The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges

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REVIEW PAPER

The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges

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Abstract

• ***Introduction*** The use of terrestrial LiDAR (light detection and ranging) scanners in forest environments is being studied extensively at present due to the high potential of this technology to acquire three-dimensional data on standing trees rapidly and accurately. This article aims to establish the state-of-the-art in this emerging area.

• ***Objectives*** Terrestrial LiDAR has been applied to forest inventory measurements (plot cartography, species recognition, diameter at breast height, tree height, stem density, basal area and plot-level wood volume estimates) and canopy characterisation (virtual projections, gap fraction and three-dimensional foliage distribution). These techniques have been extended to stand value and wood quality assessment. Terrestrial LiDAR also provides new support for ecological applications such as the assessment of the physical properties of leaves, transpiration processes and microhabitat diversity.

• ***Results*** Since 2003, both the capabilities of the devices and data processing technology have improved significantly, with encouraging results. Nevertheless, measurement patterns and device specifications must be selected carefully according to the objectives of the study. Moreover, automated and reliable programmes are still required to process data to make these methodologies applicable specifically to the forest sciences and to fill the gap between time-consuming manual methods and wide-scale remote sensing such as airborne LiDAR scanning.

Keywords Terrestrial LiDAR scanner · Point cloud reconstruction · Tree structure · Forest management · Forest ecology

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1 Introduction

Trees are large and complex objects, and assessing the spatial organisation of trees within the forest is a key objective for both forest managers and researchers. Forest inventories consist mainly of measuring structural parameters on a sample of trees to assess their variability at the plot scale, together with the spatial position of stems and crowns and tree species identification. These measurements provide important information at the forest scale to assess the distribution of stem size and quality. It allows determination of the biomass and bioenergy resources and to predict forest product breakout according to the end use of trees. Current forest inventories based on allometric relationships from standard measurements of heights and diameters at breast height (DBH) generally lead to large errors, especially in commercial volume estimates. Forestry is becoming a more precise science and now requires additional parameters linked to the tree structure [e.g. stem shape and quality, branch biomass, leaf area index (LAI)] at different spatial scales and higher time resolution (Bélouard et al. 2005; Kint et al. 2009). Understanding the ecological processes of forest ecosystems (multi-scale distribution of light in canopies, gas and water exchanges, habitat diversity, competition and growth patterns) also requires complex structural data. Such detailed forest measurements still remain time-consuming, labour-intensive, are often destructive, and can be very expensive.

Since 2001, as a complement to traditional measurements, airborne LiDAR (light detection and ranging) technology has been used to rapidly describe forest structure over large areas. It makes it possible to collect information of use for forest inventories (tree location within plots, tree height, crown dimensions and volume estimates), as well as for forest ecology (vertical forest stratification, gas exchanges, transpiration and canopy carbon content) (Koetz et al. 2007; Maltamo et al. 2005). However, airborne LiDAR scanning provides limited information at the tree scale or under the canopy, which is required for certain forest applications. Complementary terrestrial LiDAR (T-LiDAR) technologies have therefore been implemented to obtain detailed information at the tree or plot scales. Triangulation T-LiDAR scanners have been used for accurate tree structure determination. However, because of their short measurement range (up to 3 m), this technique is limited to measurements at organ or potted sapling scales under controlled conditions (Chambelland et al. 2008). The availability of long-distance T-LiDAR scanners (a range of several tens of metres) in forest science, enabling measurements from underneath the canopy and providing information for scales ranging from needle/leaf to forest plot, allows the gap to be filled between tree-scale manual descriptions and wide-scale airborne LiDAR measurements.

However, the use of T-LiDAR scanners remains a technological challenge in forest environments because of the structural complexity of forests. With this in mind, numerous studies (reviewed in this article) have been conducted to develop methods to extract suitable information from T-LiDAR data. The aim of this article is therefore: (1) to briefly describe the principles of T-LiDAR technology and the diversity of instruments and data processing software; (2) to present the current applications of this technology for the structural characterisation of standing trees and the resulting applications in terms of wood product management or forest ecology; and (3) to discuss the important factors to be considered for forest measurements using this technology according to stated objectives, as well as the benefits and limitations.

2 T-LiDAR technology

T-LiDAR scanners are instruments that enable the non-destructive, rapid and precise digitisation of physical scenes into three-dimensional (3D) point clouds. Historically, T-LiDAR technology has been used for industrial and civil engineering applications, for example to digitise the external surface of buildings and archaeological sites. The principle of T-LiDAR technology is based on the emission-reception of a laser beam. The emitted laser beam is deflected by a mirror and automatically scans a scene, the laser being reflected by the first object encountered (Fig. 1). Coupled to the angular step values of the mirror, each reflected laser beam allows the measurement of a distance and the creation of a 3D point characterised by specific 3D coordinates and a reflectance value (fraction of the emitted light reflected by the target). The resulting 3D representation of the object is a point cloud composed of millions of points (depending on the selected resolution), representing the surfaces viewed by the scanner. As an option, digital single-lens reflex cameras (DSLR) can be mounted on the T-LiDAR rotating axis. Images provided by the camera can be mapped onto the point cloud provided by the T-LiDAR scanner to assign colour values to points (Lemmens 2009).

Two different scanning protocols can be distinguished in the case of T-LiDAR measurements: single scan or multiple scans. In the single scan method, the laser scanner is placed at a single location and only one scan is made. This method is the quickest, but only one side of the objects is represented in the point cloud. In the multiple scan method, several scans (generally three or four) are made around the objects. The geometrical transformation for merging these different scans into one point cloud is then made from the respective positions of at least three reference targets placed in the scene and common to both scans. This method increases field measurement times (depending on the number of scans) and processing steps (depending on the number of targets and the method used to detect it in the

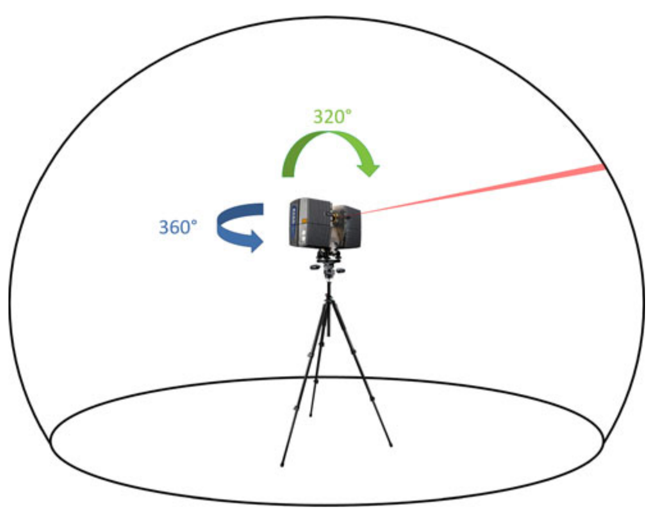

Fig. 1 Operating principle of a terrestrial LiDAR (light detection and ranging) scanner (FARO Photon 120). A laser beam deflected by a rotating mirror scans a vertical plane, and the complete rotation of the device allows hemispherical scanning. This results in the digitisation and the representation of surrounding objects in a three-dimensional (3D) point cloud

point cloud, i.e. automatic or manual detection). However, it ensures the most complete 3D description of the objects.

3 T-LiDAR scanners

T-LiDAR scanners are generally separated into two classes according to their range measurement principle: phase-shift or pulsed time-of-flight.

3.1 Phase-shift T-LiDAR scanners

In the case of phase-shift scanners, distances are estimated by analysing the phase shift between the continuously emitted and received laser beam. Only one return is recorded for each direction (Fig. 2a). Such instruments allow wide fields of view, very high point quantities and fast acquisition speeds (Table 1). Due to their range, phase-shift based scanners are well suited for high precision and detailed measurements of relatively near scenes (up to 100 m). They generally use visible wavelengths (600–800 nm), but some scanners using infrared wavelengths have appeared on the market (FARO 2010; Lemmens 2009; Pfeifer and Briese 2007; Zoller + Fröhlich 2010).

3.2 Time-of-flight T-LiDAR scanners

The time-of-flight technique is based on the calculation of the time between emission and reception of a laser pulse, divided by two. These characteristics allow very long measurement distances but relatively low acquisition speeds (Table 2). This type of T-LiDAR scanner generally uses near-infrared wavelengths (900–1,500 nm) and is well suited to 3D reconstruction of scenes at larger distances (beyond 100 m). Time-of-flight devices are generally characterised by narrow vertical fields of view. Four recording methods can be distinguished for time-of-flight scanners according to the number of return signals computed for each direction and the detection capabilities of the LiDAR sensor: (1) single return recording (for the first object that reflects a portion of the laser pulse, Fig. 2a); (2) first/last return recording (for which either the first, the last or both reflected signals are selectable, Fig. 2b); (3) multiple return recording (up to five signals, Fig. 2c); and (4) full waveform recording (continuous signal echo recording, Fig. 2d). For the first three technologies, only signal peaks are recorded according to specified thresholds. Both the third and fourth methods (and to a lesser extent, the second) provide multi-depth information when the laser spot is not fully intercepted by the first object encountered but partially intercepted by several objects. In addition, full waveform T-LiDAR scanners analyse the whole reflected signal, leading to a better assessment of the structure of the target (Jupp et al. 2009; Lemmens 2009; Optech 2010; Pfeifer and Briese 2007; RIEGL Laser Measurement Systems 2010).

