Biochemical properties from dual-wavelength laser scanning: Deriving equivalent water thickness at leaf to canopy scales.

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Highlights: Improved measurements of canopy biochemistry can allow better monitoring of tree health. The SALCA instrument is able to estimate equivalent water thickness of individual leaves from dual-wavelength laser reflectance. This paper presents the results of a controlled drought experiment and field-based tests for retrieving moisture content at forest canopy scales.

Key words: *terrestrial laser scanning, canopy moisture, tree health, multispectral LiDAR.*

Introduction

Tree health is an area of growing concern internationally. In many countries, alterations in climate are likely to cause significant increases in temperature and increased frequency and severity of extreme droughts. Recent increases in tree mortality caused by drought suggest that climatic factors may already be resulting in forest die-back in some regions (e.g. southern parts of Europe) [1]. In addition, an increased rate of global occurrence and spread of non-native tree pathogens and pests is occurring and climate changes are leading to an alteration in host and pathogen distribution and host susceptibility [2]. Early detection is vital in reducing spread of infections and methods to detect early symptoms of disease (e.g. water stress, defoliation) and physiological stress will be of major benefit to forest management. The lack of adequate data on forest health status globally has been identified as a key information gap in understanding climate change risks for forests [1].

Estimation of leaf and canopy biochemical properties (e.g. leaf pigment and water concentrations) from remote sensing can provide a means to monitor tree health over extensive areas and at frequent intervals. Leaf moisture content, often measured as Equivalent Water Thickness (EWT), is an essential early indicator of forest drought stress, infection by tree diseases and forest pests and is of key importance as an input to models of forest fire susceptibility, ignition and propagation. Whilst a range of existing physiological approaches can be used to measure vegetation stress and EWT in the field, the scope of such approaches for examining temporal and spatial heterogeneity and for long-term monitoring is limited. A number of spectral indices based on near infrared (NIR) and shortwave infrared (SWIR) wavelengths have been developed that strongly relate to EWT and these have been widely applied to satellite data. However, accurate and appropriate validation measurements are crucial if such data are to be fully utilised. Measurements of subtle variations in biochemical parameters and plant health using passive optical sensors are also complicated by the dependence of reflection on illumination and viewing geometry, shadowing effects and the presence of other objects within the pixel (e.g. woody material, understorey vegetation, bare soil). Understorey and canopy response cannot be easily separated, even when passive optical data is fused with LiDAR.

Active reflectance measurements from laser scanners have the potential to overcome these issues, whilst simultaneously providing 3-D information on forest structure and health. Experimental dual-wavelength or multispectral systems have been shown to be capable of assessing crop foliar nitrogen levels [3] and monitoring changes in needle Chlorophyll content over time [4]. This paper examines the ability of a dual-wavelength laser scanner (the Salford Advanced Laser Canopy Analyser, SALCA) to detect changes in leaf and canopy water content due to drought stress and disease. This is tested through a series of experimental and field-based studies from leaf through to canopy scales. The scanner technology and calibration is first described, followed by experimental tests of the instrument at leaf then small canopy scales. Finally applications in real forest canopies are considered.

The Salford Advanced Laser Canopy Analyser

The SALCA instrument is a dual-wavelength terrestrial laser scanner, operating at NIR (1063 nm) and SWIR (1545nm) wavelengths. The system records the full-waveform of backscattered energy in 15cm range bins, with a maximum range of 105m and acquires data over a full hemisphere above the instrument, generating 9.6 million waveforms in a full resolution (1.05 mrad angular resolution) scan. Full details of the instrument can be found in [5]. Estimates of return energy in each wavelength can be extracted from the waveform for individual targets.

For large solid targets, the averaged peak intensity measured provides a sufficient estimate for calibration to apparent reflectance [6]. However, for typically diffuse returns from vegetation canopies, the sum of digital numbers recorded over all bins comprising the return provides a more accurate and consistent measure of return energy [7] and is used here for canopy-level processing. Return energy is then calibrated to apparent reflectance in each wavelength, based on the range of the return and the deployment of calibration boards with panels covering a range of reflectance in the scan, to account for variations in laser output energy (largely due to temperature variations).

Experimental leaf and canopy scale measurements

In laboratory experiments in which individual leaves of three different species were dried and repeatedly scanned over a period of time, a significant linear relationship was obtained ($R^2 = 0.8$, RMSE = 0.0069 g cm^{-2}) between a normalised difference index (NDI) of the two SALCA wavelengths (1063 nm and 1545 nm) and the EWT of the leaves [6]. SWIR reflectance increased significantly as the leaves dried. A small increase in NIR (1063nm) reflectance was also observed from dry leaves. Normalised Difference Index from SALCA also varied significantly at a within-leaf scale, suggesting fine-scale spatial variability in EWT and / or leaf structure [6].

These results indicate potential for retrieval of EWT from active dual-wavelength laser scanner measurements. However, to apply the method at the canopy scale introduces a number of challenges. Woody material within the laser footprint is likely to influence the return intensity when working at a canopy scale, whilst the ability to detect biochemical properties of partially occluded leaves (partial laser returns) has not been experimentally tested. To investigate the potential to measure EWT at canopy scales, a controlled 'dry-down' experiment was conducted in June to July 2013. 15 potted small-leaved lime (*Tilia cordata*) trees (approximately 4m tall) were exposed to varying degrees of drought stress over a 1 month period. The pots of two groups were sealed, whilst control groups were regularly watered. Trees were scanned with SALCA several times per week and leaf spectral reflectance, stomatal conductance, Chlorophyll content and soil moisture were measured at the time of laser scans. A subset of trees were used to provide destructive samples of leaf EWT throughout the experiment. Return energy was retrieved from waveform data and calibrated to apparent reflectance as described above.

