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Introduction

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The terrestrial laser scanning revolution in forest ecology

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New laser scanning technologies are set to revolutionize the way in which we measure and understand changes in ecosystem structure and function. Forest ecosystems present a particular challenge because of their scale, complexity and structural dynamics. Traditional forestry techniques rely on manual measurement of easy-to-measure characteristics such as tree girth and height, along with time-consuming, logistically difficult and error-prone destructive sampling. Much more detailed and accurate three-dimensional measurements of forest structure and composition are key to reducing errors in biomass estimates and carbon dynamics and to better understanding the role of forests in global ecosystem and climate change processes. Terrestrial laser scanners are now starting to be deployed in forest ecology research and, at the same time, new terrestrial laser scanning (TLS) technologies are being developed to enhance and extend the range of measurements that can be made. These new TLS measurements provide a tantalizing glimpse of a completely new way to measure and understand forest structure. It is therefore a good time to take stock, assess the state of the art and identify the immediate challenges for continued development of TLS in forest ecology.

1. Introduction

This issue of *Interface Focus* is a collection of papers based on invited presentations at a Royal Society Theo Murphy Scientific Meeting held at the Kavli Royal Society International Centre, Chicheley Hall, UK, on 27–28 February 2017. The meeting was organized by Prof. Mark Danson, Dr Mat Disney, Dr Rachel Gaulton and Prof. Crystal Schaaf and was attended by around 70 participants representing 12 different countries. In addition to the invited presentations, available as audio recordings at https://royalsociety.org/science-events-and-lectures/2017/02/forest-ecology, a poster session provided an opportunity for a further 18 authors to present and discuss their work with meeting participants.

The planning of the meeting was underpinned initially by the activities of the Terrestrial Laser Scanning International Interest Group (TLSIIG), initiated by Prof. Alan Strahler and others, at the SilviLaser meeting in Vancouver, Canada, in 2012. TLSIIG is an informal network with more than 170 participants with an interest in the ecological applications of terrestrial laser scanning (TLS) (https://tlsiig.bu.edu/). The group conducted a TLS intercomparison experiment in Australia in 2013 and a series of follow-up workshops in the UK, France and Finland in 2014 and 2015. In 2015, the group successfully gained funding from the US National Science Foundation for a Research Coordination Network (RCN grant no. DBI-1455636) under the leadership of Alan Strahler and Crystal Schaaf. The RCN now has 70 participants representing 31 institutions and nine countries with the objective of developing new applications of TLS in forest ecology. The Royal Society

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meeting provided an opportunity for researchers in the RCN and beyond to come together in a highly focused and interactive environment in order to discuss their research, highlight successes and identify future challenges in the field. A particular aim of the meeting was to invite a diverse range of researchers from areas such as ecology, functional structural plant modelling and forest dynamics, in order to see how new developments in TLS might change their thinking.

The first two papers in this special issue are reviews written by ecologists working with TLS data. Malhi *et al.* [1] provide an ecological perspective on the challenges of applying TLS to characterize tree form. They outline how the pioneering work of the French botanist Francis Hallé and his 23 models of tree forms is now being extended with TLS data to develop new mechanistic theories of tree growth and development, and to test fundamental theories of metabolic scaling, which have proved extremely difficult to test any other way.

In a second review, Orwig *et al.* [2] outline the potential role of TLS in a wide range of ecological applications, focused on Harvard Forest, MA, USA. This famous test site has seen a range of new laser scanning devices deployed over the last decade aimed at characterizing forest stand dynamics. Work in the ForestGEO plot, which serves as a model for forest change in New England, includes the impacts of the invasive hemlock woody adelgid (*Adeleges tsugae*). New developments in TLS technology are introduced in the papers by Danson *et al.* [3] and Li *et al.* [4], where the concepts and applications of multi-wavelength full-waveform data collection are introduced. To date there are no commercial TLS instruments that provide both full-waveform data and measurements in two or more laser wavelengths. These papers together introduce and evaluate two experimental TLS systems that have been specifically developed to measure the structural and biophysical characteristics of forest canopies. Both focus on the particular problem of separating TLS point clouds into leaf and wood components.

There follows a series of papers on developing applications of TLS in forest ecology. Disney *et al.* [5] describe new methods for deriving above-ground biomass estimates for forest stands using geometric models from which tree volumes are computed. They emphasize the large errors in current allometric equations, particularly in tropical regions. They also assess the role of TLS measurements in reducing this uncertainty, as well as providing baseline measurements for forthcoming spaceborne missions to map forest structure. Elsherif *et al.* [6] take a novel approach to the estimation of leaf water content using TLS data. They deploy two laser scanners with different wavelengths to measure tree leaf water content, merging the point clouds and deriving a normalized difference index. The index is strongly correlated with water content in both needle-leaved and broad-leaved trees, and so provides quantitative measurements of the three-dimensional distribution of leaf water content. Åkerblom *et al.* [7] use a new approach to insert modelled oak leaves into geometric models of oak trees that have been derived from leaf-off scans recorded in the winter. The reconstructed leaf-on trees are then compared with destructively sampled data as validation. The method has potential applications in better understanding the issues in tree volume estimation for leaf-on TLS data, and for cross-validation of leaf area index estimates derived from TLS.

Several issues relating to the spectral and spatial characteristics of TLS data are addressed in the next series of papers. Kaasalainen *et al.* [8] demonstrate the importance of incidence angle effects on the intensity measurements recorded by TLS. They use their multi-wavelength TLS instrument to characterize the wavelength dependence of incidence angle and leaf structure effects on all TLS measurements. These effects may be minimized using ratios of wavelengths that are spectrally close and will be important in future systems using multiple wavelengths across the visible and short-wave infrared region. Spatial relationships between the three-dimensional shape of ecological objects and TLS point clouds are explored in the paper by Paynter *et al.* [9]. They show that the volume of ecological objects derived from a range of geometric models fitted to TLS point clouds can vary significantly with the object shape characteristics and the model selected. They also argue that generalized quantification of scanning errors can be estimated from the lower error bounds of volumes derived by such fitting. Morsdorf *et al.* [10] bring some of these ideas together and consider both the extraction of physical information from and semantic labelling of TLS point clouds. They introduce the concept of occlusion mapping that will help in understanding the limitations of data from TLS for forest mapping, as compared with data from unmanned aerial vehicle (UAV)-based or other airborne laser scanning systems. This theme is picked up in the final paper in the issue by Roşca *et al.* [11], who compare UAV-based structure-from-motion aerial photography with TLS to measure top-of-canopy structure in a tropical forest.

Taken together these papers provide a broad perspective of the current research on the rapidly developing applications of TLS in forest ecology. They highlight technical developments that are expanding the range of measurements that can be made, the advances in computer-based modelling and analysis of TLS datasets, and the new types of information, derived from TLS, which will shape forest ecology in the future.

We would like to dedicate this issue of the journal to Dr Sandra Brown, who died shortly before the meeting was convened. Sandra was a strong supporter of our research, and of the Royal Society meeting and had planned to attend. A graduate of the University of Nottingham she gained an MSc and PhD in the USA, where she remained for most of her career carrying out pioneering work on the role of forests in the global carbon cycle. The influence of Sandra's work is seen throughout the research described in this issue of *Interface Focus* and it is therefore fitting that we remember her here.

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