by far the most efficient, which involved running a single standard procedure in the ENVI software. In contrast, the MNF procedure was time and processing intensive, taking several hours to run and creating a 1.8 GB file for each of the two processing modes. In terms of identifying repeatable methods for future use, the Continuum Removal and Band Ratio techniques are easily transportable for images acquired at different times or over different geographic areas. In contrast, the MNF approach cannot be applied to new data as it is unique to the variance of each flightline.

In brief, the Continuum Removal method is a reliable method for depicting presence/absence of iceplant within a scrub community. Coupled with this is the ease and efficiency of processing, which makes it an attractive approach for inexperienced users of hyperspectral data. Such a method is also likely to be applicable to other invasives such as the giant reed (*Arundo donax*) which has a high water content in the stem. In contrast, the MNF and Band Ratio approaches were most accurate in delineating the spatial extent and density of iceplant and jubata grass. This might be particularly important for management activities, where the early detection of iceplant encroachment into endangered native scrub communities is important for prioritizing control methods and activities. By using field derived polygons as inputs for the supervised classification, these techniques also had the additional advantage of classifying all communities across the image.

Land managers wishing to use imagery for mapping and monitoring invasive plants have a tradeoff between spatial and spectral resolutions and costs. At one extreme the virtues of low spectral, high spatial resolution imagery (aerial photos) are well known, while this research illustrates that AVIRIS imagery offers improved opportunities for mapping invasive plants in a matrix of other vegetation types. The improved spectral resolution of the AVIRIS imagery permits identification of vegetation characteristics that are not possible using multispectral wavebands traditionally used in remotely sensed imagery. However, one interesting question is whether further improvements in resolutions are necessary. Interestingly, we found for the target species that it was possible to achieve adequate results using only a portion of wavebands available (Band Ratios and Continuum Removal), which could potentially mean fewer bands need to be acquired and processed, with possibly lower associated costs. However, the specific bands needed to map the full range of land cover types may still require a hyperspectral imager. Similarly, the 4 m resolution of the AVIRIS data also proved sufficient for detecting *C. edulis* and *C. jubata*. Despite the common belief that higher spatial resolutions are necessarily better, in this case it might have produced only marginally improved results, but disproportionately increased the computing and processing requirements. Although the current costs of hyperspectral data means that frequent acquisitions over large areas are probably not feasible, it is a highly appropriate technique for monitoring hotspots of invasions along selected transects. In addition, various data nesting strategies might be employed to optimize the spatial and spectral resolutions required.

5. CONCLUSIONS

This research describes encouraging findings for using hyperspectral imagery to map iceplant and jubata grass in California's Mediterranean-type ecosystems. The next step is to evaluate how well these approaches can be applied to invasions of these species in different habitat types and also their ability to detect other invasive species. Given the ecological and economic impacts of invasive plants, together with their rates of spread, they constitute one of the most critical issues for many land managers (Goodall and Naude, 1998). The immediate benefit of this research has been to contribute to the knowledge base of land managers at VAFB by providing improved information on the spatial extent and density of the iceplant and jubata grass, that will lead to better protection of the native biodiversity. Additionally, the project evaluated three different methods for processing AVIRIS imagery which can now be tested in other geographic locations or for other invasive species.