4 Point cloud processing programmes

Point clouds are unstructured data that must be reconstructed by dedicated programmes to provide information. Since the advent of laser scanners, several companies have

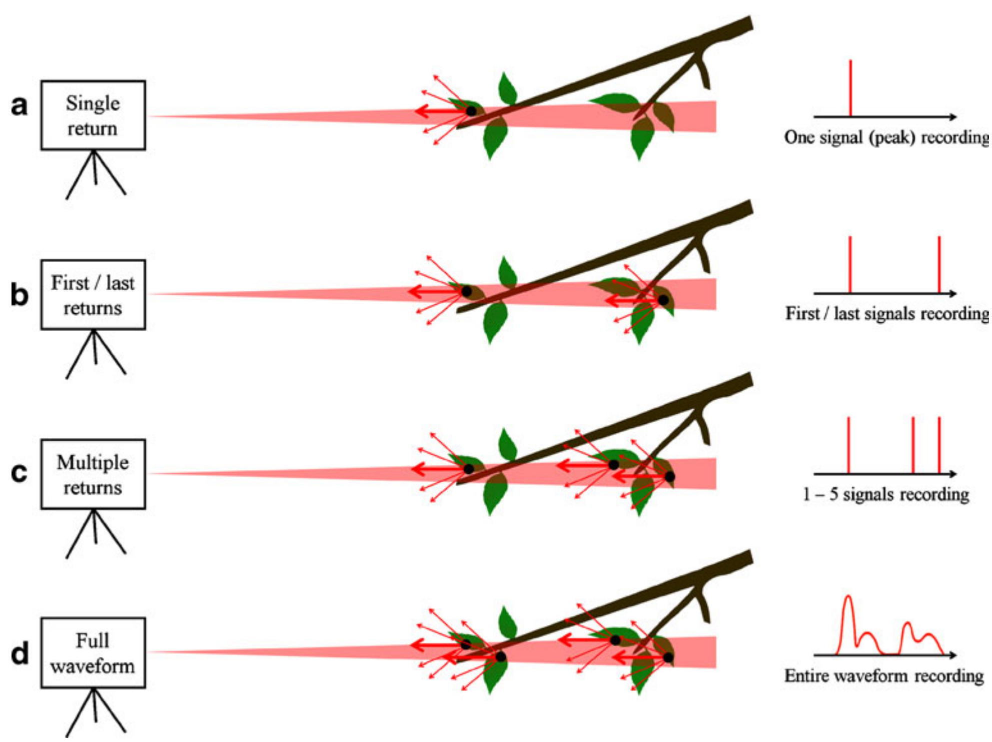

Fig. 2 a–d Types of laser returns. Depending on sensor capabilities, one or more signals can be recorded by the scanner. Phase-shift scanners only record a single signal (**a**), whereas four types can be found for time-of-flight terrestrial (T)-LiDAR. For the (**a**), (**b**), and (**c**) return types, only peaks (defined by specific thresholds) are taken into account. Full waveform T-LiDAR scanners (**d**) are able to record the entire waveform of the returning signal

Table 1 Specifications of some phase-shift T-LiDAR (terrestrial light detection and ranging) scanners and their evolution

	FARO LS 880 HE80[a]	FARO Focus 3D 120[a]	Zoller + Fröhlich Imager 5003[b]	Zoller + Fröhlich Imager 5010[b]
Availability	Commercial	Commercial	Commercial	Commercial
Date of introduction	2006	2010	2003	2010
Range finder	Phase shift	Phase shift	Phase shift	Phase shift
Wavelength (nm)	785 (visible)	905 (near infrared)	780 (visible)	1,500 (near infrared)
Return type	Single signal	Single signal	Single signal	Single signal
Measurement range (m)	0.6–76	0.6–153	1–53.5	0.3–187
Range accuracy (mm)	3 (at 25 m)	2 (at 25 m)	3 (at 25 m)	1 (at 25 m)
Spot size at exit (mm)	3	3.8	3	3.5
Beam divergence (mrad)	0.25	0.16	0.22	0.3
V x H field of view (°)	320 x 360	305 x 360	310 x 360	320 x 360
Acquisition rate (pts/s)	120,000	up to 976,000	up to 500,000	up to 1,016,000
Weight including peripherals (kg)	18.5	5	16	11.5

[a] http://www.faro.com

[b] http://www.zf-laser.com

provided their own engineering software suite. Such software suites are generic, designed mainly for industrial uses, but can also be used for forest structure assessment. Other point cloud processing software has been specifically dedicated to forest measurements. This is the case of Autostem™ software developed by the TreeMetrics Company (TreeMetrics, The Rubicon Centre, Bishopstown, Ireland). Table 3 presents a comparison of the uses and the limitations of some generic and specific software found in the literature for forest structure assessment.

5 Application of T-LiDAR scanners in forest science

Since 2003, numerous studies aimed at characterising standing trees from T-LiDAR data have been published. This section presents areas of forest science that can take advantage of T-LiDAR technology (Fig. 3), as well as devices and methods used to produce results according to the end-user's needs. Each sub-section also presents devices and programmes adapted to the application considered.

Table 2 Specifications of some time-of-flight T-LiDAR scanners and their evolution (for RIEGL scanners)

	RIEGL LMS-Z420i[a]	RIEGL LMS-VZ1000[a]	OPTECH Inc. Ilris-3D[b]	Echidna®[c]
Availability	Commercial	Commercial	Commercial	Experimental
Date of introduction	2003	2010	2002	2005
Range finder	Pulsed time-of-flight	Pulsed time-of-flight	Pulsed time-of-flight	Pulsed time-of-flight
Wavelength (nm)	1,550 (near-infrared)	1,500 (near-infrared)	1,535 (near-infrared)	1,064 (near-infrared)
Return type	First / last signal	Full waveform	First / last signal	Full waveform
Measurement range (m)	2–1,000	2.5–1,400	3–1,500	1–100
Range accuracy (mm)	10 (at 50 m)	8 (at 100 m)	7 (at 50 m)	30 (at 100 m)
Spot size at exit (mm)	8	7	14	29
Beam divergence (mrad)	0.25	0.3	0.15	2 - 15 (selectable)
V x H field of view (°)	80 x 360	100 x 360	40 x 40	267 x 360
Acquisition rate (pts/s)	up to 11,000	up to 122,000	up to 10,000	up to 10,000
Weight including peripherals (kg)	18	12	20	~ 40

[a] http://www.riegl.com

[b] http://www.optech.ca

[c] http://www.csiro.au/science/LidarDetection.html

Table 3 Example of software used for point cloud reconstruction

	AutoStem (TreeMetrics Ltd.)[a]	PolyWorks (InnovMetric Inc.)[b]	FARO Scene (FARO)[c]	Leica Cyclone (Leica Geosystems)[d]
Software type	Point cloud processing software dedicated to forestry	Retro-engineering software suite	Point cloud processing software	Retro-engineering software suite
Applications in the literature	Forest inventory measurements, plot-level wood volume estimates, optimal cutting calculation	Scan merging, forest inventory measurements, plot-level wood volume estimates	Scan merging, DBH estimates	Tree meshing
Benefits	Fully automated measurements	Polyvalent platform, advanced geometrical fitting, advanced meshing	Automatic scan merging	Polyvalent platform, advanced geometrical fitting, advanced meshing
Limitations	Restricted to conifer forests, restricted to forestry purposes	Semi-automated measurements, not adapted for advanced ecological purposes	Laborious measurements, not adapted for forestry / ecology	Semi-automated measurements, not adapted for advanced ecological purposes

[a] http://www.treemetrics.com

[b] http://www.innovmetric.com/polyworks

[c] http://www.faro.com

[d] http://www.leica-geosystems.com/en/HDS-Laser-Scanners-SW-HDS-Software_3490.htm

