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Spectral mixture analysis to monitor defoliation in mixed-aged *Eucalyptus globulus* Labill plantations in southern Australia using *Landsat 5-TM* and *EO-1 Hyperion* data

B. Somers [a,*], J. Verbesselt [b], E.M. Ampe [a], N. Sims [b], W.W. Verstraeten [a], P. Coppin [a]

[a] *Dept. of Biosystems, M3-BIORES, Katholieke Universiteit Leuven, W. de Croylaan 34, BE-3001 Leuven, Belgium*
[b] *CSIRO Sustainable Ecosystems, Private Bag 10, Clayton South, VIC 3169, Australia*

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ABSTRACT

Defoliation is a key parameter of forest health and is associated with reduced productivity and tree mortality. Assessing the health of forests requires regular observations over large areas. Satellite remote sensing provides a cost-effective alternative to traditional ground-based assessment of forest health, but assessing defoliation can be difficult due to mixed pixels where vegetation cover is low or fragmented. In this study we apply a novel spectral unmixing technique, referred to as weighted Multiple Endmember Spectral Mixture Analysis (wMESMA), to *Landsat 5-TM* and *EO-1 Hyperion* data acquired over a *Eucalyptus globulus* (Labill.) plantation in southern Australia. This technique combines an iterative mixture analysis cycle allowing endmembers to vary on a per pixel basis (MESMA) and a weighting algorithm that prioritizes wavebands based on their robustness against endmember variability. Spectral mixture analysis provides an estimate of the physically interpretable canopy cover, which is not necessarily correlated with defoliation in mixed-aged plantations due to natural variation in canopy cover as stands age. There is considerable variability in the degree of defoliation as well as in stand age among sites and in this study we found that results were significantly improved by the inclusion of an age correction algorithm for both the multi-spectral ($R^2_{\text{no age correction}} = 0.55$ vs $R^2_{\text{age correction}} = 0.73$ for *Landsat*) and hyperspectral ($R^2_{\text{no age correction}} = 0.12$ vs $R^2_{\text{age correction}} = 0.50$ for *Hyperion*) image data. The improved accuracy obtained from *Landsat* compared to the *Hyperion* data illustrates the potential of applying SMA techniques for analysis of multi-spectral datasets such as *MODIS* and *SPOT-VEGETATION*.

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1. Introduction

The amount of foliage is one of the primary physiological controls of plant functioning, which ultimately influences plant survival and growth. Repeated severe defoliation events have been linked to reduced growth rates and tree mortality in softwood plantations (Kurz et al., 2008; Verbesselt et al., 2009) and hardwood forests (Stone and Coops, 2004) throughout the world. The most commonly deployed methods of assessing defoliation are forest health surveys (FHS) including aerial surveillance, drive-through surveys and ground inspections (Carnegie et al., 2008; Johnson and Wittwer, 2008). However, FHS requires skilled staff for on-ground and airborne surveys, diagnostics, analysis and support, and the accuracy of assessments is dependent upon the skill of the surveyor (Stone and Coops, 2004). FHS assessments are therefore usually limited in frequency to once or twice a year in most areas. Incorporating remote sensing technologies to assist FHS has the potential to reduce the time and cost of assessment, and provide regular information over large areas (van Aardt and Norris-Rogers, 2008; Stone et al., 2008; Coops et al., 2009; Eklundh et al., 2009).

A number of recent studies have demonstrated the potential of measuring defoliation from remotely sensed observations of Eucalyptus crowns (Barry et al., 2008; Pietrzykowski et al., 2008). These studies use linear regression modeling between field assessments of symptom levels and vegetation indices calculated from the images to identify the level of crown damage from a range of damaging agents including fungal infections and insect predation. Good correlations were found between the expression of damage symptoms in tree crowns and vegetation index values at a range of scales from individual crowns to entire estates (Verbesselt et al., 2009).

Remote sensing methods using vegetation indices are limited, however, by their dependence on the visibility of leaves in image

* Corresponding author. Tel.: +32 16329749; fax: +32 16329760.
E-mail addresses: ben.somers@biw.kuleuven.be (B. Somers), jan.verbesselt@csiro.au (J. Verbesselt), eva.ampe@student.kuleuven.be (E.M. Ampe), neil.sims@csiro.au (N. Sims), willem.verstraeten@biw.kuleuven.be (W.W. Verstraeten), pol.coppin@biw.kuleuven.be (P. Coppin).

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pixels. When targeting defoliation, it is in fact the absence of leaves which determines the severity of the stress (Stone et al., 2003). One approach for measuring defoliation in terms of the relative proportion of leaves in image pixels is linear spectral mixture analysis (SMA) which can quantify the proportion of each pixel that is occupied by individual image components. These methods have previously been used to measure defoliation in *Pinus radiata* plantations using high-resolution multi-spectral images (Radeloff et al., 1999; Goodwin et al., 2005; Sims et al., 2007), but methods for calculating image fractions from hyperspectral image data are in their developmental infancy. The application of SMA for assessment of forest condition offers several advantages over simple regression methods using spectral indices. For example SMA has been shown to be capable of detecting vegetation cover at low levels, and the ability to reference a small number of spectrally stable endmembers results in developed repeatable models (Goodwin et al., 2005).

