A COMPARISON BETWEEN SENSORS WITH DIFFERENT SPECTRAL RESOLUTIONS, RELATIVE TO THE SUMBANDILA SATELLITE, FOR ASSESSING SITE QUALITY DIFFERENCES, IN *EUCALYPTUS GRANDIS* PLANTATIONS

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Abstract

The majority of earth observation studies have for years made use of data from multispectral spaceborne sensors. More recently though, both airborne and spaceborne narrowband hyperspectral sensors have come to the fore and are able to provide more detailed spectral information. Narrowband sensors, with their many contiguous bands, have proved useful in discriminating between vegetation states, e.g. water stress and nutrient deficiencies. However, hyperspectral remote sensing has a number of disadvantages related to the cost of data collection (especially airborne data), the low signal-to-noise ratios of spaceborne hyperspectral data, and data redundancy given the large number of contiguous bands. These challenges, exacerbated by known broadband sensor limitations, have prompted research into the reduction of hyperspectral data dimensionality towards the identification of application-specific spectral features, which ultimately could lead to the definition of new application-centric multispectral sensors. SUNSPACE, in collaboration with the University of Stellenbosch and the South African Department of Science and Technology, aim to launch a high resolution multispectral micro satellite (SumbandilaSat) in 2009. The satellite will be equipped with a multispectral sensor, with a 6.25m spatial resolution and 6 spectral bands. Two of these spectral bands have been strategically placed given *a priori* correlations between the vegetation signal in these regions and vegetation state [i.e. the red edge band (690-730nm) and xanthophyll band (520-540nm)]. The objective of this study was to investigate whether fewer and strategically placed multispectral wavebands could provide similar, and/or more cost effective information compared to common hyperspectral sensors. Canopy-level ASD data were collected and resampled to various sensor resolutions (i.e. Hyperion, HyMap, AVIRIS and SumbandilaSat). Various physiology-based spectral indicators, including ratio indices, red edge positions, continuum-removed features, and derivative features were calculated for each sensor and used as indicators of vegetation state. ANOVA results revealed that site quality can be differentiated ($p<0.05$) using the majority of the hyperspectral indices calculated in the study. The results also show that the differences between sites are subtle and only two of nine calculated SumbandilaSat vegetation indices were able to

significantly differentiate between sites. While hyperspectral indicators will always be more accurate and therefore preferred to multispectral indicators, application-based design of multi-spectral sensors has a potential for success if cost effective monitoring projects are needed.

1. Introduction

Forest managers have traditionally used labour intensive and costly ground-based methods to assess forest health and condition (Sampson *et al*. 2000). However, remote sensing offers an indirect and cost effective alternative for assessing vegetation conditions as underpinned by site-specific factors. The advent of imaging spectroscopy (hyperspectral remote sensing) now provides us with new opportunities to improve on the detection and monitoring of vegetation condition using the biochemical contents of foliage (Curran *et al*. 1997). For example, canopy chlorophyll is being used as an indicator of vegetation condition, and it allows for focused studies on the location and severity of stressed canopies in plantation forests, as well as broader studies on nutrient cycling rates, vegetation productivity, and ecosystem simulation models (Curran 1994; Barry *et al*. 2008).

Hyperspectral data are defined by a large number of contiguous bands with narrow bandwidths that can range between 1 and 15nm in spectral resolution. This results in data that are more sensitive to subtle biochemical variations, such as in chlorophyll, and can be used to identify specific bands that are linked to well-known biochemical features. The red edge has proven to be one of the most widely used remote sensing bio-indicators of chlorophyll concentration. The red edge position is the point of maximum slope between the red chlorophyll absorption region (680nm), and the region of high near-infrared reflectance (750nm) (Horler *et al*. 1983). The shape and position of the red edge are highlighted in reflectance derivative curves, and influenced by changes in the amount of chlorophyll and by leaf scattering properties (Filella and Peñuelas 1994). Water content, or water stress, also affects the shape and position of the red edge due to its effect on the internal leaf structure and resultant scattering of light (Filella and Peñuelas 1994). Quantitative hyperspectral remote sensing of terrestrial bio-chemistry therefore often makes use of red edge techniques, as well as a multitude of chlorophyll, structural, and water-related indices in order to better assess foliar chemistry state, net primary production, environmental and nutritional stresses, and the effects of disease in forest ecosystems (Filella and Peñuelas 1994; Gitelson and Merzlyak 1997; Barry *et al*. 2008). Coops *et al*. (2004) tested the ability of a number of spectral indices in detecting vegetation stress in eucalypt vegetation of varying condition, by using preselected hyperspectral bands onboard the airborne CASI-2 sensor. Coops *et al*. (2004), found leaf damage to be moderately correlated with a red-green spectral index ($r=0.68$, $p<0.01$), while leaf discolouration was highly correlated with the slope of the red-edge ($r=0.77$, $p<0.001$), and crown scale attributes such as crown density ($r=0.77$, $p<0.01$) and crown foliage condition ($r=0.88$, $p<0.01$) were well correlated with red edge and stress-related spectral indices for selected species.