5.1 Using T-LiDAR for plot-level forest inventories

5.1.1 Standard dendrometric parameters

The first studies aimed at tree structure assessment using T-LiDAR scanners focused on characterising standard dendrometric parameters, i.e. stem diameters, tree height, stem density, basal area and commercial wood volumes. They aimed at demonstrating the potential of T-LiDAR scanning for faster and more accurate measurements compared to traditional field inventories. Several processing steps were developed to extract this information from T-LiDAR data. The first step is to establish a digital terrain model (DTM) created from the point cloud, which is the basis for further parameter extraction. The point cloud is separated into a horizontal grid with a regular cell size. In each cell, the lowest Z-value is selected and specified as a ground point (Simonse et al. 2003). Next, methods are used to detect tree trunks in point clouds and to determine diameters at breast height (DBH). All points situated in a layer with a height of between 1.25 and 1.35 m above the ground are extracted from the point cloud. Within this slice, all circular point clusters are detected using shape recognition techniques (Hough transformation, see Simonse et al. 2003, or least square circle fitting, see Bienert et al. 2006a, 2006b, 2007; Maas et al. 2008). Circle rings can be fitted on these clusters (considered as trunk sections), allowing for the determination of tree position and DBH, with good accuracy. Simonse et al. (2003) showed mean errors of approximately 5 cm for tree location and 1.7 cm for DBH estimation. These principles were used widely thereafter, and were extended to the determination of diameters at different heights to obtain the stem profile of trees (Aschoff and Spiecker, 2004). These estimations showed good accuracy (an error of approximately 1 cm) for heights ranging from tree bases to the lower part of crowns. Higher error levels in diameter estimation were found in the upper part of tree crowns because of the poor description of the stem caused by branches in the foreground (Henning and Radtke 2006a; Maas et al. 2008). Finally, Bienert et al. (2007) provided a complete set of algorithms allowing for stem segmentation (point cluster search), diameter fitting for the observed portion of the stem (least square circle fitting) and for the non-observable stem heights (polynomial model smoothing of the stem).

These pioneering studies demonstrated the potential of T-LiDAR scanning for the reliable extraction of the dendrometric parameters of standing trees. T-LiDAR measurements were then applied to plot-level forest inventories (DBH, tree height, stem density and basal area estimates) and compared to standard field inventories. These comparisons were carried out for coniferous, deciduous and mixed forests of various densities and showed very good results (Table 4). Plot-scale wood volume estimation is also necessary for forest harvesters and timber buyers. With this in mind, the TreeMetrics Company aggregated the algorithms described in Bienert et al. (2007) in the AutoStem™ software (Keane 2007). This then made it possible to automatically or manually process point clouds by recording diameters along tree stems at variable height intervals, leading to the calculation of plot-level stem volumes. AutoStem™ was used by Murphy (2008) to determine the value of Douglas fir stands. To do this, he first processed point clouds provided by a FARO LS800 HE80

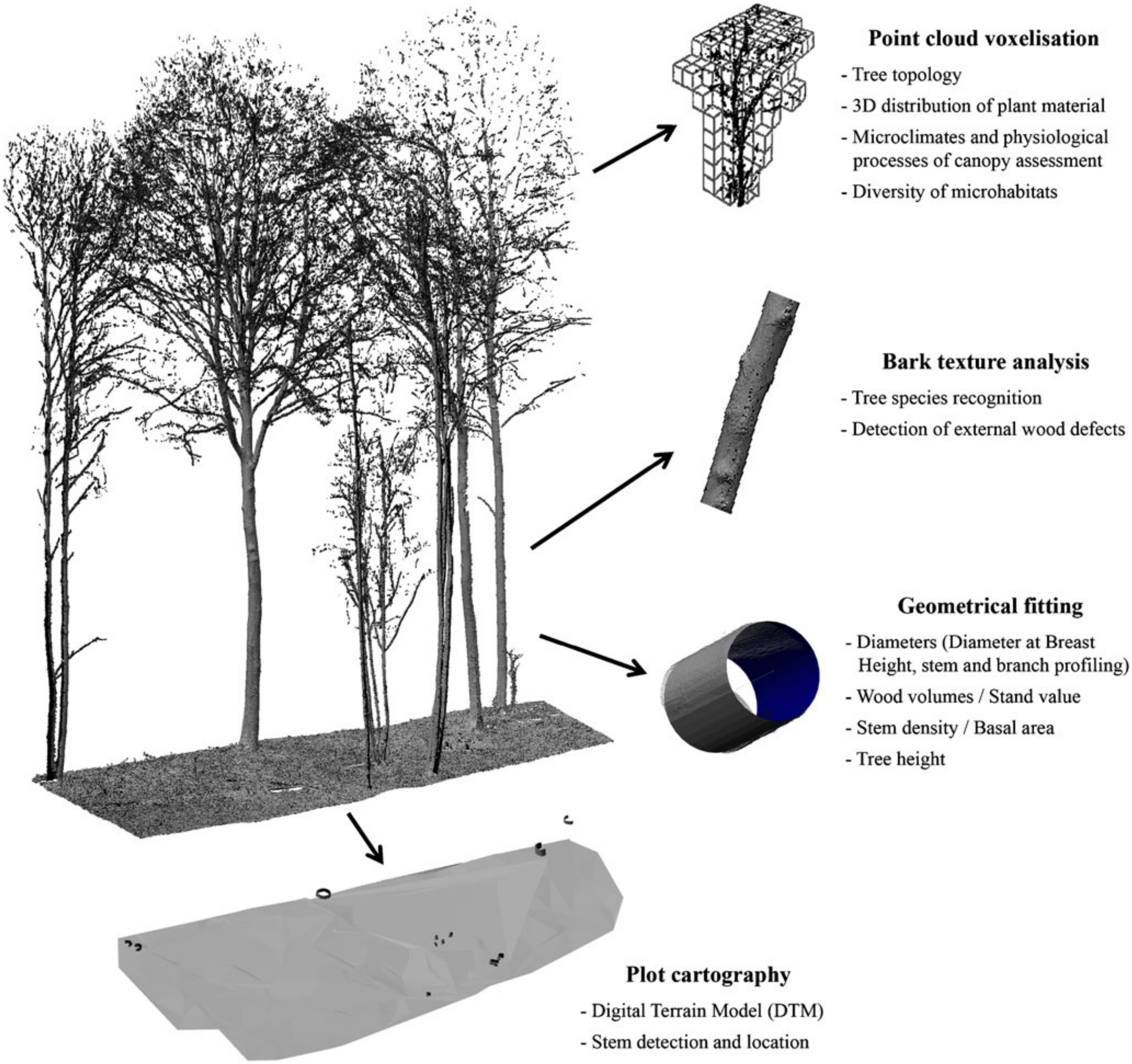

Fig. 3 Tree reconstruction and measurement. Several reconstruction methods make it possible to extract stem metrics and canopy characteristics from point cloud processing software. This information can be useful in various areas of the forest sciences such as forest inventories, stand value determination and forest ecology

scanner with Autostem^{TM}, firstly with the fully automated profiling procedure and then with the semi-automated procedure. Total and merchantable wood volumes were underestimated by 22% and 5%, respectively relative to directly measured values following felling. On this basis, he was able to determine stand value and log product yields using an optimal cutting software known as Valmax, according to the log specifications and prices of two log markets (i.e. western United States and New Zealand). Stand value and log product yields were estimated to within 9% and 6% of actual values, respectively. Finally, the authors observed that T-LiDAR could easily provide more quality parameters such as log sweep and sinuosity.

5.1.2 Species identification from bark structure analysis

Identifying species is a basic issue in forest inventories, effectively dealt with by human expertise (except in the very diverse forests such as tropical rainforests), but often with very limited success using remote sensing techniques.

Table 4 Accuracy of T-LiDAR measurements when compared to intensive field measurements for the three studies on the left and to Relaskop measurements for Strahler et al. (2008), on the right. For reasons of clarity and consistency of results, some values have been recalculated from the available values

Study	Hopkinson et al. 2004		Wezyk et al. 2007		Tansey et al. 2009	Strahler et al. 2008	
LiDAR type	OPTECH Inc. ILRIS-3D		FARO LS 800 HE80		RIEGL LMS-Z420i	Echidna® prototype	
Software	InnovMetric Polyworks		Faro Scene / Terrasolid		InnovMetric Polyworks	Specific algorithms	
Scanning method	Multiple scans		Multiple scans		Multiple scans	Single scan	
Forest type (density in stem/ha)	Coniferous (661)	Deciduous (465)	Coniferous	Deciduous	Coniferous (1000)	Coniferous	Deciduous
Plot area	35 m x 35 m	35 m x 35 m	500 m²	500 m²	23 m x 21 m	50 m radius	50 m radius
Tree detection rate (%)	95	100	96.6	100	100	92.3	87.7
DBH mean difference (cm)	-1	+1	±1	±1	±1.9	-2	+3
Stem density mean difference (%)	0	+3.2	-	-	+3.1	-21	-1.2
Basal area mean difference (%)	-0.6	-0.7	+0.26	+1.63	Acceptable	-7.7	-1.7
Tree height mean difference (m)	+1.5	+1.5	+0.44	+0.35	-	-	-

T-LiDAR-based forest inventories have been used to attempt to identify species from bark structure analysis. In Haala et al. (2004) and Reulke and Haala (2004), point clouds (provided by the Zoller+Fröhlich IMAGER 5003) and high-resolution (HR) panoramic images were co-recorded. Images were mapped on point clouds using a camera geometrical model and several control points. A curvature-based segmentation was applied on point clouds, leading to the detection of trunk surfaces. The characterisation of bark texture from images was made by a fuzzy entropy approach (Kundu and Pal 1990) for five different tree species. It showed significant differences and demonstrated the discrimination of tree species through point cloud measurements.