From field spectroscopy measurements of leaves, the normalised difference index (NDI) equivalent to that calculated by SALCA ($(\rho_{1063}-\rho_{1545})/(\rho_{1063}+\rho_{1545})$, where ρ is apparent reflectance) stayed relatively constant or increased for the control group trees (mean value ranging from 0.29 at the start to 0.34 at the end) but decreased for trees subjected to drought stress (from 0.33 to 0.18 for drying group 1 and 0.3 to 0.18 for drying group 2) over the course of the experiment. The extent of variability in the spectral index between leaves also increased as drought stress increased, suggesting leaves within the same canopy dried at different rates. Processing of SALCA data is ongoing to obtain relationships with EWT and to examine the extent of variability in the SALCA NDI within the canopies and these final results will be presented at the conference. As with laboratory measurements, the 1545nm apparent reflectance can be seen to increase markedly in the drying groups by the end of the experiment compared to the watered control, whilst the 1063nm reflectance increases to a lesser extent (Figure 1).

Forest canopy scale measurements

In real forest canopies, occlusion will play a greater role and differences in range and scanning angle across the scans will be greater, introducing increased variation in return energy, whilst differences in biochemistry (e.g. EWT) within and between canopies may be more subtle than under experimental conditions. Many UK forests are also coniferous plantations, and the presence of needles rather than broad-leaves will increase the number of partial returns from objects only partly occupying the laser footprint. As yet the ability of dual-wavelength or multispectral terrestrial laser scanners to detect variation in leaf biochemistry within mature forest canopies in field conditions is untested. To examine the potential to detect variations in EWT in forest canopies, four SALCA scans were acquired in forest plots in the Queen Elizabeth II Forest Park, Aberfoyle, Scotland during summer 2014. The scans took place in four Scot's pine (Pinus sylvestris) and Lodgepole pine (*Pinus contorta*) stands with contrasting severities of *Dothistroma septosporum* infection, a fungal infection of which one symptom is decreases in needle moisture content. Trees were visually surveyed to record disease levels and limited needle samples were analysed for EWT and spectral reflectance (measured with an ASD FieldSpecPro field spectrometer). This paper will present the preliminary results of this forest-canopy-scale analysis, comparing the calibrated canopy NDI to observed disease levels.

Conclusions

Active reflectance measurements from a dual-wavelength terrestrial laser scanner allow measurement of equivalent water thickness of individual leaves in laboratory conditions. At canopy scales, a number of complicating factors, such as the presence of occlusion, partial hits and mixed returns from woody material and foliage may complicate the retrieval of biochemical parameters from laser return energy. Despite these factors, distinct changes in apparent reflectance can be detected in trees subjected to drought stress under experimental conditions. This paper presents initial results of this experiment and of trials of dual-wavelength laser scanning for detection of stress resulting from disease in forest canopies measured in field conditions.

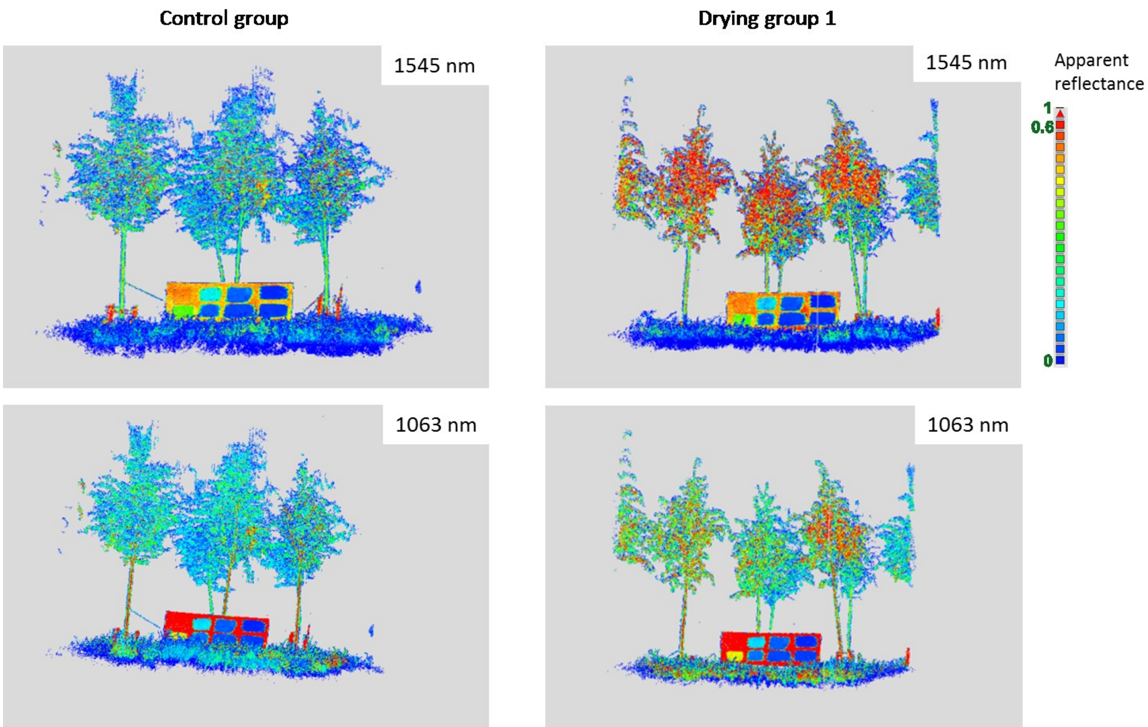

Figure 1: Comparison of apparent reflectance in the control group (watered) and drying group 1 (drought stressed) on day 21 of the experiment for 1545 nm wavelength and the 1063 nm wavelength of SALCA.

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