SPECTRAL UNMIXING FOR MONITORING MINE TAILINGS SITE REHABILITATION, COPPER CLIFF MINE, SUDBURY, ONTARIO *

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ABSTRACT

Hyperspectral imagery from the Compact Airborne Spectrographic Imager (*casi*) was used to characterize sulphide mine tailings at the Copper Cliff mine in Sudbury, Ontario. The objective of the study was to evaluate the usefulness of high spatial and spectral resolution data and their analysis techniques for characterizing mine tailings sites and monitoring their restoration. Flight data were acquired in late August 1996 in 72 contiguous 9 nm wide spectral bands from 400 nm to 950 nm along with a detailed ground survey. Image data were processed and analysed using the Imaging Spectrometer Data Analysis System (ISDAS) developed at the Canada Centre for Remote Sensing. The image data were classified using unconstrained linear spectral unmixing. Validation of the unmixing results was achieved by correlating image fractions to fractions measured on the ground. Five end-members were selected: oxidized tailings, lime, green vegetation, fresh and contaminated water. Results show that image fractions of green vegetation and lime are well correlated with the ground fractions (r-square = 0.96 and 0.92). The lower r-square (0.65) of the oxidized tailings endmember could be attributed to the variable concentrations of oxidizing agents (various degrees of oxidation) in the tailings which are difficult to assess visually.

1.0 INTRODUCTION

Environmental restoration of sulphide mine tailings is a growing concern for many mine operators. Complex chemical weathering reactions initiated when tailings are exposed to air and water lead to the production of sulphuric acid (acid mine drainage) which is capable of liberating the heavy metals already in great amount within the tailings (The Office of Surface Mining, 1997). It is difficult to revegetate such sites because of their high level of contamination in heavy metals and other toxic substances related to mining exploitation. One technique used to reduce the level of acidity over the tailings and aid revegetation is the spreading of lime. This allows certain tolerant species to initiate the revegetation process. The success of mine tailings revegetation greatly depends on the quality of tailings monitoring in order to ensure an efficient process on a long term basis.

The main objective of the study was to evaluate the usefulness of high spatial and spectral resolution data and their analysis techniques for characterizing mine tailings sites and monitoring their restoration. In a previous study (Lévesque et al., 1997), promising qualitative results were obtained using a spectral matching technique. The specific objective of this study is to quantify the results in order to improve monitoring of the mine tailings area.

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Hyperspectral imagery from the Compact Airborne Spectrographic Imager (*casi*) in the visible and near infrared was used to characterize sulphide mine tailings at the Copper Cliff tailings impoundment area in Sudbury. This site was chosen because of its well initiated revegetation program by INCO (Peters, 1988) and earlier work conducted by Singhroy (1995a, 1995b, and 1997). It contains a large variety of mine tailings, different levels of vegetation regrowth, as well as limed and non-limed areas. Image data were processed and analysed using the Imaging Spectrometer Data Analysis System (ISDAS) at the Canada Centre for Remote Sensing (Staenz, 1997a). The image was roll corrected, converted to reflectance and classified using unconstrained linear spectral unmixing. Validation of the unmixing results was achieved by correlating image fractions to fractions visually assessed on the ground.

2.0 METHODOLOGY

2.1 GROUND SURVEY

Field spectra were collected using a GER3700 spectrometer operating between 400 nm and 2500 nm. Spectra of fresh and oxidized mine tailings of different compositions (pyrite, pyrrhotite), green and dry vegetation, lime, and rock were collected in August 1996 during the same time as the flight. Ground fractions of green vegetation, lime and oxidized tailings were estimated visually at known pixel locations. The ground spectra, as well as the visual estimation of endmember fractions acquired in the field, were used to validate the results of the spectral unmixing.

2.2 IMAGE DATA

High spatial and spectral resolution *casi* radiance data were acquired on August 24, 1996 in 72 contiguous 8.7 nm wide spectral bands covering a wavelength range from 407 nm to 944 nm. Pixel size is 2.3 m in the accross track direction and 4.3 m in the along track direction. The casi sensor configuration parameters are summarized in Table 1. Only wavelengths between 450 nm and 900 nm were used because of the drop-off of the responsivity of the silicon detector at both ends of the spectrum.

