REMOTE MINE SITE REHABILITATION MONITORING USING AIRBORNE HYPERSPECTRAL IMAGING AND LANDSCAPE FUNCTION ANALYSIS (LFA)

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ABSTRACT:

Landscape Function Analysis (LFA) is an environmental monitoring technique which is internationally recognized as a method of measuring and monitoring ecosystem function and rehabilitation progress. Airborne hyperspectral data were used to generate maps of the three Landscape Function Analysis (LFA) Indices over a 5 x 20 km area of a rehabilitated bauxite mine in southwestern Australia. The technique involved measuring field spectra of 35 LFA sites and generating Final Regression Coefficients using partial least squares analysis for the three LFA Indices, *Stability, Infiltration* and *Nutrient Cycling*. Both field and airborne spectral data were used in the calibration dataset, as the ground based sampling technique was not able to capture the information on the crowns of the tall eucalypts in rehabilitation older than eight years of age. The Final Regression Coefficients were applied to the airborne hyperspectral imagery to produce LFA Maps with good correlations to the field LFA measurements (*Stability* r^2=0.76, *Infiltration* r^2=0.67 and *Nutrient Cycling* r^2=0.71 for n=15). The results demonstrated that airborne hyperspectral data could be reliably used to derive spatially continuous LFA maps over forest rehabilitated after bauxite mining in the Darling Range of Western Australia.

1. INTRODUCTION

Routine collection of biophysical measurements allows the gathering of essential information required to demonstrate to the regulators that the natural environment is not adversely impacted by exploration and mining. Currently, the majority of information is obtained via traditional methods, which primarily rely on point measurements and can be a labour intensive exercise. Sampling design for traditional methods is also somewhat fraught, because of time and technically difficult constraints on the scale of the work that needs to be performed. Remoteness, landform-related inaccessibility and cultural or environmental sensitivities can also make these measurements not only difficult but also spatially non-representative. Therefore, there is a requirement in the Australian and international mining community for operational, cost-effective techniques that can routinely provide objective and accurate environmental measurements, in a non-invasive and spatially-comprehensive manner.

This research demonstrates the ability of airborne hyperspectral imagery to remotely map and monitor the rehabilitation of bauxite mining in eucalypt woodlands of southwestern Australia for environmental management. This was performed by developing a remotely sensed method of deriving ecosystem indicators using the Landscape Function Analysis (LFA) technique. Landscape Function Analysis (Tongway & Ludwig, 2006) is an environmental monitoring technique which is internationally recognized as a method of measuring and monitoring ecosystem function and rehabilitation progress. It is the synthesis of considerable published material from a variety of sources, based mainly on processes involved in surface hydrology (*e.g.* rainfall infiltration and runoff, erosion, plant growth and nutrient cycling) (Tongway & Hindley, 2003). The limiting factor of this technique is the spatial scale at which it is performed, typically on transects between 20 and 100 m long, and its labour intensity. Airborne hyperspectral imaging offers a method of completely measuring large areas at high spatial resolution (<5 m), enabling the discrimination of ground cover as well as the quantification of surface properties.

1.1 Location

The study was performed in the southwestern region of Australia (Figure 1), where bauxite mining and subsequent rehabilitation of the eucalypt woodland has been ongoing for over 30 years. Bauxite ore is sourced from extensive deposits along the Darling Range within managed natural conservation reserves. The shallow bauxite ore is extracted by strip mining after clear felling of the forest (Gardner, 2001). Commodity reserves are sufficient to last more than 50 years at current production levels.

Figure 1 Location of the study area in the bauxite-rich Darling Range of southwestern Australia.

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One of the conditions placed on the bauxite mining companies is the demonstration of compliance to environmental regulations, such as the requirement that the forest be re-established to a functional self-sustaining state. The eucalypt woodland consists of jarrah and marri forest (Eucalyptus marginata and Corymbia calophylla) growing within laterite gravels and indurated duricrusts (Bell & Heddle, 1989).