However, hyperspectral data can also represent an over-sampled dataset that results in redundant bands (information), which are negatively influenced by various sources of noise, e.g. atmospheric influences, shadow effects, leaf and canopy architecture, and background soil or litter reflectance. The process of collecting airborne hyperspectral imagery is also expensive, while current spaceborne hyperspectral imagery often suffers from inadequate signal-to-noise ratios and spatial resolutions (Kruse 2003). Ultimately it would be more beneficial if hyperspectral sensors could be optimised for specific applications and ignore all redundant bands in order to reduce data volumes and eliminate the problem of high data dimensionality (Thenkabail *et al*. 2002). The limitations of broadband sensors are documented in terms of not being able to provide sufficiently accurate information on biophysical parameters of crops (Thenkabail *et al*. 1994), chlorophyll sensitivities (Blackburn 1999), and vegetation stress assessments (Blackburn 1998).

SUNSPACE, in collaboration with the University of Stellenbosch and the South African Department of Science and Technology, expects to launch a medium / high resolution multi-spectral micro satellite system, called SumbandilaSat (formerly ZA-002) in 2009. The satellite will be equipped with a multi-spectral sensor, which has a 6.25m Ground Sampling Distance (GSD) and 6 spectral bands. The spectral bands will include the blue band (440-510nm), a xanthophyll band (520-540nm), a green band (520-590nm), a red band (630-685nm), a red-edge band (690-730nm) and a NIR band (845-890nm). The spectral bands have bandwidths that range between 20nm and 70nm.

SumbandilaSat developers are attempting to take advantage of a potential gap that may exist between comparatively inexpensive, medium/high resolution, multispectral sensors with strategically placed broad bands, and the expensive hyperspectral sensors with high spectral resolutions, but which result in over-sampled datasets. The inclusion of the red edge band, which focuses on a spectral region that is well known for its sensitivity to changing chlorophyll content will hopefully prove more useful in ecosystem state analyses, than only having a broad red and/or NIR Landsat band available. Therefore, the objective of this study was to investigate whether fewer and strategically located SumbandilaSat multispectral wavebands could provide similar and potentially useful information compared to common hyperspectral sensors in describing differences between vegetation states.

2. Materials and Methods

2.1 Study site

Four to seven year old *Eucalyptus grandis* plantations, situated close to the town of Richmond in the KwaZulu-Natal midlands of South Africa (S29^0 49', E30^0 17'), formed the basis of this study. The region has a predominantly summer rainfall regime with an annual average of 1 000mm.,Summer temperatures can vary between 24^{0}C and 26^{0}C, and winter temperatures vary between 5^{0}C and 14^{0}C, with regular frost occurrences. The data were collected from a raised platform (cherry picker) for three different forest site qualities (good, medium, poor), which are based on total available water (TAW). TAW is determined using soil type, effective rooting depth, and rainfall and temperature class information (Smith 2005).

2.2 Spectral reflectance measurements

Canopy reflectance measurements for 68 trees (25=good, 25=medium and 18=poor) were collected on clear sky days using an ASD spectrometer (Fieldspec3 Pro FR, Analytical spectral Device, Inc, USA). The measurements were acquired during winter (August 2007). The ASD spectroradiometer samples radiation between 350 and 2500nm, and has a re-sampled bandwidth of 1nm. Averages of 10 reflectance measurements were used in order to obtain mean reflectance spectrums for each of the canopies. A 25^0 field of view bare fibre optic was used for the measurements. Canopy samples were collected from approximately 1m to 1.5m above each tree canopy, which resulted in an at-canopy footprint of between 0.44 and 0.66m. Canopy level reflectance samples were collected from each tree in a manner that accounted for as much variation in leaf age and condition as possible. This often resulted in 4 to 5 sunlit canopy level reflectance samples per tree. Radiance measurements were converted to target reflectance using a calibrated white spectralon panel. Due to the size and manoeuvrability of the cherry picker, access was often limited; hence trees were sampled in an irregular manner along access roads within the plantation.