Table1. Sensor configuration

Spectral coverage	407-944 nm
Number of bands	72
Spectral sampling interval	7.6 nm
Bandwidth at FWHM*	8.7 nm
Sensor altitude above ground	1905 m
Ground resolution: across track	2.3 m
along track	4.3 m
Width of image	406 pixels

* FWHM: full Width at Half Maximum

2.3 PRE-PROCESSING OF IMAGE DATA

A roll correction was applied using the navigation data to remove most significant aircraft motion effects from the imagery. Surface reflectance was retrieved using a look-up table (LUT) based approach implemented in ISDAS (Staenz et al., 1997b). The LUT was generated using the MODTRAN3 radiative transfer (RT) code. The RT code input parameters are summarized in Table 2. After atmospheric correction, an ISDAS algorithm based on spectrally flat targets was used to remove any lingering systematic atmospheric or sensor effects in the data. Surface reflectance retrieved with this procedure is shown in Figure 1 for a green vegetation target.

Table 2. Input parameters for the MODTRAN3 runs

Atmospheric model	Mid-latitude summer
Aerosol model	Continental (rural)
Date of overflight	24-Aug-96
Solar zenith angle	35.5º
Solar azimuth angle	176º
Sensor zenith angle	Variable
Sensor azimuth angle	Variable
Terrain elevation	0.3 km
Sensor altitude above sea level	2.21 km
Water vapor content	2.31 g/cm^2
Horizontal visibility	50 km

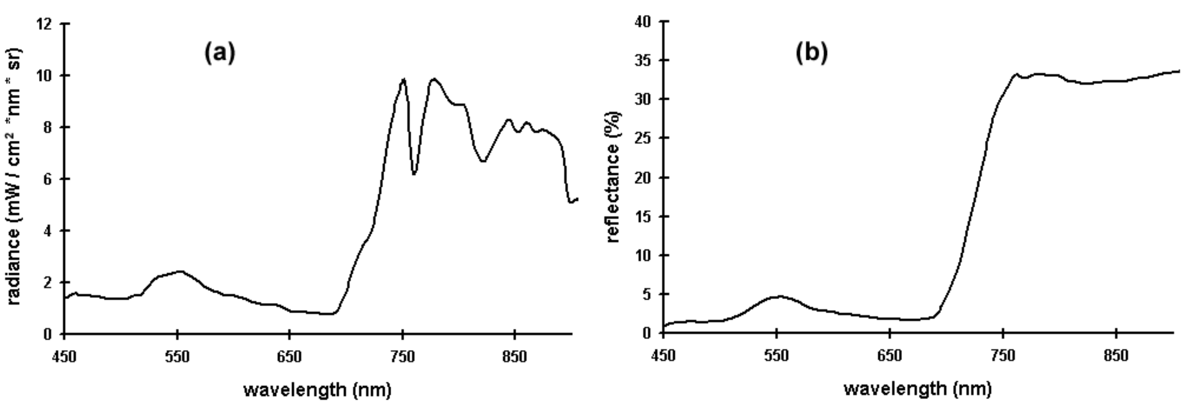

Figure 1. *casi* spectra of a green vegetation target: (a) radiance, (b) reflectance.

2.4 SPECTRAL UNMIXING

The unconstrained linear unmixing was performed on the *casi* data cube using an algorithm implemented in ISDAS (Szeredi and Staenz, 1997, Boardman, 1989, 1990). The method decomposes the image spectra into a series of endmember fractions. The end products are maps of fractional abundance of the endmembers. Endmembers were selected from the image using the three first principal components (PC) which respectively account for 77%, 21% and 1% of the variability in the data set. Endmembers are located at the extremities of the scatter plot when two PCs are plotted against each other and represent the purest pixel spectra. Five endmembers could be identified using the first three PCs (Figure2): lime, green vegetation, oxidized tailings, water 1, and water 2 which is highly contaminated by sewage, tailings, and lime.