5.1.3 External trunk quality

Wood resource inventory requires the classification of the logs of standing trees according to quality indices such as dimension, with the eventual addition of information about log shape and wood knottiness. A method was developed by Schütt et al. (2004) to detect inhomogeneous bark structures (branch scars, swollen knots) in T-LiDAR data for coupling outer features with internal wood quality. Plots were digitised using the Zoller + Fröhlich IMAGER 5003. Tree logs were segmented and transformed into reference cylinders. The virtual "unwinding" of these cylinders made it possible to obtain 2D images composed of grey tones (derived from intensity values of points). The grey tone images were segmented into fields by detecting grey tone value jumps. Several shape characteristics (intensity, roundness, etc.) were calculated for each field. Input data consisting of shape characteristics were fed into a neural network, leading to the identification of the type of wood defect and its position in metric units.

5.2 Using T-LiDAR for canopy characterisation in forest management and ecology

Due to their range of measurements and high acquisition rates, T-LiDAR scanners appear to be potential tools to describe the complex geometry of forest canopies, and to determine their structural parameters more rapidly than conventional techniques (Henning 2005).

5.2.1 Canopy cover and gap fraction assessment

The horizontal projection of tree crowns is a commonly used method for canopy cover assessment. In Fleck et al. (2007), the Leica HDS 4500 (phase-shift based) was used to digitise a deciduous plot. Virtual canopy projections were made from the point cloud using Leica Cyclone software (viewing single trees from the Z-direction) and compared to the 8-point canopy projection method (Johansson, 1985). Results were well correlated (r^2=0.90). Furthermore, the advantage of the T-LiDAR method was that it led to the more effective detection of the contact zones between tree crowns.

A major use of T-LiDAR technology in canopy characterisation is to estimate the forest canopy gap fraction. In Danson et al. (2007a, 2007b, 2008), the authors used the Riegl LMZ-210i (infrared pulsed laser scanner, first/last return) in hemispherical mode. The directional gap fraction was estimated using a ratio between the number of laser beams emitted and the number of laser beams received in each 5-degree zenith angle band. T-LiDAR measurements of the canopy gap fraction showed results comparable to those obtained with hemispherical photographs, with the advantage of 3D foliage distribution information. The same conclusions were obtained by Jupp et al. (2009) and Strahler et al. (2008), who used the Echidna® prototype (full waveform infrared laser scanner) for gap fraction assessment.

5.2.2 *Leaf area ratios and foliage distribution*

Leaf area index (LAI, i.e. the total one-sided leaf area per unit of ground area) is a key structural parameter of forest canopies. Numerous direct and indirect methods are used traditionally to estimate LAI such as foliage area estimation from allometric relationships or from the diameter of the sapwood area at breast height, litter sampling, or the use of commercial radiation analysers (Bréda 2003). These conventional techniques are subject to variable estimation that can be maintained within acceptable limits only by extensive and costly sampling. The reconstruction of T-LiDAR data offers a new way to investigate such characteristics.

Assessing leaf area ratios with T-LiDAR requires separating woody and leafy material in point clouds. Clawges et al. (2007) used the Leica HDS 3000 scanner (pulsed time-of-flight, green wavelength) to assess leafy and woody area ratios of single conifer trees. Leafy and woody materials were separated based on the intensity values of points. Leafy-to-total and woody-to-total ratios were computed based on the number of laser returns and were compared to manual measurements. A strong relationship (r^2=0.82) was reported between the number of leafy returns and the one-sided area of leaves.

A highly effective way to estimate LAI is to process point clouds by inserting them in a voxel grid. A voxel grid is a 3D space composed of adjacent cubic cells of specific size and coordinates. The potential of the voxel-based method is all the more efficient when applying ray-tracing algorithms (illumination of the scene by tracing light rays from a single point) and computing interceptions for each voxel. In Hosoi and Omasa (2006), a point cloud provided by the Riegl LPM-25HA (infrared time-of-flight laser scanner) was coupled with such an approach to estimate LAI as well as LAD (leaf area density, i.e. the total one-sided leaf area per unit of volume). The number of laser beams intercepted by leaves for each voxel was computed and led to the calculation of LAI and LAD (Henning and Radtke 2006b; Hosoi and Omasa 2007, 2009a, 2009b) and their seasonal variation (Hosoi and Omasa 2009c).

The next step was to identify factors contributing to the accuracy of these measurements. Firstly, it revealed the strong influence of the inclination angle of leaves, which reduces their illumination. This parameter requires fine resolution scanning and can be assessed by approximating a leaf to a plane and calculating its normal. The distribution of leaf inclination angles can be derived from the angle of these normals and can therefore be corrected. Secondly, the presence of non-photosynthetic tissues induced biases in LAI and LAD estimations. A way to avoid this is to remove points corresponding to woody material based on reflectance values (since woody bark reflectance is very different to leafy reflectance when using an infrared T-LiDAR scanner). Another solution is to perform scans both under leaf-off and leaf-on conditions, subtracting leaf-off returns (woody material) from leaf-on returns (leafy and woody material) based on voxel coordinates. Finally, the degree of obstruction caused by foliage within each region of the canopy is involved in LAD estimation. The degree of obstruction can be assessed by projecting leaf area onto a plane perpendicular to the direction of the laser beam (Hosoi and Omasa 2006, 2007).

5.3 Advanced modelling of the tree structure

The sections above described how T-LiDAR can be used for measuring forests "as usual". This section presents applications that aim at representing the complex 3D tree structure, which is not currently done at forest or plot scales. This is a promising approach for linking complex tree architecture to forest growth and ecology, i.e. linking the individual tree level to forest yield or ecosystem functioning (structure–function approaches).

5.3.1 *Reconstruction of the woody tree structure from T-LiDAR data*

Several methods can be used for tree topology and skeleton reconstruction. Cylinder sequences can be fitted to the point cloud to determine trunk and branch volume and geometry (Binney and Sukhatme 2009; Cheng et al. 2007; Pfeifer et al. 2004; Pfeifer and Winterhalder 2004; Thies and Spiecker 2004). The derivation of cylinder radius and orientation values allows the investigation of tree taper, sweep and lean (Thies et al. 2004). Another way to assess tree topology consists in projecting point clouds in a voxel space (Gorte and Winterhalder 2004; Lefsky and McHale 2008; Pal 2008). This technique has made it possible to structure the point cloud and to identify trunks and major branches and to make an assessment of the connectivity between them.

5.3.2 *Plausible leafy tree modelling from T-LiDAR data*

The methodologies presented in the preceding section are highly dependent on scan quality. Other studies have therefore focused on reconstructing plausible trees from incomplete T-LiDAR data. In Xu et al. (2007), the point cloud corresponding to the main woody structure of the tree was used as a basis to synthesize thin branches (using a bi-directional probing process), and thus obtain a fine woody skeleton. A leaf model was used to add foliage to this skeleton to provide a plausible leafy tree model. Another advanced reconstruction method was proposed by Côté et al. (2009) to reconstruct structurally and radiatively faithful copies of conifers from T-LiDAR data. Several scans were performed around isolated trees using the Optech ILRIS-3D scanner and several validated algorithms (too numerous to be referenced here) were used for the reconstruction of trees. First, leafy and woody materials were separated on the basis of reflectance values. Points corresponding to woody material were used to generate the trunk and the first-order branch structure using an algorithm for the generation of connected curves. Foliage points acted as "attractors" of finer branching elements to complete the construction of the woody skeleton of the tree using a shortest path algorithm. The tree was then inserted into a 3D voxel grid and submitted to a ray-tracing algorithm. This technique allowed a generic conifer shoot structure to be added or not on the woody skeleton according to the number of rays intercepted by the corresponding voxel. All these processes led to the reconstruction of plausible trees. Trees were finally submitted to a radiative transfer model to simulate both the reflectance signature and light transmission properties of crowns, giving good agreement with standard measurements (hemispherical photographs).

5.4 Specific uses of T-LiDAR for forest ecological studies

This section focuses on specific applications of T-LiDAR scanners for the assessment of the relationship between forests and their biotic and abiotic environment.