The climate of this region is warm Mediterranean with a winter dominant west to east rainfall gradient of 1300 mm pa to 700 mm pa (Heddle *et al.*, 1980). The rehabilitation practices used by the bauxite mining companies are documented by Ward *et al.* (1996).

2. METHODOLOGY

2.1 Instruments

The instrumentation used for this research consisted of a field spectrometer and an airborne hyperspectral sensor. Both instruments measured reflected light within the visible to shortwave infrared (SWIR) wavelength region.

A FieldSpec® Pro Full Range spectrometer manufactured by Analytical Spectral Devices (http://www.asdi.com) was used for the collection of field measurements and calibration of the airborne hyperspectral data. The ASD FieldSpec® Pro FR operates within in the spectral range of 350 - 2500 nm (visible to shortwave infra-red), with a spectral resolution of 3 nm at 700 nm and 10 nm at 1400/2100 nm, at sampling intervals of 1.4 nm between 350 - 1050 nm and 2 nm between 1000 - 2500 nm (Hatchell, 1999). Measurements were made in the field with the bare fibre optic cable giving a full angle cone of acceptance field of view (FOV) of 25°. An integration of 60 measurements was used in the field and reference measurements of a 0.3 x 0.3 m Spectralon™ plate were collected every 6 measurements or more frequently if atmospheric conditions changed.

The Hyperspectral Mapper (HyMap) instrument (Cocks, *et al.*, 1998), manufactured by Integrated Spectronics and operated by HyVista (www.intspec.com, www.hyvista.com), was used to collect the airborne hyperspectral data. The instrument acquires 128 bands (which may be reduced down to 125 bands after calibration) across the reflective solar wavelength region of 450 – 2500 nm. The sensor has contiguous spectral coverage (except in the atmospheric water vapour bands) with bandwidths between 15 – 20 nm. The sensor operates in a three-axis gyro stabilised platform to minimise image distortion due to aircraft motion. It is also fitted with a differential global positioning system and an integrated inertial monitoring unit to allow the production of geographically-located images. The sensor is fully calibrated at HyVista's laboratory before each campaign, ensuring laboratory-grade spectral and radiometric accuracy with a signal to noise ratio of greater than 500:1.

2.2 Landscape Function Analysis (LFA)

Landscape Function Analysis (LFA) uses visual assessments of soil surface processes that gauge how effectively a hill slope is operating as a biophysical system. The surface assessments consist of eleven Soil Surface Condition Indicators (SSCIs) covering both physical and biological processes. Each observed SSCI focuses on a specific process related to the flux or use of vital resources by plants. The SSCIs and related processes are shown on Table 1.

Indicator	Process Addressed
1. Soil cover	Rain-splash erosion
2.Basal cover of perennial grass and/or canopy cover of shrubs and trees	Below-ground biological activity
3.Litter cover, origin and degree of decomposition	Decomposition and nutrient cycling of surface organic matter
4.Cryptogam cover	Surface stability, resistance to wind and water erosion and nutrient availability
5. Crust broken-ness *	Wind ablation or water erosion
6. Erosion type and severity	Nature and severity of current soil erosion features.
7. Deposited materials	Off-quadrat soil stability
8. Microtopography (surface roughness)	Water infiltration, flow disruption, seed lodgement.
9. Surface resistance to disturbance	Effect of mechanical disturbance.
10. Slake test	Soil stability/dispersiveness when wet
11. Soil texture	Infiltration rate and water storage.

Table 1: Soil Surface Condition Indicators (SSCIs) with their respective process-based interpretations. Complete protocols for assessing these indicators are in Tongway & Hindley (1995) pages 25-32.

Figure 2 shows how combinations of the eleven SSCIs are used to derive three LFA Indices, namely: soil *Stability*; *Infiltration*; and *Nutrient Cycling*. These indices express the edaphic habitat quality and have significance for monitoring in the following manner:

1. *Stability* - The ability of the soil to withstand erosive forces and to reform after disturbance;
2. *Infiltration* - How the soil partitions rainfall into soil-water (water available for plants to use), and runoff water which is lost from the local system, or may transport material away; and,
3. *Nutrient Cycling*- How efficiently organic matter is cycled back into the soil.

