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Validation of terrestrial laser scanning data using conventional forest inventory methods

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Abstract The application of terrestrial laser scanning (TLS) in capturing forest inventory parameters such as diameter at breast height, height and diameters along stem profiles, and in monitoring forest growth, was investigated and validated by comparison with conventionally measured individual tree parameters and plot-level forest growth in a stand of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. The data acquisition for all the plots with different tree sizes and different slopes was carried out using a terrestrial laser scanner (FARO LS 800 HE80) in November 2007 and November 2009, using the same plot centres and measurement procedures. The point cloud data were processed with Autostem^{TM} software. The results showed that TLS enables the acquisition of forest stand parameters with an acceptable accuracy. Pruning of the lower branches did not improve tree recognition and the number of (partly) occluded trees stayed the same. Over the 2-year period, the average difference between the volume increment of the trees visible to the scanner derived using the conventional method and Autostem^{TM} was 4.77 m^3 ha^{-1} and resulted in scanner-derived estimates that were lower than the estimates obtained by conventional method by 6.1 %. Using a simple correction factor to account for occlusion in the laser scanner data, the difference between these estimates for all trees in the stand became an over-estimation by 6.96 m^3 ha^{-1} (8.1 %). At heights up along the stems >15 m, the errors in stem diameter estimates started to escalate.

Keywords LiDAR · Point cloud data · Forest inventory · Forest growth

Introduction

Forest inventories require measurement of parameters describing the geometry of trees, of which diameter at breast height (DBH) and tree height are the major ones. In some cases, additional parameters such as stem profile and stem shape are required (Maas et al. 2008). Plot-level tree volume is traditionally estimated using species and site-dependent allometric relationships with tree height, DBH and stem density (Schumacher and Hall 1933). Manually collecting these forest inventory parameters in the field can be time consuming, costly and susceptible to subjective errors. This is often the case with tree height estimation using standard optical methods, where accuracy is limited by the interaction of the observer, instrument and stand conditions (Bruce 1975).

Forest inventory data are essential for modern forest management in relation to timber harvest forecasting, growth monitoring, CO$_2$ fluxes and biodiversity monitoring (Tansey et al. 2009; Danson et al. 2007). Terrestrial laser scanning (TLS) is an active measurement technology independent of the sun or an artificial light source. It is capable of collecting three-dimensional (3D) data point clouds of several million data points on highly irregular surfaces within a few minutes (Pfeifer and Briese 2007).

Several studies have been carried out to automatically determine forest inventory parameters from point cloud data. These have reported on the retrieval of forest inventory parameters, such as DBH, tree height, basal area, stem

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count and branching parameters, as well as on information on standing woody and green biomass (Hopkinson et al. 2004; Watt and Donoghue 2005; Bienert et al. 2007; Russo et al. 2007; Maas et al. 2008; Tansey et al. 2009; Murphy et al. 2010). For a review of forestry-related laser scanning studies, see van Leeuwen and Nieuwenhuis (2010). Henning and Radtke (2006) reported their findings in using ground-based TLS for the retrieval of stem diameters from loblolly pine (Pinus taeda L.) in central Virginia, USA. The results indicated that the TLS-derived diameter measurements and field measurements were in close agreement, with the average error <1 cm for measurements below the base of the live crown and <2 cm for heights up to 13 m. In addition to ordinary forest inventory parameters, information on stem profile enables assessing log assortments prior to felling the forest. As a result, a reliable stem profile extraction technique is of particular interest for use in inventory applications involving large, high-value trees, where errors in estimating upper-stem dimensions could be costly (Maas et al. 2008).

To validate and verify the precision and reliability of the terrestrial laser scanner's data processing schemes in forest inventory applications, Maas et al. (2008) conducted a study, based on five pilot studies, covering different types of forests, scanners, data acquisition schemes and seasons. They reported an overall success rate of detection of 97.5 % and a DBH determination with a root mean square error (RMSE) of 1.48 cm for multiple scan mode and 1.80–3.25 cm for single scan mode. Their results showed a difference of −0.64 m between the mean tree height derived automatically from the laser scanner point cloud and the one derived using a hand-held tachymeter.