5.4.1 Interaction between light and canopies

T-LiDAR scanning offers new ways to assess relationships between trees and their light environment. In Van Der Zande et al. (2009), T-LiDAR was used to upscale transpiration rate from the leaf to the tree scale for *Quercus ilex*. These authors used the SICK LMS200 (near-infrared time-of-flight laser scanner, first return). The tree point cloud was inserted in a voxel space and submitted to a ray-tracing programme to simulate the light environment through the crown. Voxels were classified into illumination classes. In each voxel, physiological traits (stomatal conductance, transpiration) were estimated according to the level of light intercepted. The total transpiration rate of the tree was obtained by integrating transpiration of all voxels and was highly correlated to direct (sap flow) measurements. The 3D distribution of light classes was computed according to the coordinates of the voxels, revealing that the most highly shaded parts of the canopy contributed the most to the total transpiration because of their greater area.

5.4.2 Interaction between floods and forests

Another specific application of T-LiDAR concerned interactions between tree structure and floods in riparian zones. This study was conducted by Antonarakis et al. (2009) and was aimed at understanding the resistance of riparian forests in flood modelling, for which tree branching structure is a key parameter. The Leica HDS 3000 was used to obtain the 3D leaf-off forest structure. Point clouds were reconstructed using (1) complex tree meshing with triangles linking the nearest points (Leica Cyclone programme), and (2) tree voxelisation (open source POV-Ray programme, http://www.povray.org). Flow resistance parameters of trees were assessed by applying resistance equations and river flood modelling (Järvelä 2004). The two reconstruction methods were then compared to a direct assessment of flow resistance caused by woody vegetation (branching ratios described in Järvelä 2004). Results showed that the methods were in agreement and also revealed that T-LiDAR scanning led to better descriptions of tree branching parameters.

5.4.3 Distribution of microhabitats in forest canopies

The final example of ecological applications using T-LiDAR is the analysis of habitats used by animals in the forest environment. The first example was presented by Michel et al. (2008). The aim was to link the structure of a New Zealand conifer forest to the choice criteria of the nesting site of two bird species. Ten nest sites were selected. In each site, vegetation structure was recorded within a 20 x 20 m quadrat centered on the nest point using the I-SITE R650 scanning system (Riegl LMS210i core). Four scans per plot were carried out. Vertical variations in vegetation density were qualified by deriving three commonly used indices from the point clouds [the mean height of canopy (MCH), the evenness index (E_{var}) and the functional diversity index (FD_{var})]. The T-LiDAR vegetation sampling technique was also compared to a standard method of canopy sampling (Allen 1992). T-LiDAR measurements appeared to be reliable and more effective in quantifying variations in canopy height (particularly in the estimation of the evenness and functional diversity indexes). The results revealed that both bird species preferred to establish their nests in low forest areas (< 5 m) with a dense understorey. The second example presented a similar approach to assess the hunting activity of several bat species according to the vertical variation of vegetation density (Aschoff et al. 2007). Forest structure was digitised and the number of bat hunting flights was recorded along the vertical axis. This revealed that most flights were at a height of 1–14 m, whereas the endangered species, *Barbastella barbastellus*, was limited to a height of 1.8–3.8 m, but had the fastest flight speed. The *Myotis* species was also shown to be the most capable of flying into narrow areas with many branches.

6 T-LiDAR scanning for forest science

6.1 Advantages of T-LiDAR technology for forest purposes

The previous section showed the suitability of T-LiDAR technology for providing information about forest structure usable for numerous fields within the forest sciences. T-LiDAR scanners provide non-destructive, accurate and extensive information about forest structure that is difficult or impossible to obtain using traditional methods. Forest inventories should take advantage of the new possibilities offered by these instruments to rapidly assess plot-level stem profiles and shapes, and understorey characteristics (Loudermilk et al. 2009). Their non-destructive measurements make it possible to freeze information at a given moment and make it available to the user at a later date, if necessary. Therefore, it is possible to assess the growth parameters of trees and the evolution of stands over time. The 3D information it provides is also a great advantage in LAI estimates, especially in highly clumped stands (Huang and Pretzsch 2010). From an ecological point of view, using T-LiDAR should be a more convenient way to sample vegetation and to provide more sophisticated competition indexes.

6.2 Disadvantages of T-LiDAR technology for forest purposes

6.2.1 Data size, scanning and processing times

T-LiDAR scanners are tools that provide very complete information about forest structure, especially if using several scans and high scanning resolutions. However, using multiple scans increases measurement times, requires placing reference points in the field to merge scans, and adds processing steps. Moreover, forest scanning make it necessary to use the lowest acquisition speed to improve signal-to-noise ratios and to avoid aberrant points, which leads to higher scanning times. Using high resolutions also increases data loading and processing times. For example, using the full resolution of the phase-shift based FARO Photon 120 (one point every 2 mm at 25 m) takes 2 h per complete scan and leads to a file size of more than 2 GB. Using 1/2 the resolution (one point every 4 mm at 25 m) or 1/4 the resolution (one point every 8 mm at 25 m) is sufficient to obtain excellent descriptions of trees. Only 30 min and 7 min with an acquisition rate of about 120,000 points/s are necessary for file sizes of approximately 660 MB and 160 MB, respectively. In the future, solutions should be found to deal easily with such quantities of data, especially in the case of standardised forest inventories using T-LiDAR. Finally, the user must be willing to compromise in order to obtain sufficiently detailed data in the shortest time possible according to their specific objectives and taking post-processing capacities into account.

6.2.2 Occlusions and stand density

A major problem to overcome when using T-LiDAR in the forest environment is occlusions caused by lower branches, surrounding trees and understorey. This phenomenon leads to lower point density and, therefore, to poor descriptions in the upper part of crowns and partially or totally hidden trees (Van Der Zande et al. 2006). A distinction must also be made between deciduous and coniferous stands because of species-specific differences in tree canopy structures. In the case of conifers, the finest foliage elements (needles) are often grouped together tightly into shoots, contrary to the leaves of deciduous species, which can be very scattered. Thus, measurements appear to be a little more difficult for deciduous stands because of the multi-tiered and overlapping nature of the vegetation.

Up until now, forest inventory measurements have shown good results only for low-density stands (Table 4). However, stand density is a key factor that affects occlusion levels and tree description (Watt and Donoghue 2005). If the effect of stand density is less restrictive when focusing on single tree measurements, it can become a real problem in the case of plot inventories. Table 5 presents the way vegetation structure leads to occlusion, as a function of the specific application. Thus, T-LiDAR scanners appear to be very suitable for commercial forest measurements, but additional research must be conducted to test and validate these instruments on dense and old-growth complex forests.

6.2.3 Weather and sky conditions

Weather conditions must be considered carefully to obtain high quality point clouds. Wind constitutes the most troublesome factor since it depreciates tree description, especially in the upper part of the trees. The displacement of vegetation elements during a progressive scan means that they are scanned at different positions, leading to the poor description of tree axes and foliage distribution and the increase of noise points (Fig. 4a). It is therefore difficult to obtain accurate estimations of tree characteristics during the processing phases. The device must not be exposed to extreme temperatures while it is in operation (operating temperature generally between 0 and 40°C). In case of rain or snow, scanning can be carried out even if some raindrops are present on the mirror. Nevertheless, rain and snow are two factors that reduce point cloud quality by intercepting numerous laser beams, leading to an increase of noise points as well (Fig. 4b). The deposition of snow on tree elements can lead to inaccurate estimation of wood diameters and volumes, whereas its deposition on reference

Table 5 Factors to consider for forest scanning and for choosing equipment according to objectives. *DBH* Diameter at breast height, *LAI* leaf area index, *LAD* leaf area density

Application field	Objectives	Causes of occlusions (Consequences)	Work requirements	T-LiDAR requirements	Examples of processing methods
Plot-level forest inventory	DBH / Basal area, stem profiles, stem volumes	High stem density, presence of understorey, heavy branching, corrugated ground (missing diameters, partial profiles)	Scanning in leaf-off conditions (if possible), scanning in acceptable wind conditions (<20kmh), possible with single scan method, more accurate with multiple scans method	Wide field-of-view, high acquisition speed, suitability for intensive campaigns (ergonomics, autonomy, weight)	Circle / cylinder fitting Voxel approaches Meshing processes
	Stem detection and location, stem density, tree height	High stem density, presence of understorey, heavy branching, corrugated ground (hidden trunks)			Circle / cylinder fitting Direct measurements on point clouds
	Species recognition, external wood defects recognition (Bark texture analysis)		Fine scanning resolution, RGB information	RGB camera	Dedicated algorithms
Canopy characterisation	Gap fraction	Leaf clumping (biases in gap fraction estimates)	Fine scanning resolution, acceptable wind conditions (<20kmh), thin laser beam	Hemispherical field-of-view, low beam divergence, last return / full waveform rangefinder	Point computation
	LAI / LAD foliage stratification	Leaf clumping, leaf inclination angles, presence of non-photosynthetic tissues (biases in LAI and LAD estimates)	Multiple scan method, fine scanning resolution, acceptable wind conditions (no wind for leaf angles), separating leafy and woody material, thin laser beam	Infrared wavelength (1,000–1,500 nm), low beam divergence, last return / full waveform rangefinder	Separating leafy and woody points from intensity values, voxel / ray-tracing approaches
Detailed plant description	Woody tree architecture	Heavy branching (discontinuity)	Scanning in leaf-off conditions (if possible), multiple scans method, acceptable wind conditions (no wind for thin branches)	High acquisition speed (reduces wind effect)	Circle / cylinder fitting, voxel approaches, meshing processes
	Entire leafy tree	Heavy branching, presence of foliage (non-visible internal tree structure)	Multiple scans method, fine scanning resolution, separating leafy and woody material, thin laser beam	Infrared wavelength (1,000–1,500 nm), low beam divergence, last return / full waveform rangefinder	Separating leafy and woody points from intensity values, voxel / ray-tracing approaches