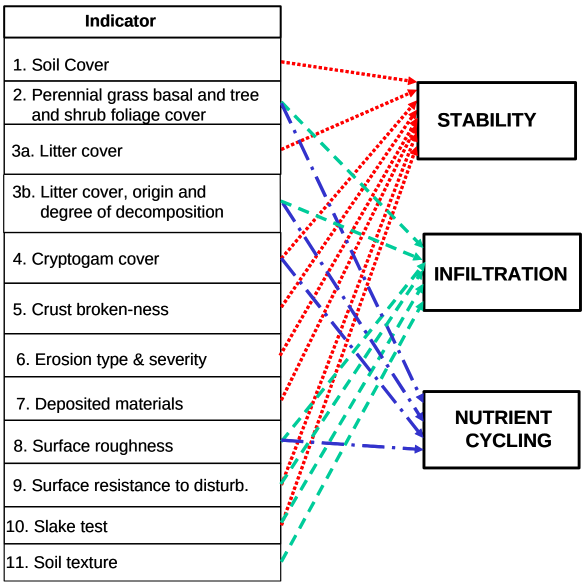

Figure 2: The combination of Soil Surface Condition Indicators (SSCIs) to derive LFA Indices of *Stability*,

Infiltration and *Nutrient Cycling* (after Tongway & Hindley, 1995).

The three LFA Indices have scores between 0 to 100 and represent the ecosystem function of the site. The scores for the unmined forest act as an analogue or reference and are compared to the rehabilitated sites in assessing their ecosystem function. The technique was first developed for the rangelands of Australia (Tongway & Hindley, 1995; Ludwig, *et al.*, 1997) but was found to successfully capture information at mine sites throughout the world (Kearns & Barnett, 1998; Tongway, *et al.*, 1997; Bell, 2001).

The process of using spectral methods to map LFA over a wide area firstly involves the traditional collection of LFA measurements along with ground based spectral measurements as a training dataset. This is used to generate coefficients of the LFA Indices using Partial Least Squares (PLS) (Haaland & Thomas, 1988). Once the spectral variations of environmental measurements are understood the next step is the application of the algorithms, developed from experimental studies, to data acquired from the airborne platform. Here it is essential that the experimental and airborne spectral data are accurately cross-calibrated.

2.3 Data acquisition and processing

Field sampling consisted of thirty five plots, performed over 10 days in December 2006, on a range of different aged rehabilitated mining pits and in unmined eucalypt forest at the bauxite mine site. Figure 3 shows the experimental design adopted to link the spectral data to LFA measurements. The blue box depicts a typical site of 3 x 3 HyMap pixels, measuring approximately 10 x 10 m. Within each site, five transects are located at equally spaced intervals, parallel to the downslope orientation, as shown by the black lines. Figure 8 demonstrates a laid out plot at a recently rehabilitated site at the bauxite mine.

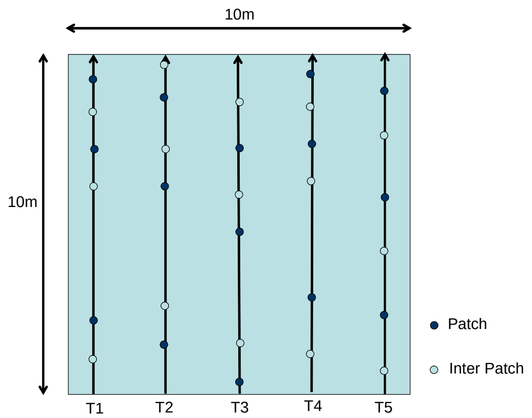

Figure 3: Experimental design for the collection of the eleven SSCIs. T denotes transects.

