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Terrestrial LiDAR: a 3D revolution in how we look at trees

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Summary

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Terrestrial laser scanning (TLS) is providing new, very detailed 3D measurements of forest canopy structure. The information that TLS measurements can provide in describing detailed, accurate 3D canopy architecture, offer fascinating new insights into the variety of tree form, environmental drivers and constraints, and the relationship between form and function, particularly for tall, hard-to-measure trees. TLS measurements are helping test fundamental ecological theories and enabling new and better exploitation of other measurements and models that depend on 3D structural information. This Tansley insight introduces the background and capabilities of TLS in forest ecology, discusses some of the barriers to progress, and identifies some of the directions for new work.

Keywords (5-8): light detection and ranging (LiDAR), 3D, structure, tree, canopy, function, terrestrial laser scanning (TLS).

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I. Introduction

Trees are deceptively simple; they are instantly and universally recognizable, captured by a child's drawing. This apparent simplicity belies a complex, extraordinarily effective and even beautiful solution to the problem of survival and adaptation on evolutionary time scales. Trees are slow-growing and static and yet thrive across diverse environments, forming complex multi-layered communities. Trees comprise a compendium of individual variations, both inter- and intraspecific, overlaid on the fundamental observable property of tree architecture: the 3D shape and arrangement of the above-ground part of the tree.

There have been many ingenious attempts to relate tree form and function (Fisher, 1984): Da Vinci's observation of the branch and trunk scaling (Richter, 1970); D'Arcy Wentworth Thompson's beautiful illustrations of size and strength (Wentworth Thompson, 1917 p73); tree archetypes (Hallé *et al.*, 1978); fractal approaches (Honda, 1971; Mandelbrot, 1983) and growth grammars (Prusinkiewicz & Lindenmeyer, 1990). Many of these approaches have used scaling arguments to explain form, via *inter alia*: pipe model theory and hydraulics (Shinozaki, 1964), mechanical constraints (McMahon & Kronauer, 1976), functional-structural relationship (Sievänen *et al.*, 2014), through to theories of metabolic function (West *et al*., 1997; Enquist *et al*., 2009; Price *et al*., 2012) and thermodynamics (Bejan *et al*. 2008).

Here, I describe new terrestrial laser scanning (TLS) measurements of above-ground 3D tree architecture. These data say nothing about below-ground structure, nor are they observations of function. But these very precise and detailed measurements of structure can help answer fundamental questions about tree size and shape, allometric scaling, metabolic function and plasticity of form. Perhaps most importantly, these measurements help us look at trees differently and ask new questions. **Figure 1** illustrates varying perspectives on the simplicity and variety of tree form, from children's drawings, through natural and urban-grown trees measured via TLS. This exemplifies the inter- but also intra-specific variations that TLS elucidates so clearly.

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II. Terrestrial laser scanning (TLS)

Light detection and ranging (LiDAR) using laser wavelengths in the visible and near-infrared domain have been used for several decades (Lovell *et al*. 2003; Newnham *et al*. 2015). Primarily developed for surveying, LiDAR sends out tens to hundreds of thousands of pulses per second which allow very precise measurement of the 3D position (and size) of reflecting targets. Terrestrial laser scanning (TLS) is a ground-based counterpart to air- and spaceborne LiDAR, and can measure 3D vegetation structure to potentially mm accuracy and precision at range of potentially several km. TLS measures 3D position via recording the time it takes pulses emitted in known directions to return to the sensor (in 'time-of-flight' systems), or from measuring the phase shift between a continuous outgoing signal and its reflected counterpart i.e. how many wave cycles out-of-step they are. Commercial TLS systems currently operate at single wavelengths, but there is much research-led development on dual or multiple wavelength systems to help differentiate leaf and wood as well as detect water status and biochemical composition (Danson *et al*., 2014; Howe *et al*., 2015). In the mid-2010s, small hand-held and mobile laser scanning systems (HMLS, MLS) emerged, with much lower range (few 10s of m), but designed for rapid, mobile scanning. Low cost, small size and increased speed may offset the lack of range, precision and detail to make HMLS/MLS a viable alternative to static systems for rapid characterisation of low-stature, sparse vegetation (Bauwens *et al*., 2016).