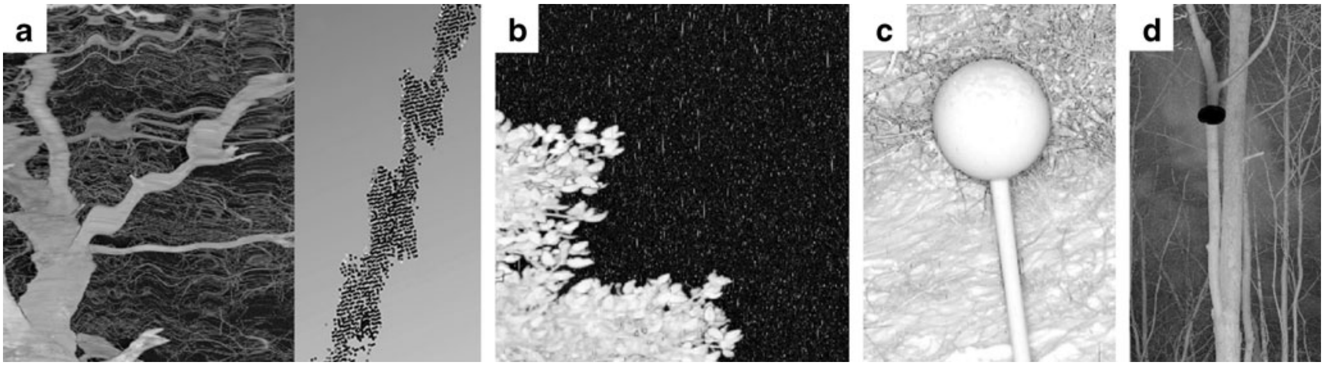

Fig. 4 Impact of climatic and sky conditions on scan quality. Wind leads to poor descriptions of tree axes (**a**), whereas snow intercepts laser beams and leads to an increase of noise points (**b**) and poor adjustments of geometrical shapes on both spheres and trees (**c**). The high reflectance of the sun causes information to be ignored by the scanner (**d**)

spheres can lead to poor adjustment of digital sphere models essential for merging scans with good accuracy (Fig. 4c). T-LiDAR scanners also work well, regardless of the light conditions, whereas other optical systems are not usable under low light conditions and can be affected by light halos (for example, hemispherical photographs). However, because of incident solar radiation, no information is recorded for beam directions corresponding to the sun position (scanner dazzled) and some noise points may appear in the surrounding area (Fig. 4d).

6.3 Guidelines for choosing equipment according to objectives

6.3.1 Devices

Table 5 presents the key device characteristics to be considered for forest measurements using T-LiDAR, as a function of the objectives. Currently, phase shift T-LiDAR scanners clearly offer the most appropriate characteristics for forest inventories (high acquisition speed, wide field-of-view). The latest generation phase-shift scanners such as the FARO Focus 3D also offer excellent ergonomics (reduced weight and size, integrated camera). Canopy characterisation, on the other hand, requires time-of-flight T-LiDAR scanners. The first reason is because time-of-flight scanners generally use near infrared wavelengths, leading to the easier separation of leafy and woody materials based on the intensity values of points. The second reason is because first/last return and full waveform time-of-flight scanners can provide multi-depth information (Fig. 2). Full waveform T-LiDAR scanners have long been experimental (e.g. the Echidna® scanner), but the latest generation RIEGL scanners now offer waveform analysis (Table 2). However, because of the narrow field of view of most time-of-flight scanners, several scans must be merged to obtain a complete description of the canopy (especially for hemispherical gap fraction assessment). The availability of time-of-flight laser scanners with fields of view as wide as phase-shift instruments (the Optech ILRIS-36D currently being developed) could be a way to fill this gap after future tests and validation. Canopy characterisation also requires using scanners with low beam divergence to detect small gaps in vegetation and, therefore, to provide better canopy descriptions. However, time-of-flight scanners are penalised by low acquisition speeds. The recent release of phase-shift T-LiDAR scanners using infrared wavelengths (Zoller + Fröhlich IMAGER 5010) or low beam divergence (FARO Focus 3D) could change the rules for canopy characterisation (Table 1).

6.3.2 Software

Several methods can be used for forest assessment from T-LiDAR data (Table 5). AutoStem™ appears to be the most advanced solution to assess forest metrics and to automatically estimate wood volume and value at the plot scale. It is currently used primarily to assist timber producers, but is restricted to professional applications in relatively homogenous environments (commercial conifer forests). AutoStem™ is not suitable for advanced tree and canopy modelling. Generic engineering software also provides useful solutions for forest metric measurements, plot-scale wood volume estimates and woody tree structure reconstruction. The main problem with this type of software is its limited automation. Detailed tree and canopy reconstruction requires using advanced reconstruction processes (voxels, ray-tracing) and, therefore, intensive programming steps. Scientific communities focusing on ecological studies require high levels of parameter control to test and to validate various hypotheses, according to the information of interest. Consequently, ecological studies require advanced modelling processes (voxels, radiative transfer model), which also require intensive programming.

6.4 Cost-benefit analysis

Despite their potential, T-LiDAR scanners have only just begun to be used in forestry communities (especially in the research environment) and are still not considered as standard tools. The main reason lies in the cost of T-LiDAR instruments and peripherals (reference targets, tripods, software suites, graphic workstations). However, the price of devices has decreased by half in the last year, especially in the case of the new generation of phase-shift scanners (FARO Focus 3D). This trend should continue for some time. When prices become acceptable for foresters, T-LiDAR instruments should become essential tools to provide extensive information about forests with a smaller investment in time and labour than current field measurements.

7 Future development

7.1 Device improvements

T-LiDAR is now a mature technology with sufficient characteristics in terms of resolution and accuracy for forest purposes. Efforts must now to be made to increase acquisition speeds and to improve signal-to-noise ratios, especially when using the fastest acquisition modes, for both phase-shift and time-of-flight scanners. An important step would be to test multispectral LiDAR (using several wavelengths) and multi-source measurements (LiDAR coupled with photographs) to provide even more information about the physical properties of vegetation. The limits due to the wind effect could be reduced by an increase in the acquisition speed of devices and the availability of emergent technologies such as LiDAR cameras.

7.2 Developing methods for forestry applications

Forestry applications using T-LiDAR scanners appear to be applicable at this time but require automated tools to extract useful information at stand and forest scales. A first step forward was made with AutoStem™ software developed by TreeMetrics. Until now, this tool has only been effective for conifer forests, but work is currently underway to process deciduous forests. The next challenge will be to adapt this software to different inventory contexts in various forest environments such as mixed forests. However, such an automated tool would probably be limited in the case of very dense forest stands.

T-LiDAR scanners also provide different but complementary information when compared to airborne LiDAR data. Thus, another goal would be to develop methods that allow the coupling of both airborne and terrestrial LiDAR datasets to obtain multi-scale information about forest structure (Chasmer et al. 2006; Van Leeuwen and Nieuwenhuis 2010).

7.3 Perspectives for ecological applications

T-LiDAR technology opens many perspectives in forest ecology. Our review provides examples of intra-canopy microclimate and microhabitat assessments, but many other applications related to structural-functional plant modelling could be considered. It should be possible to analyse light distribution and its impact on the natural regeneration of tree species, or to assess the photosynthetically active radiation absorbed and the resulting photosynthetic rate. Other developments could concern the way trees and forests develop a mechanically efficient and acclimatised woody structure in their natural environment, which is a major constraint (and challenge) for forest ecosystems (Chave et al. 2009). Tree biomechanical response to wind and unbalanced biomass allocation during growth, which have major consequences on wood functional properties, have been studied mainly from the theoretical point of view and applied to only a small number of trees (Barbacci et al. 2009; Brüchert and Gardiner 2006; Moulia and Fournier 2009). However, this requires wide-scale measurements of tree shape and biomass, which could benefit from T-LiDAR scanning.