Each transect is examined for the Landscape Organisation and the patches and inter-patches dimension recorded for each transect, as in the classical LFA procedure. Geographic coordinates were collected at the corners of the plot along with photographs and site descriptions. A typical plot consisted of 25 measurements, which was gauged sufficient to capture the weighted average of the range of cover types and surface morphologies at the site. Stakes were used to mark the location for the measurement with a field spectrometer, which was performed immediately after the collection of the SSCIs along the transects. The design of the spectral measurements was based on a convenient holding position for the spectrometer fibre optic cable. This consisted of measuring at approximately 1 m height from the ground, to collect a 0.2 m^2 area at nadir orientation over the location of the individual LFA surface assessments.

2.3.1 Airborne hyperspectral data pre-processing

Airborne hyperspectral data were acquired across the site in December 2006 at the same time as the field measurements. The data consisted of three flight lines in a northeast orientation over part of the bauxite mining operations and rehabilitation at the mine site. The mosaic of the three strips of data was 5 km wide and 20 km long. Calibration was performed using a combined method which firstly applied a radiative transfer model and then an empirical line technique from co-acquired field spectral measurements of invariant targets.

2.3.2 Relationship between LFA Indices and spectral data

The field spectral measurements were averaged for the whole plot for each of the 35 sites and resampled to the same bandpasses as the airborne hyperspectral reflectance data. The field reflectance measurements were found to be highly comparable to the calibrated airborne hyperspectral data in the plots containing bare soil and newly established vegetation up to 5-7 years from initial rehabilitation. However, a lack of spectral detail was found in the field spectra at sites where a tall overstorey of eucalypt was present. This is attributed to the fact that the field spectral measurements were collected at ground level in areas shaded by the forest canopy. The spectra from these sites were dominated by reflectance of decaying leaf litter and did not resemble the spectral reflectance of the overstorey, which was captured by the airborne hyperspectral scanner. In order to overcome the lack of field measurements comparable to the airborne data in these shaded sites, averages were extracted from pixels in the airborne hyperspectral data corresponding to the field plots. This data, along with the resampled field spectra of the sites without or possessing low canopies, were used in the calculation of the regression coefficients of the three LFA Indices.

One of the main outputs from a PLS analysis is a set of final regression coefficients (FRCs) for all the spectral bands. The FRCs, when multiplied to an unknown spectrum, produce a prediction for the measurement of interest. The FRCs were generated for the three LFA Indices using PLS analysis using a reduced dataset, with 15 sites set aside for use in the validation process. The FRCs were applied to the calibrated airborne hyperspectral data acquired in 2006 to generate spatially comprehensive maps of the three LFA Indices for an area of 100 km^2.

3. RESULTS

3.1 LFA Maps

Figure 4, Figure 5 and Figure 6 show the individual LFA Indices as rainbow colour scale products, with the values stretched to highlight the dynamic range within the airborne survey's 5 x 20 km area. The images have been masked to remove pixels containing water, roads, tracks and pit floors.

The *Stability* map (Figure 4) had a higher average value than the other two LFA maps and displayed high values for the unmined forest and water courses. The older rehabilitation also had high values, whereas the mid aged rehabilitation had moderate values. The young rehabilitation and open pits that were being mined at the time of the acquisition had low *Stability* values.

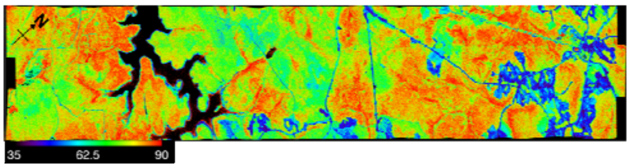

Figure 4 *Stability* Map, masked to remove negative values and linear stretched 0-100%.

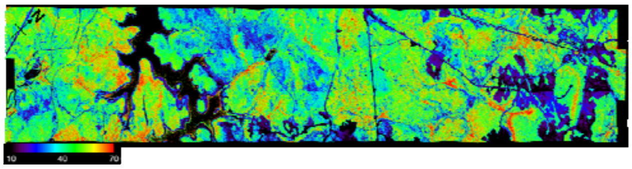

Figure 5: *Nutrient Cycling* Map, masked to remove negative values and linear stretched 0-100%.