TLS beneath or within the canopy overcomes many of the limitations of the top-down views of aerial LiDAR, including: point density (>> 1000s of points per m^2), resolution (point sizes of cms at 100 m distance), penetration up through the canopy and with a complete view of the understory and terrain. This perspective is illustrated in **Figure 2**. Weighed against this are the much smaller coverage and the challenge of extracting quantitative properties. Exploiting TLS data for ecological applications has required a confluence of equipment, tools and methods, which in turn has stimulated new interest (Dassot *et al*., 2011; Newnham *et al*., 2015; Disney *et al*. 2018; Malhi *et al*., 2018; Wilkes *et al*., 2017).

New structural insights from TLS

TLS applications to trees and forests fall broadly into the following three categories: i) measurements that are made without TLS but could potentially be done better with TLS i.e. more quickly, more precisely, more directly or with added value; ii) measurements that can be made

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without TLS but may be impractical, expensive, destructive or very indirect; and iii) measurements that are only really feasible with TLS (particularly non-destructively and/or for large trees). The first category includes height, DBH, crown size, canopy gap fraction (and derived properties such as LAI). The second includes more detailed measurements of tree trunk form, taper and woody volume; leaf size, angle and shape; crown projection and crown form/shape; vertical profiles of leaf and wood material; size and shape of larger branches. The last category includes properties such as 3D crown interactions (**see Figure 2**); branch size, shape and angle for higher order branches; branch topology and path fraction (network analysis); detailed characterisation of the surrounding environment (understory, terrain, other trees).

III. Turning points into trees

Ecological insight arises via 3D tree architecture extracted from TLS point clouds. Progress in this has come from various directions. Procedural approaches have been used to develop visually realistic tree structures through stochastic growth rules, fractals and growth grammars such as 'L-systems' (Honda, 1971; Prusinkiewicz & Lindenmayer, 1990). Ecologically accurate models have also been considered (De Reffye *et al*., 1988; Potapov *et al*., 2016). General tree architecture metrics such as crown size and volume, lower trunk, larger branches, have been derived variously from freehand sketching, photography and manual digitisation (Preuksakarn, 2012). More detailed and quantitative crown morphological metrics of projection and volume have also been developed from TLS (Barbeito *et al*., 2017). However, reconstructing full 3D tree architecture i.e. topology, size (length, volume) and shape of every (or even most) branches, has proved much more difficult.

Challenges to extracting detailed 3D architecture include: automatically separating individual trees from large point clouds containing many trees (as opposed to TLS from a single tree), accounting for variations in density and resolution of point clouds (Burt *et al*., 2018) and dealing with gaps in coverage of branch and leaf structure caused by obscuring foreground objects (Wilkes *et al*., 2017). A significant further challenge is separating wood and leaf points (Yun *et al*., 2016) in leaf-on canopies. Current approaches exploit the 3D geometric properties of the point cloud - size, orientation, spatial context of clusters e.g. distance from non-leaf clusters - to classify leaves. This has the added benefit of potentially providing very detailed measurements of leaf size, shape and angle distributions. These are likely to be a great improvement over more indirect methods, not least because they are spatially explicit, rather than bulk, canopy-average values. Lastly, a general

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challenge to extracting accurate 3D architecture from TLS is weather: wind speeds need to be near zero ideally and no more than a few ms^{-1}, with no rain or snow. Wind effects can make it impossible to retrieve fine detail, although larger trunk and branch measurements are unaffected.

3D architectural reconstruction

The adoption of TLS for ecological applications has led to development of robust automated methods for extracting crown-scale morphology metrics, as well as full 3D architecture. Extracting crown shape and related metric is attractive where detailed within-crown architecture is less important. These developments show great promise for applications relating to light interception (Côté *et al*., 2009), competition and demography (Taubert *et al*., 2015; Barbeito *et al*., 2017), and function more generally (Pretzsch, 2014).

TLS point clouds with increasingly high resolution have opened the possibility of full topological reconstruction, primarily via local clustering and shape fitting (Yan *et al*., 2009; Preuksakarn, 2012). These approaches tend to 'follow' the tree geometry up through the point cloud, segmenting it into trunk and branch sections constrained at either end by bifurcation. Each section is then enclosed e.g. by multiple cylinders fitted along its length to account for localised variations in shape and orientation (Raumonen *et al*., 2013; Hackenberg *et al*., 2014). In this way, branches down to diameter of ~5 cm can routinely be reconstructed, even in dense, tall (> 40 m) canopies (branching order 5 or 6). As branch size decreases to the size of the laser beam, reconstructed shape and become much more variable. Reconstructing each tree many times provides a distribution of possible architecture, with uncertainty (Burt *et al*., 2018).