2.3 Data analysis

The ability of continuum-removed spectra to detect site quality differences was evaluated. Continuum-removal attempts to eliminate external sources of spectral noise and enhances absorption troughs of biochemicals, thereby increasing the chances of detecting significant relationships between spectra and associated biochemical states (Kokaly and Clark 1999). In this study the continuum-removal approach was only applied to the major absorption region between 550nm to 750nm. Normalisation of the reflectance spectra, by calculating band depth ratios (BDR) and normalised band depth indices (NBDI), was carried out in order to minimize any external effects on the spectra (Mutanga *et al*. 2005).

The spectral information content, related to vegetation physiological and structural properties, was assessed for the detection of differences between site qualities across spectral data of varying resolutions (from high to low). The high resolution ASD data were re-sampled to AVIRIS, HyMap, Hyperion and SumbandilaSat resolutions. A gaussian fitting algorithm, within the ENVI software, was used to perform the resampling procedures. Well-established physiology- and structure-based vegetation indices were used for the analyses. Subsequently, one-way analysis of variance (ANOVA) was used to determine whether significant differences between site qualities could be detected.

3. Results

3.1 Assessing differences in site quality using narrow band indices

The results of the ANOVA between the ASD-calculated continuum-removed indices (i.e. BDR and NBDI) and site quality showed that all the bands between 692 and 750nm exhibited significant ($p<0.05$) differences between site qualities.

Similar results were observed for the resampled AVIRIS, Hyperion and HyMap continuum removed indices. ANOVA results between each of the hyperspectral narrow band indices and site quality classes revealed that all of the water-related indices [i.e. Normalised Difference Water Index (NDWI) (Gao 1996), Moisture Stress Index (MSI) (Hunt and Rock 1989) and Water Index (WI) (Peñuelas *et al*. 1993)] detected significant ($p<0.05$) differences between site qualities (Table 1), as did four of the nine chlorophyll indices that were tested [i.e. Carter Index (CI) (Carter 1994), R_{750}/R_{700} (Lichtenthaler *et al*. 1996), Datt Index (DI) (Datt 1999) and Datt $Index_2$ (DI_2) (Datt 1999)]. The Carter Index, however, failed to detect significant site quality differences when using the AVIRIS and Hyperion data (i.e. $p>0.05$). The gradients of the MSI and WI water-related indices increased from the good to the poor sites (Figure 1), while the NDWI gradient decreased from the good to the poor sites. The gradients of the chlorophyll indices all decreased from the good to the poor sites (Figure 1). The linear four point interpolation red-edge technique (Four Point REP) (Guyot and Baret 1988), as well as the linear extrapolation red edge technique (Extrap. REP) (Cho and Skidmore 2006), were both able to detect significant differences ($p<0.05$) between site qualities for each of the hyperspectral sensors, while the maximum red edge position technique was only able to detect a significant difference between the ASD data and site quality. Tukey HSD *post hoc* tests revealed that significant differences only occurred between good and poor quality sites for all of the sensors.

3.2 Assessing differences in site quality using multispectral indices

Only five of the chlorophyll-related indices and none of the water-related indices could be calculated using multispectral SumbandilaSat data due to the bandwidths and placement of the SumbandilaSat spectral bands. However, ANOVA results revealed that two of the chlorophyll-related indices (DI & DI_2), based on SumbandilaSat simulated data, were able to significantly differentiate between site qualities (i.e. $p<0.05$). The Photochemical Reflectance Index (PRI) (Gamon *et al*. 1992), which was of special interest due to the strategically placed xanthophyll waveband, did not detect any significant differences between sites (i.e. $p>0.05$) and neither did the other pigment-related indices, namely the Structure Insensitive Pigment Index (SIPI) (Peñuelas *et al*. 1995) and Plant Senescence Reflectance Index (PSRI) (Merzylak *et al*. 1999) (i.e. $p>0.05$).

4. Discussion

In line with the study's objectives, the ability of strategically placed, multispectral SumbandilaSat bands to detect differences in *E. grandis* states was assessed and compared against common narrow-band sensors using a variety of vegetation indices and techniques.

Degradation of spectral resolution from the ASD to SumbandilaSat sensor resolution significantly reduced the number of spectral features that could be applied to differentiate between *E. grandis* growing on different site qualities. Potentially useful indices such as water indices, the red-edge position, and continuum-removed indices cannot be derived from SumbandilaSat data. However, two SumbandilaSat red-edge indices exhibited significant differences between *E. grandis* site qualities. The significant SumbandilaSat indices were derived from far-red (710nm) and NIR reflectance. It has been proven that indications of stress are more often expressed as increases in reflectance in the 690-720nm region of the spectrum than in other regions (Carter 1994). A number of studies have been able to show that indices that are based on the far-red (690-720nm) reflectance region are best suited to the accurate estimation of leaf chlorophyll concentration (Carter 1994; Gitelson and Merzlyak 1996, 1997; Datt 1999). This body of literature proves that spectral bands near 700nm, such as the SumbandilaSat red edge band, are vitally important in the detection of stress and estimation of chlorophyll concentrations (Carter and Knapp 2001). The gradients of significance were found to be highest between good and poor sites, indicating that differences between medium site qualities were subtle and undetectable using either hyperspectral or multispectral data.