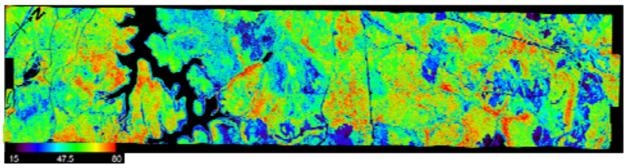

Figure 6: *Infiltration* Map, masked to remove negative values and linear stretched 0-100%.

The average values for the *Nutrient Cycling* (Figure 5) and *Infiltration* (Figure 6) maps were lower than for the *Stability* map, as found with the field measurements. Unmined forest had values of 50-70, whereas rehabilitated pits were lower with values of 20-60. Newly rehabilitated pits had low values of 5-25 for *Nutrient Cycling* due to the lack of vegetation and litter materials. *Infiltration* values were slightly higher than *Nutrient Cycling* for cleared and newly rehabilitated pits. These data values are typical for the rainfall regime at this site and by comparison, the numerical values for all indices are similar to those found in primary tropical rain forest.

The older rehabilitation had similar values to the unmined forest. Anomalous to this trend was the rehabilitation performed between 1982 and 1996 which were clearly visible as having lower values to the surrounding unmined forest. These plots had higher values than the young rehabilitation (2000-2005) which appeared to be improving and trending towards the higher values of the older plots. A large area of the dataset north of the dam was burnt by bushfires which occurred in December 2005 and had lower LFA values for all three indices than the equivalent aged rehabilitation and unmined forest in other areas of the scene. This was attributed to the lower density of the regrowth of the vegetation in the burnt areas and the presence of lower abundances of litter on the forest floor, causing lower values for the three LFA Indices.

The results from the LFA Maps and field LFA measurements indicated an increase in ecosystem function with increasing rehabilitation age at the mine site. The pattern showed an increase in the three indices for all the field plots and stable values for the unmined forest (as shown in Figure 7). The field LFA measurements showed a rise in values with increasing rehabilitation age, approaching the highest values observed for the unmined forest. When the indices were plotted against age, the data followed an exponential trajectory, which was indicative of the rapid regrowth and colonisation of the rehabilitated pits by the vegetation.

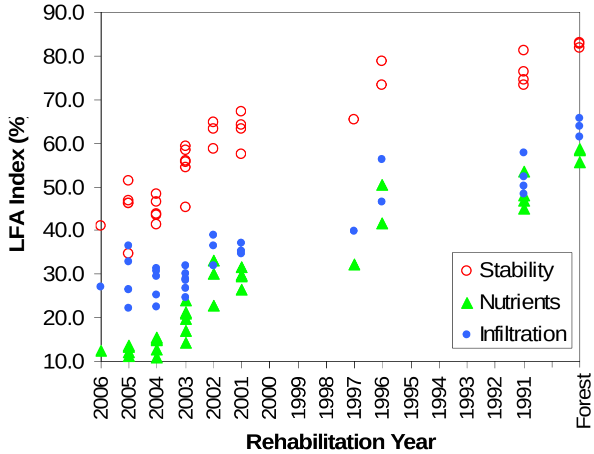

Figure 7 Field measurement LFA Index results from the 35 sites sampled for the calibration dataset.

The LFA Maps and field data displayed low values (*Nutrient Cycling* = 12 and *Infiltration* = 27) for one year old pits due to the lack of vegetation and litter at the surface. An example of a newly rehabilitated site, conducted in 2006, is shown in Figure 8. Vegetation at this site comprised of sparse, 5-10 cm tall seedlings. Deposits of dispersed clay in the trough sections indicated evidence of erosion.

Figure 8: A recently rehabilitated site (2006) marked out for SSCI and spectral measurements.