6. ACKNOWLEDGEMENTS

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8. FIGURES AND TABLES

Fig. 1. Iceplant

Fig. 2. Jubata grass

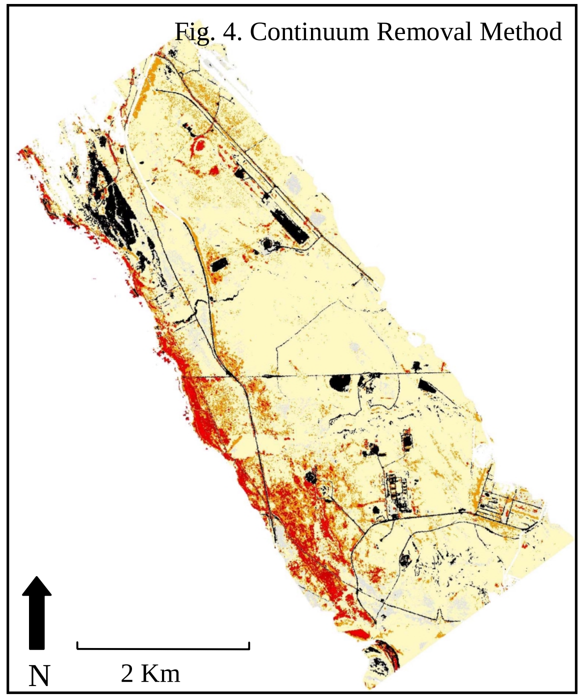

Fig. 4. Continuum Removal Method

Intact scrub
Iceplant 91-100%
Iceplant 76-90%
Iceplant 51-75%

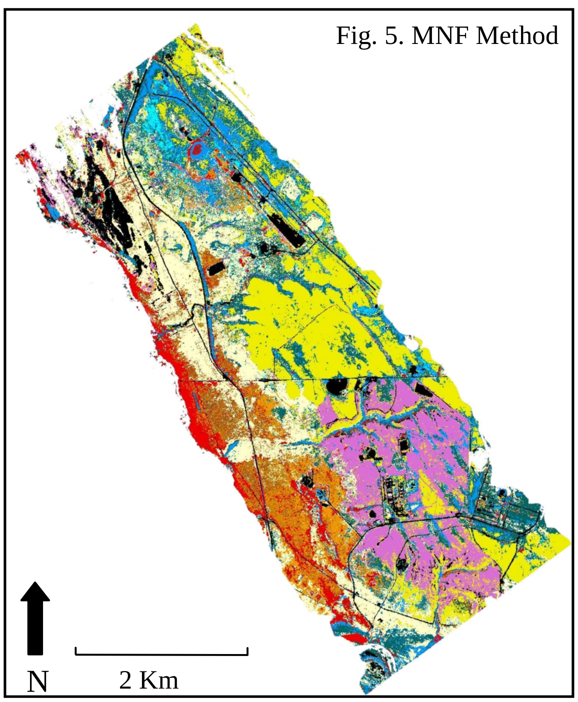

Fig. 5. MNF Method

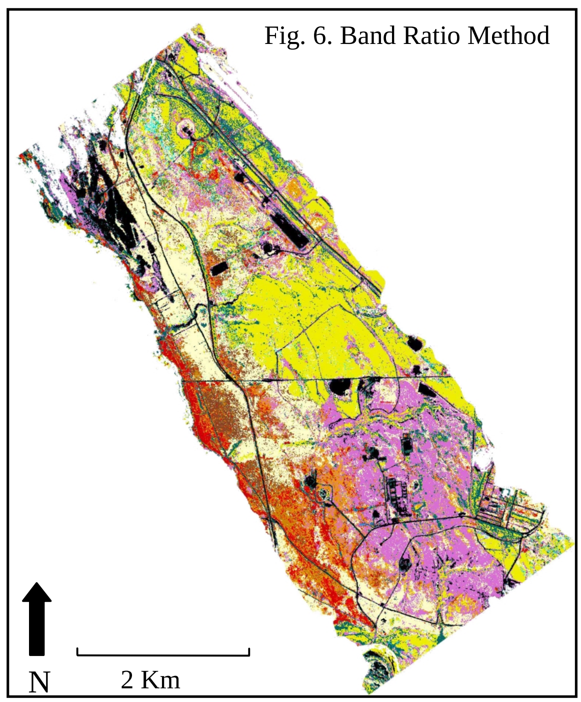

Fig. 6. Band Ratio Method

Intact scrub
Iceplant 91-100%
Iceplant 76-90%
Iceplant 51-75%
Iceplant 26-50%
Iceplant 0-25%
Jubata grass 0-33%
Jubata grass 34-66%
Jubata grass 67-100%
Chaparral with Iceplant
Intact chaparral
Masked