Once we have a 3D tree representation, how can we validate it, particularly non-destructively? Crown morphology metrics have the advantage of providing insight without the need for direct validation, although the task then is explaining their relation to function, competition etc. One approach is to use simulated TLS point clouds of 3D model trees, where the tree architecture is known (specified) *a priori* (Raumonen *et al*., 2013). This also allows sensitivity analysis of stochastic reconstructions and shows 'observed' and reconstructed tree structure (volume, branch size) agree to within a few % (Raumonen *et al*., 2013; Hackenberg *et al*., 2014). However, this is purely model-based, not real trees. In practice, a combination of simulation, indirect measurements and destructive sampling is needed.

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IV. Current and future applications of TLS

Above ground biomass (AGB) and allometry

One of the most direct application of TLS is estimating tree volume and, combined with wood density, AGB. Current estimates of AGB use empirical allometric scaling equations (ASEs) to relate tree size and shape (primarily of the trunk) to AGB as follows

$$ln(AGB) = \beta_0 + \beta_1 ln(D^2 H\rho)$$

where D is DBH, H is height and ρ is wood density (e.g. Chave *et al*., 2014). ASEs underpin all spatial estimates of AGB, including from remote sensing (Avitabile *et al*., 2016). The uncertainty of allometric AGB typically grows with species diversity and tree size due to the inherent heteroscedasticity of tree size-to-mass allometry and the undersampling of large trees (Clark & Kellner, 2012; Disney *et al*., 2018). Differences between AGB estimates can be large, partly due to allometric uncertainties (Mitchard *et al*. , 2014). Using TLS, we can measure the volume of many trees of all sizes (and varying shapes) than is possible destructively. These can be used to construct new, more general allometries as well better quantify uncertainties of existing ones (Réjou-Méchain *et al.*, 2017). **Figure 3** shows comparisons between TLS and destructive estimates of AGB or volume. TLS agrees to within a few % of destructive harvest values across sites and species. TLS is likely to be key to calibrating and validating new satellite estimates of AGB (Stovall & Shugart, 2018).

3D structure and metabolism

The metabolic theory of ecology (MTE) seeks to predict allometry across scales, from individual trees (West *et al*., 1997) to whole forests (Enquist *et al*., 2009), in terms of the fundamental constraints of mass balance, hydrodynamics, biomechanics, and thermodynamics. MTE encapsulates the relationship between size and metabolism in simple power law relationships, typically of the form $Y = Y_0 M^x$ where M is mass, x is the scaling exponent and Y_0 is some species- or environment-specific constant. MTE is attractive as it provides a way to both explain and predict allometry via clear testable hypotheses. But MTE is also the subject of much debate, as many specific assumptions and predictions are apparently not supported by observation (Price *et al*., 2012). TLS offers the opportunity to test MTE comprehensively for the first time, using measurements of many trees across size classes and environments (Malhi *et al*. 2018). **Figure 4** illustrates the architectural detail of a large tree revealed by TLS, which is needed to test MTE and other theories of tree form.

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Input to other 3D models

TLS can also benefit other areas of plant science that require information on 3D canopy architecture. Radiative transfer (RT) models are widely-used to understand the radiation regime in plant canopies for applications including energy partitioning, photosynthesis, stress response, and remote sensing parameter retrieval (Jetz *et al.*, 2016). Many of these models require detailed descriptions of 3D canopy architecture, which have been scarce to date but TLS is filling this gap. Côté *et al*. (2009) used TLS to derive crown envelopes for 3D RT model simulations. Calders *et al*. (2018) produced a 1 ha 3D model of deciduous woodland from TLS down to the leaf-level. The resulting RT model simulations are of photo-realistic quality, but crucially with an accurate underlying structural basis.

TLS-derived 3D architecture is also helping drive developments in Functional Structural Plant Modelling (FSPM) (Sievänen *et al.*, 2014). FSPMs seek to understand at the organ level how physiology and morphology interact in determining plant function, very often predicting 3D plant architecture in the process. Accurate TLS-derived architecture is being used to parameterise, constrain and test the structural predictions of FSPMs (Beyer *et al.*, 2017).