In contrast the unmined but previously logged jarrah forest areas displayed relatively high LFA Index measures (*Stability* = 83, *Infiltration* = 64 and *Nutrient Cycling* =58). An example of a unmined forest is shown in Figure 9.

Figure 9: An unmined forest site which contained a deep layer of leaf litter and an abundance of woody material.

This site was been selected as an analogue site and represented the criteria of the LFA Index values for a completely rehabilitated site. The overstorey canopy was relatively dense with little sunlight reaching the forest floor. The ground surface was covered by a deep layer of leaf litter and an abundance of coarse woody debris, including a large jarrah log present within the plot. The airborne hyperspectral data displayed high values for the unmined forest, as shown by the red areas in the LFA Maps (Figure 4,Figure 5 and Figure 6).

The site shown in Figure 10 has intermediate LFA Index scores with *Stability* (48), *Infiltration* (25) and *Nutrient Cycling* (15). This previously mined site began its rehabilitation in 2004 and at the time of measurement, comprised abundant vegetation of approximately 1-2 m in height. The visual appearance of the vegetation had progressed in comparison to the younger site in Figure 8. Due to the open canopy and lack of litter development rehabilitated sites of this age have moderately low values and appear blue-green in colour in Figure 4, Figure 5 and Figure 6.

Figure 10: A 2 year old rehabilitation site displayed good vegetation growth.

3.2 Validation

Validation of the LFA maps was performed using a dataset of 15 sites collected at the same time as the calibration dataset and set aside for calibration purposes. The LFA Indices predicted from the airborne hyperspectral data showed a high correlation with the field measured LFA and was able to predict all three LFA Indices for densely vegetated sites with good accuracy (*Stability* r^2=0.76, *Infiltration* r^2=0.67 and *Nutrient Cycling* r^2=0.71). The scatter plots of the airborne hyperspectral-derived versus field measured LFA values for the validation sites are shown in Figure 11.

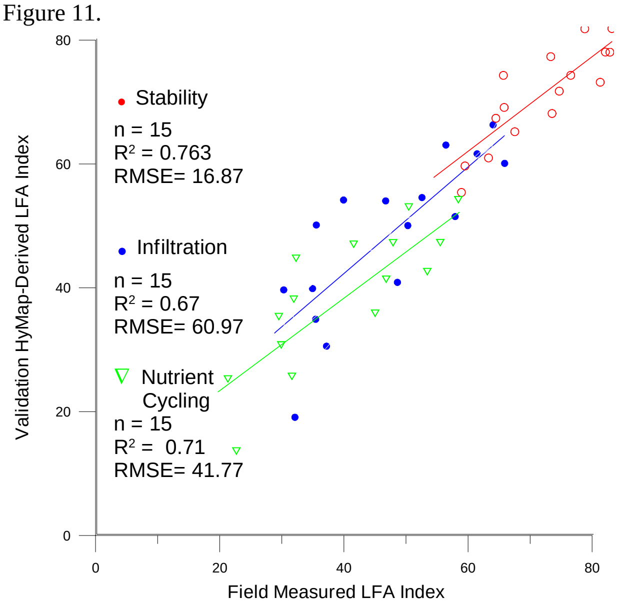

Figure 11: Validation result of LFA Maps using airborne hyperspectrally derived LFA Indices against field measured LFA Indices for plots not used in the calibration.

4. DISCUSSION

Vector data, consisting of the outlines of the rehabilitated plots, were used to extract the average LFA Indices predicted by the airborne hyperspectral data for each year of rehabilitation. This was preformed for the purpose of assessing the rehabilitation progress with time. The assumption here is that the rehabilitation practices were consistent between years. Although, it is known that rehabilitation practices have changed over the life of the mining operations and some areas have endured a mixed pattern of prescribed bushfire burns, which has had an influence on the landscape and therefore the reflectance data collected by the airborne hyperspectral instrument. Overall the airborne hyperspectrally derived LFA values and field measurements demonstrated an improvement of the rehabilitation with age, with minor fluctuations due to bush fire events, as shown in Figure 12.

