Improving estimates of leaf area index with a dual-wavelength full-waveform TLS: The Salford Advanced Laser Canopy Analyser (SALCA)

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Highlights: Calibrated laser reflectance in two wavelengths was used to extract returns resulting from leaf hits and corrected for amount of material in each footprint and clumping of material. True LAI was calculated using an inversion of gap fractions, validated for individual trees, and analysed for multi-temporal forest plots.

Key words: *TLS, LAI, phenology, dual-wavelength, calibration, SALCA*

Introduction

In the past decade, Light Detection And Ranging (LiDAR) systems have proven their ability to collect three-dimensional (3D) datasets with high detail and accuracy. Applications for forest structure measurements and associated biophysical parameters have been demonstrated from both airbourne (ALS) and ground-based (TLS) laser scanning systems. However, challenges still remain that limit the full characterisation of tree structures from these sensors. One of these is the inability to directly distinguish returns resulting from woody and leaf material. As a result, important ecological parameters such as leaf area index (LAI) and foliage profiles are often calculated from the entire forest point cloud leading instead to the generation of plant area index (PAI) and whole plant profiles. The accurate separation of tree leaf and wood returns would have far-reaching benefits including increasing accuracy in forest structural measurements, providing a validation tool for other indirect approaches, and in reducing uncertainty in hydrological, ecological, and climate modelling. Carbon allocation among tree organs is a topic of significant ecological interest due to the differing functioning roles of wood as slow decomposable carbon pools with low metabolic activity, and leaves as fast decomposable dynamic carbon pools which control moisture, gas exchange, and collect radiation. The relationship between ecological processes and Gross Primary Production (GPP) differs between the tree components and therefore their potential effect on carbon sequestration in times of rising carbon dioxide. It has been found that total biomass alone is not a good predictor of carbon flux in forests [1]. Therefore rather than assuming whole plant carbon use, it has been recommended that estimates are made by component. Forests are also sensitive indicators of climate change *via* vegetation phenology. Improved measurements of the seasonal accumulation and loss of leaf material would provide a significant resource with which to examine how species and ecosystems have responded to temperature variations and how they may respond to future climate change [2].

Although the physiological mechanisms involved in leaf and woody material growth are relatively well understood, directly measuring how much of each pool is present at one time, and its spatial and temporal characteristics, poses a significant challenge in structurally complex heterogeneous forest environments. Recent development of innovative multi-spectral sensors could provide a solution. Multi-spectral TLS instruments measure their surroundings using different wavelengths of radiation exploiting the spectral properties of forest target features. The aim of this paper is to offer an improved approach to estimating leaf area index with dual-wavelength full-waveform TLS.

The Salford Advanced Laser Canopy Analyser

The Salford Advanced Laser Canopy Analyser (SALCA) [3] is a dual-wavelength full-waveform TLS. The sensor was developed by the University of Salford and Halo Photonics Ltd as an experimental research instrument to measure forest canopies using a hemispherical scanning pattern. Two lasers are fired for every one 'shot' at wavelengths 1545nm and 1063nm and the full backscattered signal from both is recorded. Information is extracted from the return signal by decomposing each full waveform into a series of individual echoes using custom built algorithms.

An improved method of LAI estimation from TLS

The ability to generate apparent reflectance from a laser scanning system is essential for inferring information on target properties. In forest environments, this relates to data of increased ecological value and is the first step to distinguishing leaves from woody material, as well as parameters relating to the health of vegetation. For the SALCA instrument, a novel approach has been applied to perform a radiometric calibration using artificial neural networks to convert recorded intensity into reflectance with a RMSE of 6% for both wavelengths. Based on the reflective properties of leaf and woody components in the wavelengths inherent to SALCA, and demonstrated in [3] and [4], taking a reflectance ratio of the wavelengths at each point should allow separation of these materials. Returns were matched between wavelengths and the SALCA Normalised Ratio Index (SNRI) calculated according to (equation 1):

$$SNRI = \frac{(\rho_{1063} - \rho_{1545})}{(\rho_{1063} - \rho_{1545})} \qquad (1)$$

where ρ indicates reflectance. A threshold was then applied to separate the point cloud into two components representing leaves and wood. This allowed LAI to be calculated directly from the photosynthetically active material alone. To take into account the amount of material in each shot a weighting was applied based on the leaf reflectance of a 'full hit'. Leaf area index, the most important variable for modelling a range of ecological processes, was then derived using an inversion of the gap fraction model (equation 2):

$$LAI(z) = -2 \int_{0}^{\pi/2} \frac{\ln\left(P_{gap}(\theta, z)\right) cos\theta}{\Omega(\theta)} sin\theta d\theta \qquad (2)$$

where LAI is the leaf area index; $P_{gap}(\theta, z)$ is the gap fraction in the direction of the zenith angle θ at height z, and; $\Omega(\theta)$ is the canopy element clumping index. The clumping index measures the spatial aggregation of foliage elements, and was calculated by applying nearest neighbour point pattern analysis to each leaf point cloud in a 3D domain. Incorporating the clumping index corrects for the non-randomness in the 3D distribution of the foliage that often leads to underestimation of LAI.

From a single tree to multi-temporal forest plots

This approach was first tested on SALCA scans of three individual oak trees. Accuracy was assessed using destructive sampling of foliage carried out at the Forest Research UK site at Alice Holt, Farnham, in July 2014 as part of a collaboration initiative with Forest Research, University College London (UCL), University of Newcastle, and University of Salford.

Secondly, the spatial and temporal characteristics of LAI was examined for a range of common UK forest plots. Data was acquired over 32 field visits to Delamere Forest, Cheshire, UK, over a full annual phenological cycle between March 2014 and April 2015, and included broadleaf deciduous, evergreen conifer, and deciduous conifer species. Coincident digital hemispherical photographs were also acquired. This paper report s the first results of this experiment demonstrating accurate, fully validated, estimates of true LAI at different forest stands.

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