Table 1. Wavebands used to calculate vegetation indices (adapted from Fuentes, 2001)

Index	Bands	Wavelengths	Source
Red/green ratio	Chlorophyll	683/510	Gamon and Surfus (1999)
Index of pigment	Pigment	750/710	Gamon and Surfus (1999)
Index of water 1	Water content	970/900	Penuelas et al. (1997)
Index of water 2	Water content	1193/1126	Image inspection
NDVI	Green vegetation	895-675/895+675	Modified from Tucker (1979)

Table 2. Summary of confusion matrix results for the three methods

Class	MNF	Kappa	Continuum Removal	Kappa	Band Ratios	Kappa
Single Class						
Iceplant 0-100%	98.98%	N/A	97.95%	N/A	97.98%	N/A
Scrub & 1 iceplant class						
Scrub and iceplant 0-100%	91.3%	0.50	N/A	N/A	92.3%	0.51
Scrub and iceplant > 50%	87.5%	0.44	89.1%	0.60	90.3%	0.50
Scrub and iceplant > 75%	86.4%	0.55	84.9%	0.63	89.7%	0.63
Scrub and iceplant > 90%	82.4%	0.56	77.5%	0.58	80.3%	0.57
Scrub & all 3 density classes	55.2%	0.36	38.5%	0.20	44.2%	0.26

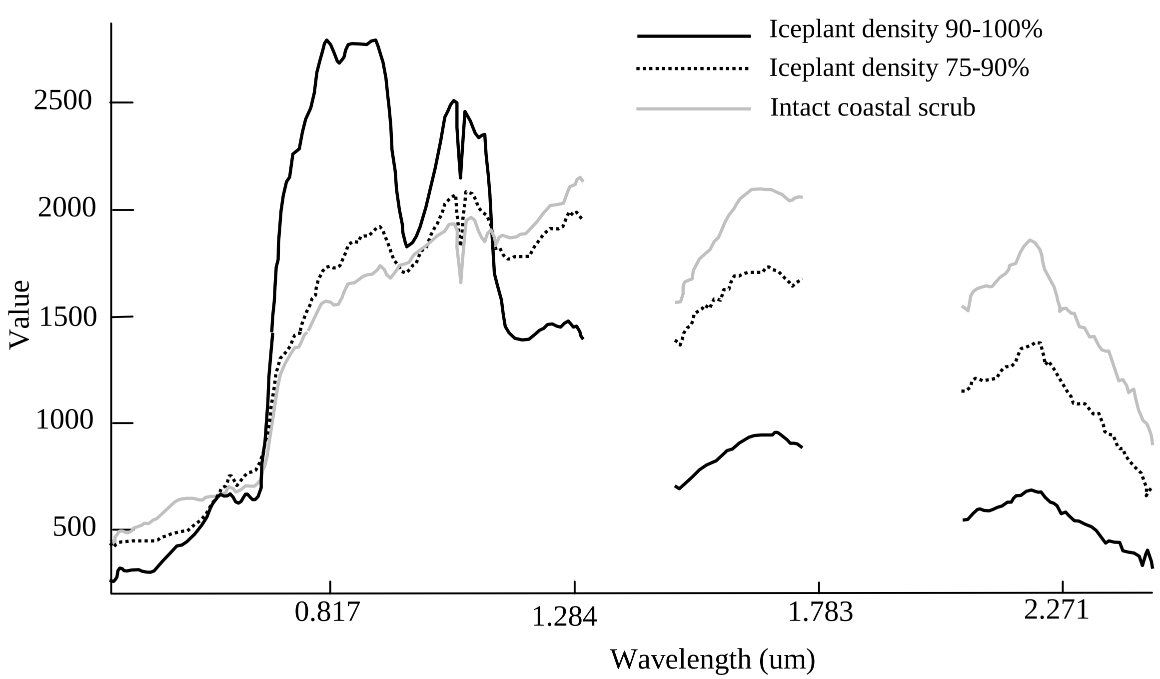

Fig. 3. Reflectance Spectra Showing Absorption in the Water Band