It was also possible for differences in site quality, based on TAW, to be effectively detected using canopy-level untransformed spectroscopy data and resampled hyperspectral sensor data for the *E. grandis* forest stands The hyperspectral results revealed the potential of water and chlorophyll spectral features for discriminating between site qualities as defined by TAW. Moisture stress indices (e.g. MSI) appropriately showed increasing gradients of significance when moving from the good to the poor sites, while leaf water content indices (e.g. NDWI and WI) showed decreasing gradients between good and poor sites. All of the chlorophyll indices also exhibited decreasing gradients between the good and poor sites, which are indicative of decreasing chlorophyll contents. Due to the significance of both water- and chlorophyll-related indices, we can assume that it is water stress that causes the changes in canopy chlorophyll, which is subsequently detected using chlorophyll-related indices calculated from a range of sensor resolutions. Further evidence of decreasing chlorophyll contents can be found in the fact that the REP moved towards shorter wavelengths (i.e. a ‘blue shift’) for the poor sites, which is usually associated with stress events or senescence (Rock *et al*. 1988).

It has previously been shown that red-edge continuum-removed features have been able to discriminate between plants growing under different soil nitrogen treatments (Mutanga *et al*. 2005). This study confirmed, through the calculation of continuum-removed indices (i.e. BDR & NBDI) and their subsequent significance to individual wavebands in the 692-750nm range, the importance of the red edge region in detecting differences in leaf biochemical states (Kokaly and Clark 1999; Mutanga *et al*. 2005). The continuum-removed indices, calculated using ASD data, represented a best case scenario for this study by proving that detectable differences existed between the site qualities for each of the sensor resolutions tested. Significant differences were also detected when the continuum indices were calculated using resampled AVIRIS, Hyperion and HyMap data. The continuum index analysis was a precursor to the investigation into how these significant relationships were affected when making use of increasingly course resolution data as well as physiology-based indices, calculated from untransformed spectra. Ultimately these relationships were evaluated using a limited number of broad SumbandilaSat wavebands.

Table 1: A selection of the significant results of the ANOVA for the detection of differences between site qualities using various sensor resolutions.

	ASD	**AVIRIS**	**Hyperion**	**HyMap**	**SumbandilaSat**
Water-related indices					
MSI	**0.01***	**0.01***	**0.02***	**0.01***	
WI	**0.01***	**0.01***	**0.01***	**0.01***	
Chlorophyll indices					
R_{750} / R_{700}	**0.01***	**0.01***	**0.01***	**0.04***	
DI	**0.01***	**0.01***	**0.01***	**0.01***	**0.01***
DI_2	**0.01***	**0.01***	**0.01***	**0.01***	**0.01***
Four Point REP	**0.00***	**0.00***	**0.00***	**0.00***	
Extrap. REP	**0.01***	**0.05***	**0.04***	**0.02***	