Airborne laser scanning is also increasingly being used as a means for conducting forest structural measurement over large areas (Hyyppä et al. 2008; McInerney et al. 2010). While the airborne platform provides rapid coverage of large areas, it is limited to a near-vertical view of the forest. This view makes it difficult to obtain direct measurements of many key aspects of the forest structure, and the measurements must be carefully calibrated against ground-based measurements. The use of ground-based laser scanning systems, either by themselves or in combination with airborne LiDAR, allows for the acquisition of levels of detail far beyond what airborne and spaceborne laser scanning are capable of on their own under a forest canopy (van Leeuwen and Nieuwenhuis 2010). Several factors have been reported as contributors to errors in estimating parameters from TLS. For example, high stem densities prevented Tansey et al. (2009) from estimating height and volume.

The objectives of this study were to assess the accuracy of TLS-derived measurements of forest inventory parameters, such as DBH, tree height, stem profile and volume in a stand of Sitka spruce (Picea sitchensis (Bong.) Carr.) in Ireland, to investigate the effects of occlusion on stand volume estimation and to evaluate the suitability of multi-temporal TLS data for tree growth monitoring. The effect of distance, slope and condition of lower branches in assessing the accuracy of forest inventory parameters was also investigated.

Materials and methods

Stand characterization, plot selection, and field measurement

The stand of Sitka spruce is located in Clonmel (52° 20′N, 7°45′W) and was planted in 1976 at an initial density of 2,500 trees per hectare in a 2 × 2 m grid. It has been progressively thinned over time to a density of 600 trees per hectare. The topographic condition of the site is characterized by a slope ranging from 15 to 25 %.

A total of nine 0.0701-ha circular plots (30 m diameter) were randomly located in the forest stand. Seven of these plots were included in the 2007 forest inventory parameter assessment and all nine in the 2009 assessment. All trees in each plot were clearly numbered sequentially to enable reconciliation of scan data with manually measured data for each stem. As each tree was numbered, lines were painted around the stem at 1.3 and 2.0 m above ground level with a recognizable permanent spray before the scanning was carried out. The trees in each plot were scanned: in 2007 before and after applying a low pruning up to three metres and in 2009 before and after pruning up to six metres high. Field validation data, which include DBH, tree height and number of stems per plot, were collected concurrently using conventional forest inventory methods. The DBH measurement was carried out using a diameter tape, and tree height was measured with a calibrated Vertex IV hypsometer (Haglof Inc, USA). The mean values for the measured parameters are presented in Table 1. In each plot, four to five trees were selected based on distance from the scanner and tree size and were felled, and their diameters were measured at half-metre intervals along the stem to validate volume estimates. Two years later, scanning was repeated in the same stand using the same scan positions.

Additional heights of nine representative trees were measured in each plot in order to be used as an input into a DBH–height model to determine the height of the trees whose top part was not visible. Crown heights were measured on the trees marked for felling in each plot to investigate the correlation between crown height and the accuracy of upper-stem diameter estimation.

Laser scanner data acquisition

The data acquisition was carried out with a terrestrial laser scanner FARO LS 800 HE80 (FARO Technologies, Inc.,

Lake Mary, FL). The scanner employs range determination technology based on the phase-based principle and uses a wavelength of 785 nm. It has a field of view of 360° horizontal and 320° vertical, a range up to 80 m with a distance accuracy of ±3 mm and a data collection rate of 120,000 points per second. The scanner was placed on a built-in spirit level at a height of 1.3 m, and the start direction was aligned to north to calculate azimuths without an offset.