V. Conclusions

Understanding how and why trees take the variety of forms they do, and the implications for understanding their function, is a fascinating and important topic. Capturing tree form in a complete, quantitative and repeatable way is key to advancing this understanding. TLS allows us to make these measurements for the first time, and in the process explore our understanding of just what it is that makes a tree a tree. The adoption of TLS systems designed for surveying, by the ecological research community has led to new interest, experimentation and development of tools and methods. This virtuous circle of instruments, measurement and processing is advancing rapidly, opening new areas of research along the way in relating tree structure and function across scales. Unmanned aerial systems (UAS), aircraft and satellite remote sensing are providing additional opportunities to exploit these measurements. TLS is moving from the fringes to the mainstream, and has the potential to revolutionise our understanding of the 3D ecology of trees.

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Figure captions

Figure 1. **(a)** The response of Hazel Class (Year 2), Jubilee Primary School, Hackney (UK) when asked to draw a tree. **(b)** Terrestrial laser scanning (TLS) scans of plane trees (*Platanus* × *Hispanica*) in Russell Square, London (UK) showing height and mass (t), after Wilkes *et al*. (2018). **(c)** TLS scans of two coastal redwoods (*Sequoia sempervirens*), Armstrong State Park, California (USA), over 60 m tall. TLS data were collected using a Riegl VZ-400, using angular resolution of 0.02°, from *c*. 10 opportunistic scan locations in *c*. 0.25 ha in **(b)**; and 36 scan locations on a regular 10 × 10 m grid over 0.5 ha in **(c)**. Each scan takes *c*. 5 min in this configuration.

Figure 2. Terrestrial laser scanning (TLS)-derived tree architecture captured from beneath a deciduous broadleaf woodland canopy, Wytham Woods, UK (see Calders *et al*., 2018). Colours represent separate branch segments derived from the TLS data. 'Crown shyness' is clearly visible.

Figure 3. Comparison of terrestrial laser scanning (TLS)-derived estimates of tree above ground biomass (AGB) and volume, with values from destructive harvests. **(a)** Calders *et al*. (2015) TLS-derived and weighed AGB for three Eucalyptus species, Australia. **(b)** Gonzalez de Tanago *et al*. (2017) TLS-derived and destructive volume across three tropical sites, with buttressed and non-buttressed trees marked a and b, respectively. **(c)** Momo *et al*. (2017) TLS-derived and destructive volume from eastern Cameroon. In **(a, b)** the vertical bars represent the range of possible (stochastic) fits to the TLS data; in (**b, c)** the shaded area is the 95% confidence interval of the regression fit.

Figure 4. A chestnut-leaved oak (*Quercus castaneifolia*) scanned at Kew Gardens, one of the largest in the UK. **(a)** The tree pictured in leaf-off conditions. **(b)** Terrestrial laser scanning (TLS) point in black (sub-sampled by 90% for visibility) and the reconstructed architectural cylinder model (QSM) in red. The tree is 36.5 m tall, with a wood volume of 135 m^3 and has an extraordinary 33 km of branches, 80% of which are < 5 cm in diameter. As in Fig. 1, TLS data were collected using a Riegl VZ-400, from 10 locations in a ring of *c*. 30 m radius.

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Figures

(a)

(b)

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(c)

Figure 1. **(a)** The response of Hazel Class (Year 2), Jubilee Primary School, Hackney when asked to draw a tree; **(b)** TLS scans of plane trees (*Platanus × Hispanica*) in Russell Square, London showing height and mass (t), after Wilkes *et al*. (2018); **(c)** TLS scans of two coastal redwoods (*Sequoia sempervirens*), Armstrong State Park, California, over 60 m tall. TLS data were collected using a Riegl VZ-400, using angular resolution of 0.02°, from approx. 10 opportunistic scan locations in ~ 0.25 ha in **(b)**; and 36 scan locations on a regular 10 × 10 m grid over 0.5 ha in **(c)**. Each scan takes approximately 5 minutes in this configuration.