*= p is significant at <0.05

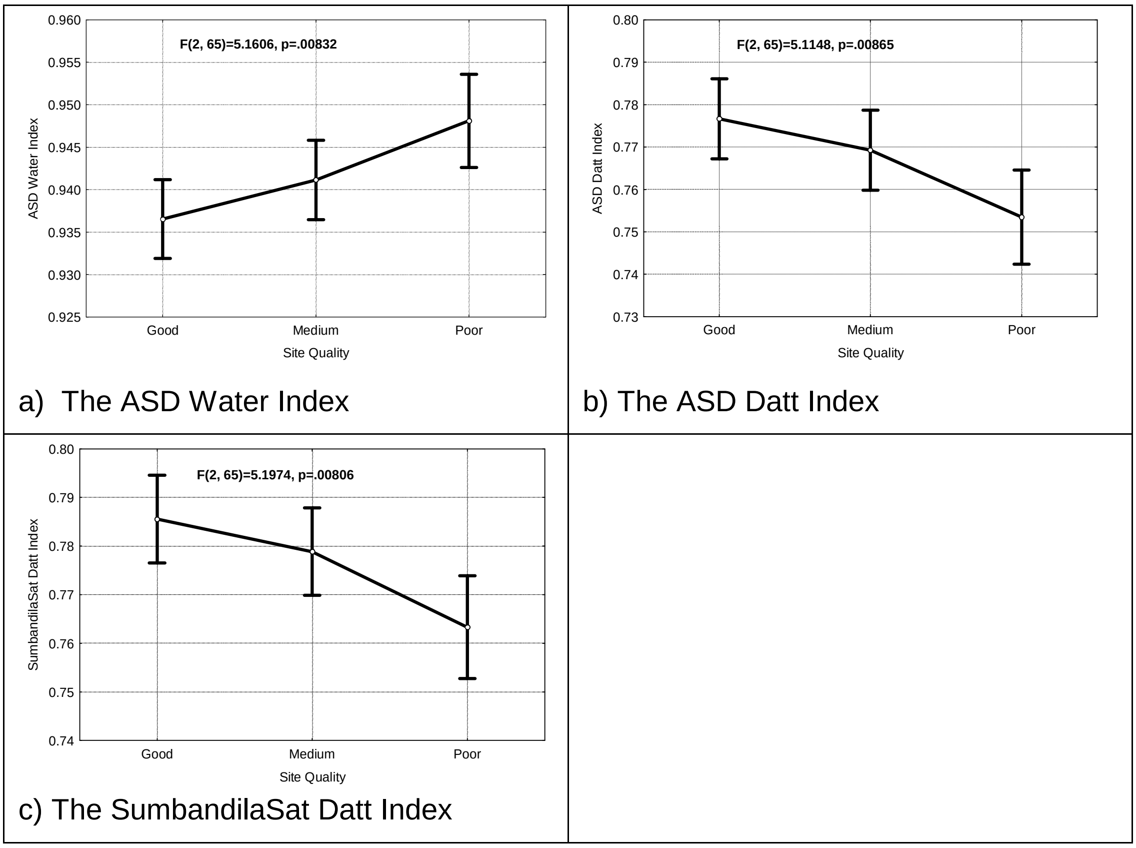

Figure 1: Significant ANOVA relationships between the *E. grandis* site qualities and the ASD water- and chlorophyll-related (a and b) indices, as well as the SumbandilaSat chlorophyll related index (c).

Subtle differences between sites could not be detected using xanthophyll-related indices, which were specifically included due to the presence of the SumbandilaSat xanthophyll band. The PRI has been successfully correlated with xanthophyll pigments and light use efficiency at various scales, including leaf, small canopy and ecosystems (Gamon *et al*. 1992; Peñuelas *et al*. 1995; Rahman *et al*. 2001; Nichol *et al*. 2002;). Despite convincing relationships between these xanthophyll-related indices and physiological states, many of the results point towards field scale correlations being weaker than leaf level correlations (Grace *et al*. 2007). This is often due to factors such as canopy structure, atmospheric effects, soil background noise, and spectral and spatial resolutions, many of which could have combined to complicate the accurate remote detection of physiological states in this study and thus render the pigment-related indices useless (Grace *et al*. 2007). Neither the hyperspectral nor multispectral sensors were able to detect significant differences between sites when using the pigment-related indices, which suggests that spatial and spectral resolution may not have been the sole cause and perhaps the reason is based on physiological, structural, and seasonal (i.e. winter) influences on the reflectance spectra. The impact of multi-seasonal observations deserve special attention in future studies.

5. Conclusion

The strategic placement of multispectral bands led to a successful assessment of chlorophyll-related differences between site qualities of *E. grandis* forest stands during winter periods in the KwaZulu Natal midlands of South Africa. It was shown in this research that while hyperspectral data offer opportunities to calculate a wide variety of physiology-based indices, the strategic placement of the red edge multispectral waveband was able to overcome problems of averaging at-sensor radiation and resulted in the detection of significant differences in vegetation state. The detection of xanthophyll pigments was not successful, probably due to physiological, structural, and/or seasonal influences on the reflectance spectra. It is also acknowledged that these results, derived from degraded ASD data, do not fully account for disruptive affects, such as background reflectance, leave and canopy structural influences, and atmospheric influences that confound the accurate detection of vegetation state using airborne or spaceborne remote sensing methods. However, the results do in principle show the potential of the SumbandilaSat red edge band for aiding the multispectral detection of vegetation state from space, which could go a long way in aiding large area forest state assessments and regional ecosystem modelling efforts. The applicability of these results to other species and/or scenarios is also unknown and will require further research. The applicability of these results to other species and/or scenarios is unknown and will require further research.

Acknowledgements

The research was supported by Parliamentary Grant (PG) funding from the South African Department of Science and Technology (DST), and was part of a co-operative research agreement between the CSIR and Mondi Business Paper of South Africa.

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