8 Conclusion

The aim of this article was to establish the state-of-the-art of the current applications of T-LiDAR technology in forest science, as well as to determine its applicability for its intended use. It appears that T-LiDAR instruments have the potential to enhance forest measurements and to overcome metrological difficulties by describing the under-canopy structure faster and in greater detail than time-consuming manual techniques. T-LiDAR scanning also provides information inaccessible to large-scale airborne LiDAR measurements. Its potential implications in the fields of forest inventories, commercial wood management and forest ecology are many. Two aspects need to be improved to make this technology specifically applicable to forestry. The first concerns the T-LiDAR devices themselves, particularly in terms of acquisition time, signal-to-noise ratio, and cost. The second concerns the development of cheap and easy-to-use software that would make it possible to automatically extract information from incomplete data. T-LiDAR has also been used within the field of forest ecology over the past few years. These studies concerned very specific applications, but demonstrated the potential of this technology to provide a good background for ecological questions such as microhabitat distribution and the assessment of the ecological processes that occur in the forest environment. Despite the maturity of these devices, some progress remains to be made in the analysis of the 3D cloud to enhance the extraction of relevant information. There is no doubt that the evolution of devices and computing science will make T-LiDAR technology an important source of information for describing natural environments in the future.

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References

Allen R.B., 1992. RECCE, an inventory method for describing New Zealand vegetation. Forest Research Institute Bulletin No. 176, Protection Forestry Division, Forestry Research Institute, Christchurch, New Zealand.

Antonarakis A.S., Richards K.S., Brasington J., and Bithell M., 2009. Leafless roughness of complex tree morphology using terrestrial lidar, Water Resour. Res. 45:W10401. doi:10.1029/2008WR007666

Aschoff T., and Spiecker H., 2004. Algorithms for the automatic detection of trees in laser scanner data. ISPRS 36:66–70

Aschoff T., Spiecker H., and Holderied M.W., 2007. Terrestrische Laserscanner und akustische Ortungssysteme: Jagdlebensraeume von Fledermaeusen inWaeldern. AFZ Der Wald 62:172–175

Barbacci A., Constant T., and Nepveu G., 2009. Theoretical and experimental study of a mechanical model describing the trunk behaviour of mature beech trees (*Fagus sylvatica* L.) under the static loading of the crown. Trees 23:1137–1147

Bélouard T., Vidal C., Hervé J.C., and Robert N., 2005. The new French forest inventory, a systematic and annual sampling. De l'observation des écosystèmes forestiers à l'information sur la forêt, 2nd-3 rd February 2005, Paris. Available online at http://www.symposcience.org/exl-doc/colloque/ART-00002046.pdf. Last accessed 28 January 2011.

Bienert A., Maas H.G., and Scheller S., 2006a. Analysis of the information content of terrestrial laser scanner point cloud for the automatic determination of forest inventory parameters. Workshop on 3D Remote Sensing in Forestry, 14th-15th Feb 2006. Vienna. Available online at http://www.tu-dresden.de/ipf/photo/publikationen/2006/Bienert_Maas_Scheller_ForestryVienna2006.pdf. Last accessed 28 January 2011.

Bienert A., Scheller S., Keane E., Mullooly G., and Mohan F., 2006b. Application of terrestrial laser scanners for the determination of forest inventory parameters. Image Engineering and Vision Metrology. ISPRS Commission V Symposium, WG 3, Dresden, 25–27 September 2006 36, Part 5. Available online at http://www.isprs.org/proceedings/XXXVI/part5/paper/1270_Dresden06.pdf. Last accessed 28 January 2011.

Bienert A., Scheller S., Keane E., Mohan F., and Nugent C., 2007. Tree detection and diameter estimations by analysis of forest terrestrial laser scanner point clouds. Laser scanning 2007 and Silvilaser 2007. ISPRS Commission III Workshop 36, Part 3, Espoo, Finland. Sept. 12–14, 2007. Available online at http://www.isprs.org/proceedings/XXXVI/3-W52/final_papers/Bienert_2007.pdf. Last accessed on 28 January 2011.

Binney J. and Sukhatme G.S., 2009. 3D tree reconstruction from laser range data. In: Proc. of the 2009 IEEE international conference on Robotics and Automation. Available online at http://cres.usc.edu/pubdb_html/files_upload/598.pdf. Last accessed on 28 January 2011.

Bréda N.J.J., 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J Exp Bot 54:2403–2417. doi:10.1093/jxb/erg263

Brüchert F., and Gardiner B., 2006 The effect of wind exposure on the tree aerial architecture and biomechanics of Sitka spruce (*Picea sitchensis*, Pinaceae). Am J Bot 93:1512–1521

Chambelland J.C., Dassot M., Adam B., Donès N., Balandier B., Marquier A., Saudreau M., Sonohat G., and Sinoquet H., 2008. A double-digitizing method for building 3D virtual trees with non-planar leaves: application to the morphology and light capture properties of young beech trees (*Fagus sylvatica*). Funct Plant Biol 35:1059–1069

Chasmer L., Hopkinson C., and Treitz P., 2006. Investigating laser pulse penetration through a conifer canopy by integrating airborne and terrestrial lidar. Can J Remote Sens 32:116–125

Chave J., Coomes D., Jansen S., Lewis S.L., Swenson N.G., and Zanne A.E., 2009. Towards a worldwide wood economics spectrum. Ecol Lett 12:351–366. doi:10.1111/j.1461-0248.2009.01285.x

Cheng Z.L., Zhang X.P., and Chen B.Q., 2007. Simple reconstruction of tree branches from a single range image. J Comput Sci Technol 22:846–858

Clawges R., Vierling L., Calhoon M., and Toomey M., 2007. Use of a ground-based LIDAR for estimation of biophysical properties of western larch (*Larix occidentalis*). Int J Remote Sens 28:1–14

Côté J.F., Widlowski J.L., Fournier R.A., and Verstraete M.M., 2009. The structural and radiative consistency of three-dimensional tree reconstruction from terrestrial LIDAR. Remote Sens Environ 113:1067–1081

Danson F.M., Hetherington D., Morsdorf F., Koetz B., and Allgöwer B. 2007a. Forest canopy gap fraction from terrestrial laser scanning. IEEE Geosci Remote Sens Lett 4:157–160

Danson F.M., Giacosa C., and Armitage R.P. 2007b. Two-dimensional forest canopy architecture from terrestrial laser scanning. ISPRS 36:1682–1777

Danson F.M., Armitage R.P., Bandugula V., Ramirez F.A., Tate N.J., Tansey K.J., and Tegzes T., 2008. Terrestrial laser scanners to measure forest canopy gap fraction. SilviLaser 2008, 17th-19th September 2008. Edinburgh, UK. Available online at http://geography.swan.ac.uk/silvilaser/papers/oral_papers/Terrestrial Laser scanning & Laser Cameras/Danson.pdf. Last accessed 28 January 2011.

FARO, 2010. Available online at http://www.faro.com. Last accessed 28 January 2011.

Fleck, S., Obertreiber, N., Schmidt, I., Brauns, M., Jungkunst, H.F., and Leuschner, C., 2007. Terrestrial LIDAR measurements for analysis canopy structure in an old-growth forest. ISPRS36: Part 3 / W52.

Zoller + Fröhlich, 2010. Available online at http://www.zf-laser.com. Last accessed on 28 January 2011.

Gorte B., and Winterhalder D., 2004. Reconstruction of laser-scanned trees using filter operations in the 3D-raster domain. ISPRS 36:39–44

Haala N., Reulke R., Thies M. and Aschoff T., 2004. Combination of terrestrial laser scanning with high resolution panoramic images for investigations in forest applications and tree species recognition. ISPRS 34: Part 5/W16.

Henning J.G., 2005. Modeling forest canopy distribution from ground-based laser scanner data. M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 171 p.

Henning J.G., and Radtke P.J., 2006a. Detailed stem measurements of standing trees from ground-based scanning lidar. For Sci 52:67–80

Henning J.G., and Radtke P.J., 2006b. Ground-based laser imaging for assessing three-dimensional forest canopy structure. Photogramm Eng Remote Sens 72:1349–1358

Hopkinson C., Chasmer L., Young-Pow C., and Treitz P. 2004. Assessing forest metrics with a ground-based scanning lidar. Can J For Res 34:573–583

Hosoi F., and Omasa K., 2006. Voxel-based 3-D modelling of individual trees for estimating leaf area density using high-resolution portable scanning lidar. IEEE Trans Geosci Remote Sens 44:3610–3618. doi:10.1109/TGRS.2006.881743

Hosoi F., and Omasa K., 2007. Factors contributing to accuracy in the estimation of the woody canopy leaf area density profile using 3D portable LIDAR imaging. J Exp Bot 58:3463–3473

Hosoi F., and Omasa K., 2009a. Estimating vertical plant area density profile and growth parameters of a wheat canopy at different growth stages using three-dimensional portable LiDAR imaging. ISPRS 64:151–158. doi:10.1016/j.isprsjprs.2008.09.003

Hosoi F., and Omasa K., 2009b. Estimating vertical leaf area density profile of tree canopies using three-dimensional portable LiDAR imaging. In Proceedings of the ISPRS workshop Laser-scanning 09, Paris, France. pp. 152–157. Available online at http://www.isprs.org/proceedings/XXXVIII/3-W8/papers/p55.pdf. Last accessed 28 January 2011.