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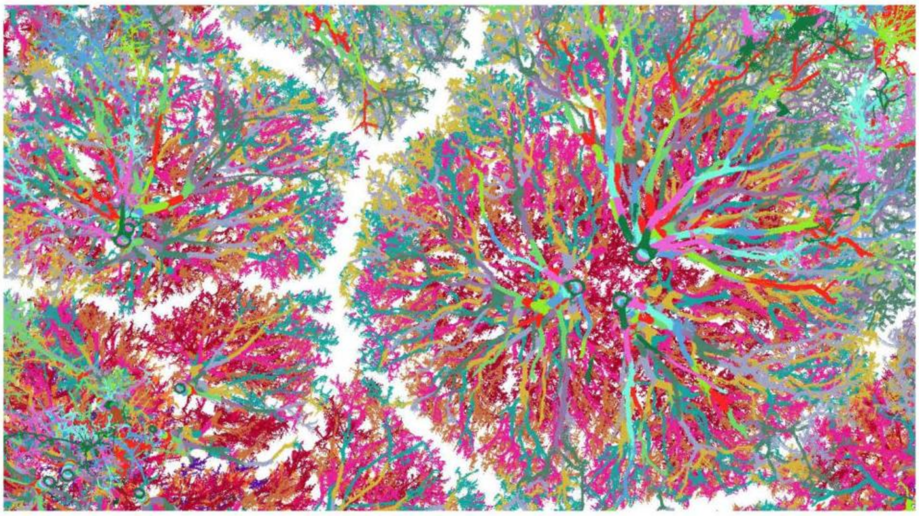

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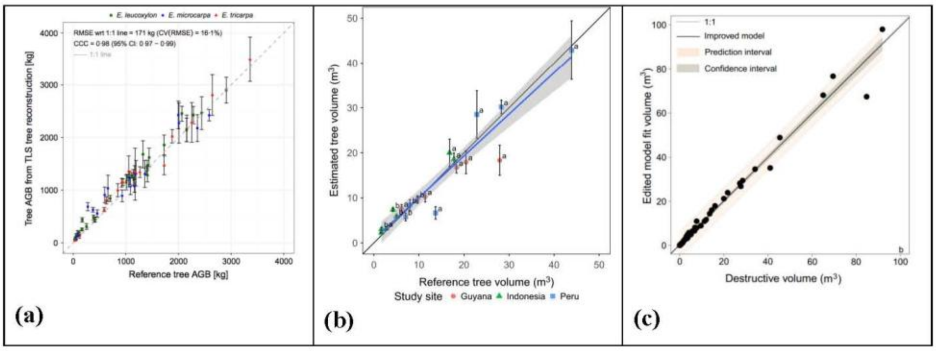

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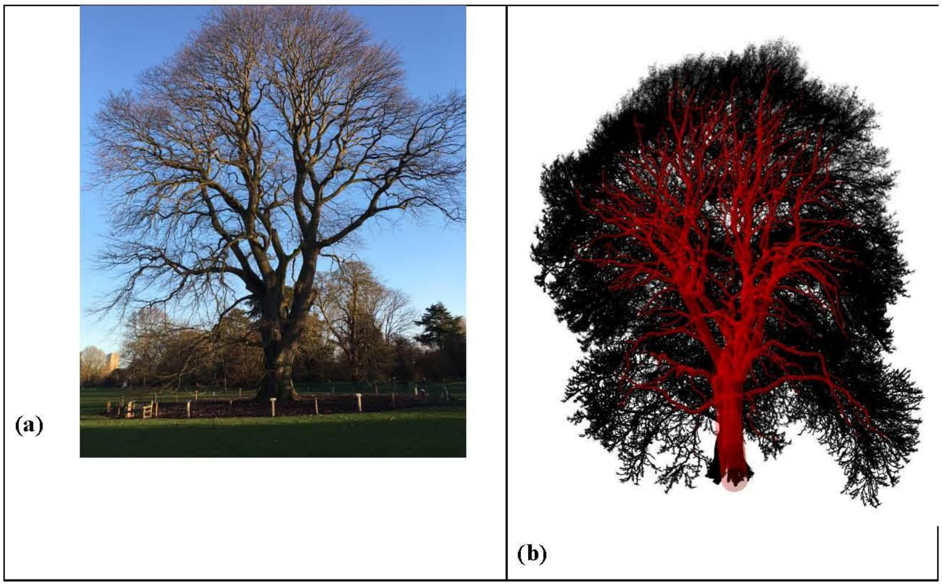

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