Data processing

Determining digital terrain models and diameter fitting

Techniques for the automatic derivation of task-relevant parameters from point clouds are of great importance from a scientific and economic point of view. During the preprocessing of the acquired point cloud data, the data were filtered and 'ghost points' that can be caused by ambiguity of phase measurement technology were removed. The Autostem[TM] software (TreeMetrics, Ireland) was used to clip the parts of the point cloud data within a 15 m radius for further processing. The software uses a density allocation along the Z-axis of a digital elevation model (DEM) patch for extracting the digital terrain model (DTM) without ghost points. This enables it to determine the ground level or the lowest point of a tree (Aschoff and Spiecker 2004; Bienert et al. 2006).

The software performs object detection in the plots within the radius of 15 m. It uses a horizontal slice of 5-cm-thick point cloud data at the DBH position. After detecting the objects, diameter fitting was performed based on user-specified input parameters for minimum count of point cloud data, disc thickness height and intra disc interval height. Once a circle is fitted to the point cloud data in the section specified in the diameter fitting step, the diameter will be processed using specified levels of circularity filtering and interpolation. The circularity filtering only filters the fitted circles whose reliability factor is less than the value specified in the filtering process. The reliability factor of the fitted circles, introduced by Bienert et al. (2007), is computed based on a number of parameters (i.e. circle arc length, errors of fitting, standard deviation and median filtering of neighbour elements). If the sliced section of the point cloud data extends over a small angle, a lower reliability factor value will normally be assigned. Specifying a high reliability factor in diameter, processing will leave out the sections of the tree or whole trees with poorer point cloud data. Any section of the stem omitted due to poor point cloud data can be filled by the interpolation function of Autostem[TM]. The software has a built-in option for linear and spline interpolation methods.

Based on previous study by Bienert et al. (2006), the best combination of disc thickness, disc thickness interval, filtering percentage and interpolation method was obtained from data processed using 3-cm disc thickness, 5-cm disc interval height and the linear interpolation method. These settings were used in this study. The reliability factor was set at 85 % to avoid the impact of unreliable data during model fitting.

Stem profile and diameter processing

For the trees selected for felling in 2009 in all nine plots, the stem profile, at 0.5 m intervals, was derived from the point cloud data using the Autostem[TM] software starting from the DBH position and proceeding upwards and downwards. The principle behind this processing was based on a least square circle fitting algorithm provided by Bienert et al. (2007) that had been integrated into Autostem[TM]. This algorithm allows stem segmentation (point cluster search) and diameter fitting for the observed portion of the stem.

A stem profile prediction task was incorporated, both in terms of interpolating the missing sections and in terms of extrapolating to the upper reaches of the tree based on polynomial model smoothing of the stem (Bienert et al. 2007). Diameter information gaps occurred mainly at greater heights on the stem, due to the absence of stem point cloud data caused by occlusion by branches, and these were filled by interpolated values based on the diameter values retrieved immediately above and below the gaps. Diameter values at the top of the trees, where no further data were obtained using circle fitting, were filled by extrapolation. The selection of the sample trees was based on distance from the scanner and tree size. Two trees that were selected (i.e. one tree each in plots 1 and 4) were not included in the point cloud data due to occlusion.

Table 1 Mean DBH, tree height and trees per plot in 2007 and 2009, based on conventional measurement methods

Plot no.	Stems per plot		Mean DBH per plot (cm)		Mean tree height per plot (m)	
	2007	2009	2007	2009	2007	2009
1	40	36	31.9	33.8	23.9	25.1
2	43	39	30.4	32.3	22.5	23.2
3	43	39	29.8	32.0	22.6	23.5
4	41	37	29.1	31.3	21.3	22.4
5	43	39	29.9	32.8	23.6	24.7
6	48	43	28.9	30.8	22.1	23.6
7	50	45	29.4	31.4	21.8	22.7
8		38		33.3		24.6
9		42		33.1		25.0
Mean	44	40	29.9	32.3	22.6	23.9

Distance, slope, pruning

The effect of the distance and slope between the trees and the scanner on the diameter estimation accuracy was investigated. The data for 2009 in all nine plots were used for this investigation. The distance from the scanner to each tree was determined from the point cloud data using Autostem^{TM}. The slope from the scanner to the breast height of each tree in the plot was collected in the field using clinometers. Pruning was performed up to a height of 6.0 m to reduce the effect of occlusion by branches and to investigate whether this would significantly improve diameter accuracy.