To date, the full potential of SMA for forest defoliation assessment has not yet been achieved. Residual error in fraction estimates provided by SMA is often introduced by the natural variability in the conditions of scene components, i.e., soil, plant, etc. inherent in remote sensing data. Recently, a number of solutions have been developed to reduce this effect (e.g., Roberts et al., 1998; Asner and Lobell, 2000; Zhang et al., 2004). In particular, the most suitable methods for selecting wavelengths that provide the best separation between image components are currently under development (Somers et al., 2009a,b, in press). In this light, the current study investigates a range of SMA methods to assess defoliation in a Blue Gum (*Eucalyptus globulus* Labill) plantation in southern Australia from both multi-spectral and hyperspectral satellite images. The objectives of this study are three-fold:

(i) Explore the potential of SMA for defoliation monitoring in broadleaved forests, i.e., mixed-aged Eucalyptus plantations;
(ii) Introduce a novel SMA technique for better accounting the natural variability in the conditions of the surface components, i.e., the endmember variability problem;
(iii) Compare its performance on both multi- (i.e., *Landsat 5-TM*) and hyperspectral (i.e., *Hyperion*) satellite data.

2. Materials

2.1. Description of the study area and damaging agents

An area of approximately 30,000 ha of Blue gum (*E. globulus* Labill.) plantation, located at Wattle Range near the state border between Victoria and South Australia was selected as the study site for this research. The trees are planted in grids of 4 m × 4 m resulting in planted stockings of approximately 1200 stems per hectare. The youngest stands were planted in 2006, the oldest in 2000. This region is characterized by low-relief topography (mean elevation ±65 m) and generally sandy loam soils that increase in depth towards the north. Mean monthly temperatures range from a maximum of 20 °C in February to a minimum of 9 °C in July. Mean annual precipitation in this region is approximately 709 mm (Mt. Gambier airport) and average annual pan evaporation is approximately 1350 mm, which makes plantations in this area susceptible to drought stress. Understorey vegetation is usually sparse but *Phelaris* grass, a widespread weed in this region, occasionally creates a lush understorey in more poorly drained areas.

The major vectors of defoliation in the study area are insect pests and diseases, drought and frost. Most of the biotic defoliators are herbivores such as spring beetles (*Liparetrus* spp.), grasshoppers, Chrysomelid Leaf beetles (*Chrysophtharta, Paropsis* spp.), leaf blister sawfly (*Phylacteophaga froggatti* spp.), Christmas beetle (*Anoplognathus* spp.) and Autumn gum moth (*Mnsesampela privata*) (Smith et al., 2008a,b). The main disease causing defoliation is *Mycosphaerella* spp. which is a fungus that infests juvenile leaves (Pietrzykowski et al., 2008).

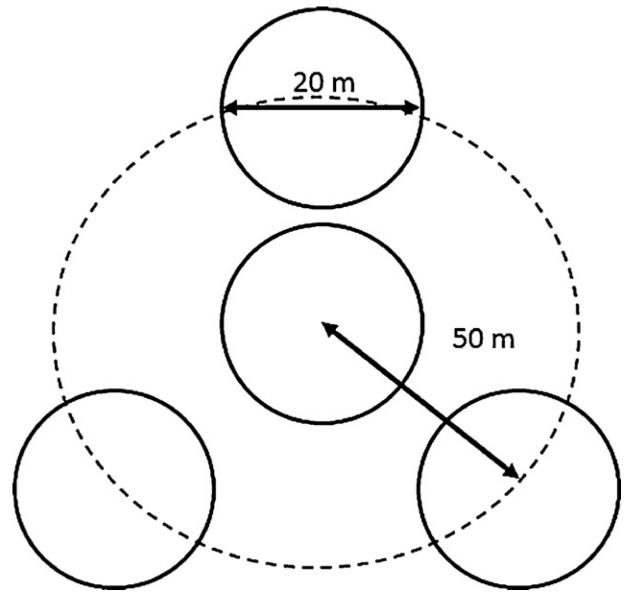

Fig. 1. Cluster plot design based on the USDA's FIA plot design.

2.2. Field data collection

The forest inventory and health data was measured using a four-subplot cluster plot configuration similar to that of the USDA's Forest Service's Forest Inventory and Analysis (FIA) approach (USDA Forest Service, 2003; Haapanen et al., 2004). The sampling scheme was established within the Cooperative Research Centre for forestry (http://www.crcforestry.com.au/) framework as a multi-purpose study area for long term forest monitoring aiming at the integration of field data with a range of remote sensing analyses (Stone et al., 2008).

In the study area 46 plots were established using a stratified random sampling approach. Plot locations were stratified by stand age and to ensure that plots were widely distributed throughout the study area. The plot design, illustrated in Fig. 1, consists of four 10 m fixed-radius circular subplots per cluster, with each of the three outer subplots located 50 m from the centre subplot. 12 trees were randomly selected for forest health and growth measurement within each subplot, with four in each cardinal direction from the cluster centre.

Forest inventory (i.e., height and diameter-at-breast-height) and visual defoliation measurements were collected in March 2008 for all selected trees within the 46 plots. Defoliation was estimated in comparison to the expected foliation levels for a healthy crown, as determined by forest health experts (Smith et al., 2008a,b), and indicate the leaf area judged to be missing compared to a local healthy reference tree (Barry et al., 2009). A local reference tree is here defined as the most vigorous tree with full foliage (0% defoliation) that could grow at a particular site, and accounts for factors including altitude, latitude, tree age, site conditions and social status. This tree represents the typical crown morphology and age of trees in the plot (Eichorn et al., 1996). Similar techniques for defoliation assessment are used by USDA Forest Service (USDA Forest Service, 2003; Redfern and Boswell, 2004). Defoliation percentage of the whole tree is the sum of defoliation of the new and old foliage of the upper and lower crown (Barry et al., 2009). Mean defoliation scores were derived for each plot to obtain a spatially

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