Hosoi F., and Omasa K. 2009c. Detecting seasonal change of broad-leaved woody canopy leaf area density profile using 3D portable LiDAR imaging. Funct Plant Biol 36:998–1005

Huang P., and Pretzsch H. 2010. Using terrestrial laser scanning for estimating leaf areas of individual trees in conifer forests. Trees 24:609–619

Järvelä J., 2004. Determination of flow resistance caused by non-submerged woody vegetation. Int J River Basin Manage 2:61–70

Johansson T., 1985. Estimating canopy density by the vertical tube method. For Ecol Manage 11:139–144

Jupp D.L.B., Culvenor D.S., Lovell J.L., Newnham G.J., Strahler A. H., and Woodcock C.E., 2009. Estimating forest LAI profiles and structural parameters using a ground-based laser called Echidna®. Tree Physiol 29:171–181

Keane E., 2007. The potential of terrestrial laser scanning technology in pre-harvest timber measurement operations. Harvesting/Transportation 7, Coford Connects, Coford, Dublin, Ireland. 4 p.

Kint V., Aertsen W., Wouters J. and Muys B., 2009. Stem and wood quality assessment in national forest inventories. In: Proc of the IUFRO Division 4, Extending Forest Inventory and Monitoring over Space and Time, May 2009, Quebec City.

Koetz B., Sun G., Morsdorf F., Ranson K.J., Kneubühler M., Itten K., and Allgöwer B., 2007. Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization. Remote Sens Environ 106:449–459

Kundu M.K., and Pal S.K., 1990. Automatic selection of object enhancement operator with quantitative justification based on fuzzy set theoretic measures. Pattern Recognit Lett 11:811–829

RIEGL Laser Measurement Systems (2010) Available online at http://www.riegl.com. Last accessed 28 January 2011.

Lefsky M., and McHale M., 2008. Volumes estimates of trees with complex architecture from terrestrial laser scanning. J Appl Remote Sens 2:023521

Lemmens M., 2009. Terrestrial laser scanners. GIM International. 8 (August 2009): 62–67. Available online at www.gim-international.com/productsurvey/id34-Terrestrial_Laser_Scanners,_August.html. Last accessed 28 January 2011.

Loudermilk E.L., Hiers J.H., O'Brien J.J., Mitchell R.J., Singhania A., Fernandez J.C., Cropper W.P., and Slatton K.C. 2009. Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. Int J Wildland Fire 18:676–685

Maas H.G., Bienert A., Scheller S., and Keane E., 2008. Automatic forest inventory parameter determination from terrestrial laser scanner data. Int J Remote Sens 29:1579–1593

Maltamo M., Packalen P., Yu X., Eerikäinen K., Hyyppä J., and Pitkänen J., 2005. Identifying and quantifying structural characteristics of heterogeneous boreal forests using laser scanner data. For Ecol Manage 216:41–50

Michel P., Jenkins J., Mason N., Dickinson K.J.M., and Jamieson I.G., 2008. Assessing the ecological application of lasergrammetric techniques to measure fine-scale vegetation structure. Ecol Inform 3:309–320

Moulia B., and Fournier M., 2009. The power and control of gravitropic movements in plants: a biomechanical and systems biology view. J Exp Bot 60:461–486

Murphy G., 2008 Determining stand value and log product yields using terrestrial LIDAR and optimal bucking: a case study. J For 106:317–324

Optech Incorporated, 2010. ILRIS-3D and ILRIS-36D technical overview. Available online at http://www.optech.ca. Last accessed 28 January 2011.

Pal I., 2008. Measurements of forest inventory parameters on terrestrial laser scanning data using digital geometry and topology. ISPRS 37:1682–1750

Pfeifer N. and Briese C., 2007. Laser scanning - Principles and applications. Institute of Photogrammetry and Remote Sensing, Publication database of the Vienna University of Technology, Austria. Available online at http://publik.tuwien.ac.at/files/pub-geo_1951.pdf. Last accessed 28 January 2011.

Pfeifer N. and Winterhalder D., 2004. Modelling of tree cross sections from terrestrial laser-scanning data with free-form curves. ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. 36 (8 / W2): 76–81. Available online at http://www.isprs.org/proceedings/XXXVI/8-W2/PFEIFER.pdf. Last accessed 28 January 2011.

Pfeifer N., Gorte B. and Winterhalder D., 2004. Automatic reconstruction of single trees from terrestrial laser scan data. In: Proc. of the 20th ISPRS Congress, Commission 5, Istanbul, Turkey, \July 2004. Available online at http://www.citg.tudelft.nl/live/binaries/3b390ae2-9b55-4cbc-8255-da55928dd925/doc/automatic reconstruction.pdf. Last accessed 28 January 2011.

Reulke R., and Haala N., 2004. Tree species recognition with fuzzy texture parameters. IWCIA 2004. Lecture Notes Comput Sci 3322:607–620

Schütt C., Aschoff T., Winterhalder D., Thies M., Kretschmer U. and Spiecker H., 2004. Approaches for recognition of wood quality of standing trees based on terrestrial laser scanner data. ISPRS 36: 8/W2.

Simonse M., Aschoff T., Spiecker H. and Thies M., 2003. Automatic determination of forest inventory parameters using terrestrial laserscanning. In: Proc. of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests, Umea, Sweden, pp. 251–257. Available online at http://www.natscan.uni-freiburg.de/suite/pdf/030916_1642_1.pdf. Last accessed 28 January 2011.

Strahler A.H., Jupp D.L.B., Woodcock C.E., Schaaf C.B., Yao T., Zhao F., Yang X., Lovell J., Culvenor D., Newnham G., Ni-Miester W., and Bozkin-Morris W., 2008. Retrieval of forest structure parameters using a ground-based lidar instrument (Echidna®). Can J Remote Sens 34:426–440

Tansey K., Selmes N., Anstee A., Tate N.J., and Denniss A., 2009. Estimating tree and stand variables in a Corsican Pine woodland from terrestrial laser scanner data. Int J Remote Sens 30:5195–5209

Thies M. and Spiecker H., 2004. Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. 36: 8/W2. Available online at http://www.isprs.org/proceedings/XXXVI/8-W2/THIES.pdf. Last accessed 28 January 2011.

Thies M., Pfeifer N., Winterhalder D., and Gorte B.G.H., 2004. Three-dimensional reconstruction of stems for assessment of taper, sweep, and lean based on laser-scanning of standing trees. Scand J For Res 19:571–581

Van Der Zande D., Hoet W., Jonckheere I., Van Aardt J., and Coppin P., 2006. Influence of measurement set-up of ground based for derivation of tree structure. Agric For Meteorol 141:147–160

Van Der Zande D., Mereu S., Nadezhdina N., Cermak J., Muys B., Coppin P., and Manes F., 2009. 3D upscaling of transpiration from leaf to tree using ground-based LIDAR: application on a Mediterranean Holm oak (*Quercus ilex*) tree. Agric For Meteorol 149:1573–1583

Van Leeuwen M., and Nieuwenhuis M., 2010. Retrieval of forest structural parameters using LiDAR remote sensing. Eur J For Res 129:749–770

Watt P.J., and Donoghue D.N.M., 2005. Measuring forest structure with terrestrial laser scanning. Int J Remote Sens 26:1437–1446

Wezyk P., Koziol K., Glista M. and Pierzchalski M., 2007. Terrestrial laser scanning versus traditional forest inventory: First results from the Polish forests. In: Proc. Laser scanning 2007 and Silvilaser 2007. ISPRS Commission III Workshop, Vol. 36, Part 3, Espoo, Finland, Sept. 12–14, 2007. Available online at http://www.isprs.org/proceedings/XXXVI/3-W52/final_papers/Wezyk_2007.pdf. Last accessed 28 January 2011.

Xu H., Gosset N. and Chen B., 2007. Knowledge and Heuristic Based Modeling of Laser-Scanned Trees. In: Proc. of the 2007 ACM Transactions on Graphics. Available online at http://portal.acm.org/citation.cfm?id=1289603.1289610. Last accessed 2 November 2010.