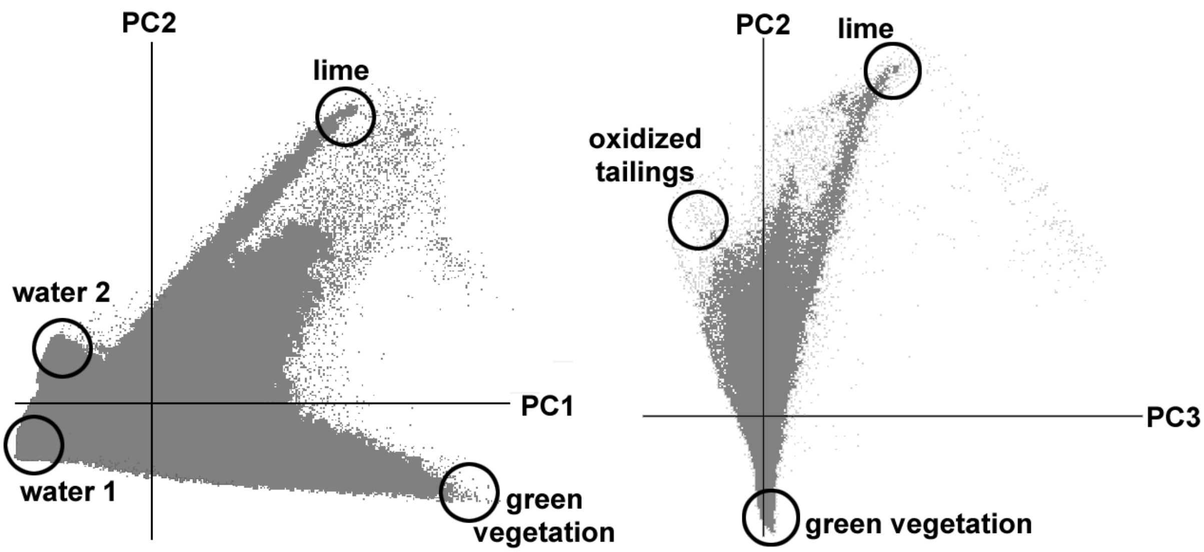

Figure 2. Scatter plots of PC1 versus PC2 and PC2 versus PC3 showing the five endmembers.

The spectra of the five endmembers from the image are illustrated in Figure 3a. Figure 3b shows the spectra of three of the endmembers (lime, green vegetation, oxidized tailings) as measured on the ground with the GER3700. The image and ground spectra appear similar for those three endmembers. Since validation data were only collected on the land, the unmixing results presented in this paper concentrate on these three endmembers.

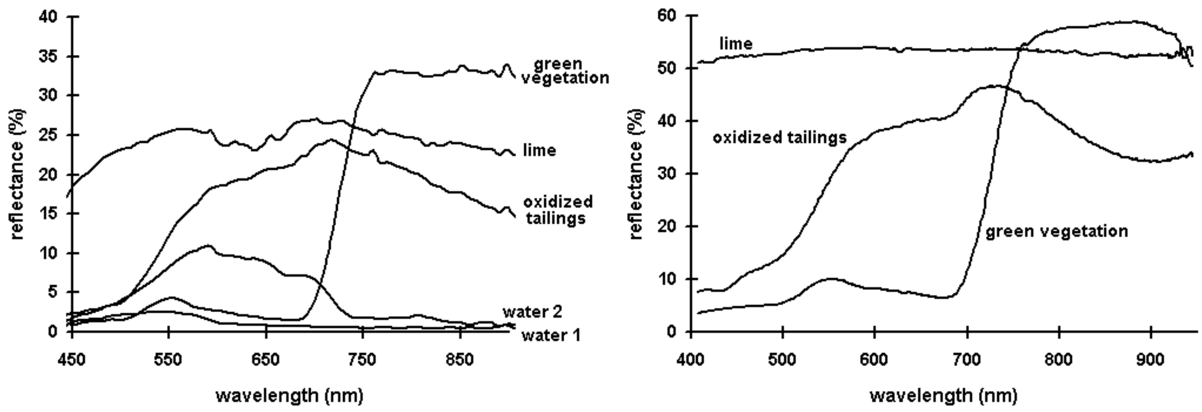

Figure 3. *casi* reflectance spectra(a) and GER reflectance spectra (b).