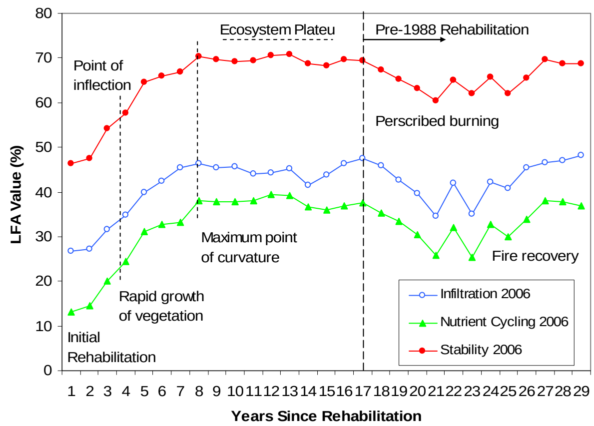

Figure 12: LFA Indices of rehabilitation plots extracted from the airborne hyperspectrally-derived LFA Maps.

For sites younger than 8 years the airborne hyperspectral data were highly comparable to the plot-weighted average field spectral measurements. The vegetation cover of the rehabilitated pits increased rapidly over the first 8 years. Rehabilitation older than 8 years displayed stable values, with little increase in *Stability* and *Infiltration*. The values remained steady until approximately 17 years where there was a fall for all three LFA Indices. However, the values recovered to similar levels as 8 year old rehabilitation at around 27 years. The fluctuations in the older year rehabilitation values are attributed to seasonal bush fire events. Immediately after a fire the LFA Index values are reduced and recover to pre-fire conditions at a similar rate as the early progress of the young rehabilitation. The rate of "recovery" can be used as an assessment of the sites resilience and can demonstrate that the ecosystem is sufficiently developed to be self-sustaining.

The calibration dataset used for the development of the PLS prediction consisted of rehabilitation at various ages, hence different canopy coverage between the sites. Most of the data, especially for the older rehabilitation, were collected at sites which were functionally well-developed. This was displayed by a good build up and decomposition of litter, evidence of soil formation, a diverse range of species and a multi-storey forest architecture. Such areas are represented by high LFA Index values. This is reflected in the FRCs, where the presence of mineral absorption features was synonymous with low LFA values, whereas strong green vegetation features are associated with high LFA values. The use of the FRCs from these PLS predictions were found to be adequate where the progress of rehabilitation is ideal but the accuracy is reduced for sites where the rehabilitation possesses a dense canopy overstorey over a forest floor with low ground level parameters. That is, where an abundance of hard, bare soil, no understorey vegetation, and a leafy canopy of eucalypts is present.

Field measurements from rehabilitation sites older than 8 years contained spectral features related to shadow, litter, understorey vegetation and soil, whereas the spectra of the airborne hyperspectral data were dominated by the green vegetation signatures of the eucalypt crowns. Therefore the field measurements were unable to capture comparable representative spectra to the airborne hyperspectral data in the older sites due to the nature of the ground based sampling program. This was accounted for by using a combination of the field spectral and airborne data for the PLS analysis.

Although the accuracy of using hyperspectral imagery to remotely determine LFA decreased as the rehabilitation became older (*i.e.* increased canopy density), this is consistent with the ability of the LFA technique to classify systems which have reached the upper level of their biophysical potential, as shown by achieving plateau numerical values. The results show that the initial rehabilitation rapidly increased its functionality, which was reflected in an increase and subsequent plateau in LFA values. It is suggested that other techniques should be introduced for monitoring the rehabilitation at the point at which the values are reaching their "plateau" maximum. For LFA, this would be between the point of inflection and the maximum point of curvature of the rehabilitation progress as the ecosystem approaches maturity. At this location in the Darling Range this would be at seven or eight years after initial rehabilitation, as indicated from the average airborne hyperspectral extracted LFA values for all the field plots, which show a change in the rate of increase in their LFA Index values around this point. The changeover process may involve the phasing out of LFA by performing a reduced suite of SSCIs (such as erosion identification, litter decomposition and soil formation) or episodic measurement in response to fire or large rainfall events.