2.5 VALIDATION OF RESULTS

The results were validated by correlating the image fractions to the fractions visually assessed on the ground at 34 known pixel locations varying between 10 m X 10 m and 20 m X 20 m. Fractions of lime, green vegetation, and oxidized tailings were estimated at the 34 sites. Image fractions were averaged over the pixels corresponding to the surface of the site on the ground.

3.0 RESULTS AND DISCUSSION

Figure 4 shows the original image at 720 nm and the three endmember fraction maps (lime, green vegetation, oxidized tailings).

Figures 5, 6 and 7 illustrate the relationship between image-based fractions and ground-based fractions for the three endmembers lime, green vegetation, and oxidized tailings. The lime and green vegetation endmembers (Figures 5 and 6) show strong relationships between image and ground fractions (r-square = 0.92 and 0.96 respectively). Figure 7 shows that image oxidized tailings fractions do not relate as well to their ground fractions (r-square = 0.65). This could be attributed to the variable concentrations of oxidizing agents in the tailings. According to Peters (1988), tailings composition, and therefore their oxidizing potential, varies according to the nature of the ore being mined at the time it was produced and dumped. It is almost impossible to average its composition over an area. Unlike tailings, lime and green vegetation are easy to assess visually because of their contrasting colours compared to the surrounding environment (white and green). Oxidized tailings on the other hand vary greatly in colours, ranging from bright yellow to dark brown, due mostly to variations in its composition and its moisture content. For these reasons, the ground signature of oxidized tailings differed significantly from the oxidized tailings endmembers signature extracted from the image.

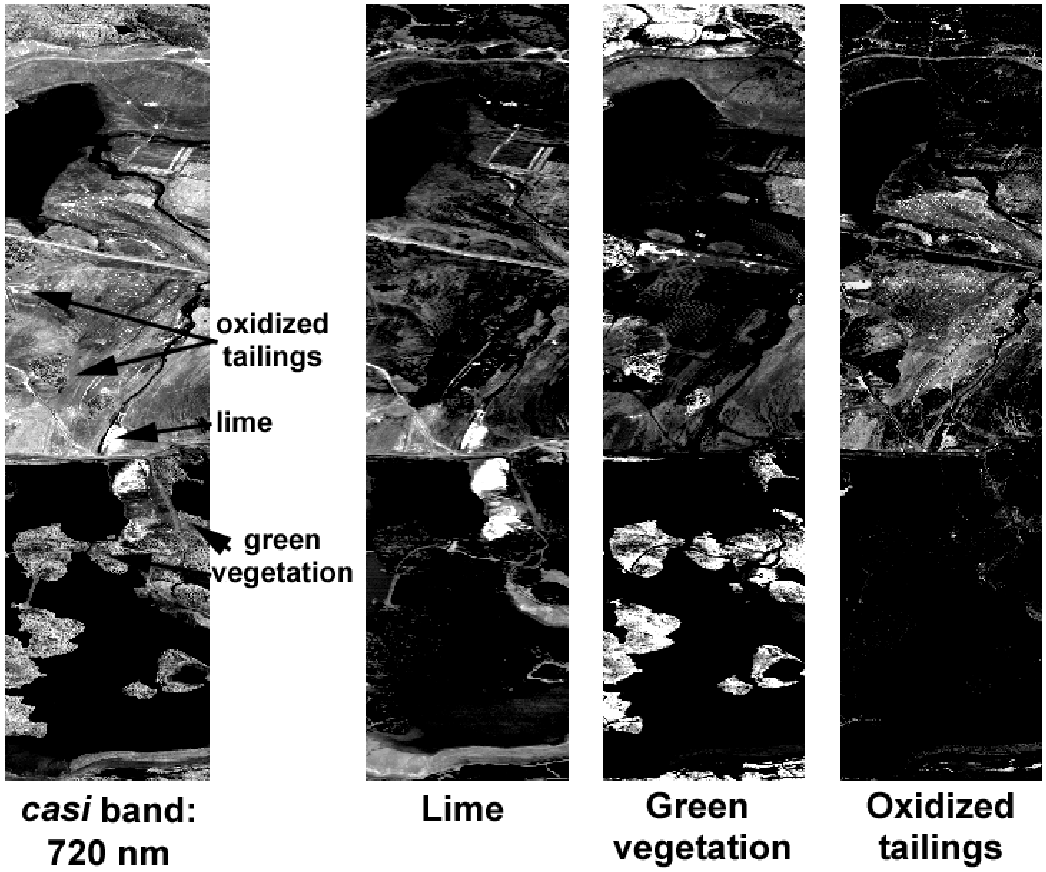

Figure 4. Original *casi* image (band 720 nm) and fractional abundance maps of the three endmembers, lime, green vegetation, and oxidized tailings.

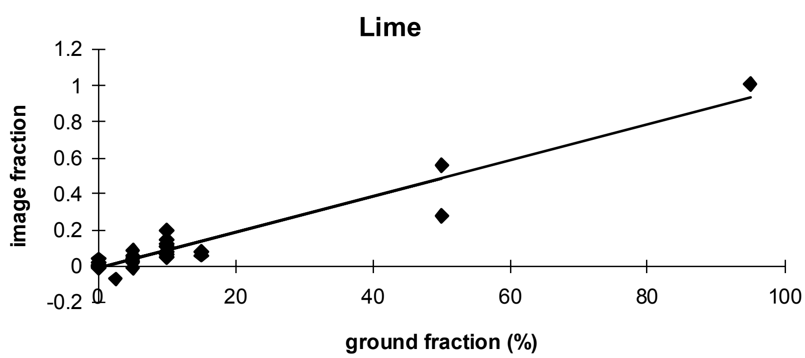

Figure 5. Correlation between ground and image lime fractions (r-square = 0.92).

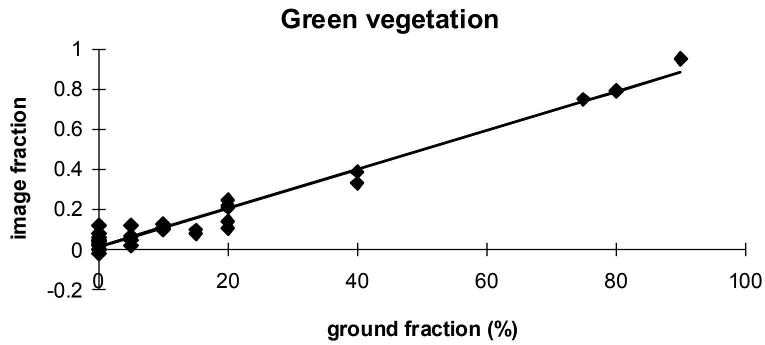

Figure 6. Correlation between ground and image green vegetation fractions (r-square = 0.96).

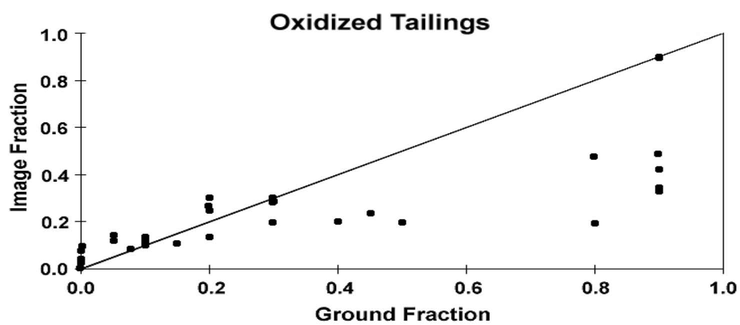

Figure 7. Correlation between ground and image oxidized tailings fractions (r-square = 0.65).

Since tailings composition is so variable over an area, knowing the proportion of lime and vegetation over the tailings area from year to year can help the end user (INCO) to determine areas where lime spreading and vegetation seeding is needed. Not enough or too much lime can both lead to unsuccessful revegetation.

4.0 CONCLUSIONS

This study has demonstrated the usefulness of hyperspectral *casi* data to quantify three types of surfaces at a mine tailings site (lime, green vegetation, and oxidized tailings). Although image oxidized tailings fractions do not relate as well as lime and green vegetation fractions to the ground fractions, their knowledge is less critical for the monitoring of a successful revegetation process as long as the fractions of lime and green vegetation can be well quantified.

5.0 AKNOWLEDGEMENT

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