5. CONCLUSION

The study demonstrated that the three LFA Indices could be mapped remotely using airborne hyperspectral imagery, which was directly associated with soil mineralogy, vegetation and litter cover in the early years of the rehabilitation. As the age of the rehabilitation increased, the eucalypt overstorey developed and the canopy became increasing closed. However, the airborne hyperspectral imagery was still able to map the improvement of ecosystem function, which appeared to be associated with the increase vegetation biomass and therefore a rise in green vegetation and lower amount of soil and litter spectral features. In summary, the *Stability, Infiltration* and *Nutrient Cycling* ecosystem related indices have been demonstrated to be reliably generated from a combination of ground based and airborne spectral data. There is great potential for this technique to be used as a monitoring tool and there is need for further case studies in other environments.

REFERENCES

Bell, D. T. & Heddle, E. M., 1989. Floristics, morphology and vegetation diversity. *In:* The Jarrah Forest. *Eds.* Dell, B, Havel, J. J. & Malajczuk, N., Kluwer Academic Publishers, Dordrecht, pp. 53-66.

Cocks, T., Jenssen, R., Steward, A., Wilson, I., & Shields, T., 1998. The HyMap^{TM} airborne hyperspectral sensor: The system, calibration and performance. *Eds*. Schaepman, M., Schlapfer, D., & Itten, K. I., Zurich, EARSeL, Paris, pp. 37-43.

Gardner, J. H., 2001. Rehabilitating miners to meet land use objectives: bauxite mining in the jarrah forest of Western Australia. *Unasylva*, 207, pp. 3-8.

Haaland, D. M. & Thomas, E. V., 1988. Partial Least Squares, *Analytical Chemistry*, 60, pp. 1193-1200.

Hatchell, D. J. (Ed), 1999, Analytical Spectral Devices, Inc. (ASD) Technical Guide 4th Edition. http://www.asdi.com/TG_Rev4_web.pdf. (accessed 29th April 2008).

Heddle, E. M., Loneragan, O.W. & Havel, J. J., 1980. Vegetation Complexes of the Darling System. *In:* Atlas of natural resources of the Darling System Western Australia. Department of Conservation and Environment, Perth, Australia.

Kearns, A. & Barnet, G., 1998. Use of Ecosystem Function Analysis in the mining industry. Indicators of ecosystem rehabilitation success, Proceedings of Workshop on Indicators of Ecosystem Rehabilitation Success (*Eds*. Asher, C. J. & Bell, L. C.) Melbourne, Victoria, 23 - 24 October 1998, pp. 31-46.

Koch, J. M., Ward, S. C., Grant, C. D. & Ainsworth, G. L., 1996. Effects of bauxite mine restoration operations on topsoil seed reserves in the Jarrah forest of Western Australia. *Restoration Ecology,* 4, pp. 368-376.

Ludwig, J., Tongway, D., Freudenberger, D., Noble, J., & Hodgkinson, K., 1997. 'Landscape Ecology, Function and Management: Principles from Australia's Rangelands'. CSIRO, Melbourne, Australia.

Tongway, D. J., & Hindley, N. L., 1995. Manual for the Assessment of Soil Condition of Tropical Grasslands. CSIRO Wildlife and Ecology, Canberra, Australia.

Tongway, D. J. & Ludwig, J., 2006. Assessment of landscape function as an information source for Mine Closure. Proceedings of the 1st International Seminar on Mine Closure, Australian Centre for Geomechanics, Perth, Australia.

Ward, S. C., Slessar, G. C., Glenister, D. J., & Coffey, P. S., 1996. Environmental resource management practices of Alcoa in southwestern West Australia. *In:* Environmental management in the Australian minerals and energy industries – Principles and practices. *Ed:* Mulligan, D,, UNSW Press, Sydney, Australia. pp. 383-402.

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