The random intercepts model (Eq. 1) was fitted to the DBH and 2.0 m dataset using a standard normal error mixed model in SAS Proc Mixed (SAS Institute Inc., 2009). The dataset was trimmed to remove scanner errors >5 cm in absolute value.

$$E(y|u_i) = \mu + u_i + \text{heightonstem} + \text{pruned} \\ + \text{distance}|\text{slope}|\text{actualdiam} \quad (1)$$

where y (cm) is the scanner-derived diameter error, μ is an intercept, $u_i \sim$ Gaussian $(0, \sigma_u^2)$ is a random intercept for each plot and the notation, "$a|b|c$" is shorthand for "$a + b + c + a*b + b*c + a*c + a*b*c$". *Heightonstem* is a binary dummy variable for whether the data point is measured at DBH (0) or 2.0 m (1) up the stem. *Pruned* is a binary dummy variable for the pruned (1) or unpruned (0) state. *Distance* has a range (0, 15 m), *slope* is slope from scanner to the tree [range (−18.5, 25 %)], and *actualdiam* is the calliper diameter measurement (cm).

Occlusion correction factor

When a forester conducts a manual inventory, the opportunity exists to move freely in the forest. Even when carrying out an angle count survey from a fixed point, the observer's position can be changed slightly to eliminate occluded trees. A stationary instrument such as the FARO scanner does not have this advantage; some trees will be partially or completely obscured from view. In this study, the method used to account for the effect of hidden and undetected stems for estimating total number of trees and volume in the stand using TLS data was based on the use of an occlusion correction factor (Eq. 2).

$$CF = \frac{TOT}{(TOT - OT)} \quad (2)$$

where CF is correction factor for occlusion, TOT is total number of counted trees per plot and OT is number of occluded trees, obtained using manual tree counts.

Volume calculation

The conventional method used to calculate the volume of individual trees was by considering a form height table (Matthews and Mackie 2006), while the Autostem^{TM} volume was derived by segmenting the stem of individual trees into cylinders with a thickness of 1 cm. The data from the seven plots that were included in both the 2007 and 2009 assessments were used for this analysis (Table 2).

The visibility of the top part of trees in the point cloud data was limited in the dense forest stand, and, as a result, obtaining sufficient information to determine accurate tree height using Autostem^{TM} was found to be impossible for most trees. Therefore, in each plot, the heights (h) of trees that were not measured by conventional methods were estimated using a DBH–height relationship based on the data from trees for which both DBH and height were determined, following the standard forest inventory procedure of using uniform height curves with species specific coefficients b_0, b_1, b_2 (Hradetzky 1999) as shown in Eq. 3.

$$h = (h_m - 1.3) \\ \cdot \exp\left((b_0 + b_1 \cdot h_m + b_2 \cdot d) \cdot \left(\frac{1}{DBH} - \frac{1}{d}\right)\right) + 1.3 \quad (3)$$

Table 2 Numbers and percentages of non-detected occluded and partly occluded tree per plot, in 2007 and 2009, after pruning

Plot no.	2007			2009		
	Actual	Occluded	Occlusion %	Actual	Occluded	Occlusion %
1	40	9	22.5	36	7	19.4
2	43	9	20.9	39	5	12.8
3	43	9	20.9	39	6	15.4
4	41	6	14.6	37	3	8.1
5	43	10	23.3	39	6	15.4
6	48	7	14.6	43	6	14.0
7	50	9	18.0	45	3	6.7
8				38	5	13.2
9				42	8	19.0
Mean	44	8	19.3	40	5	13.8

Fig. 1 Normalized (mean = 0, standard deviation = 1) diameter errors (x-axis) along the stem profile (y-axis) for felled trees per plot, depicting the errors in the diameter derived from the point cloud data of 2009 after pruning compared with the diameter from field measurements at 50-cm intervals along the stem. The *different symbols* in the graphs for each plot represent the individual felled trees
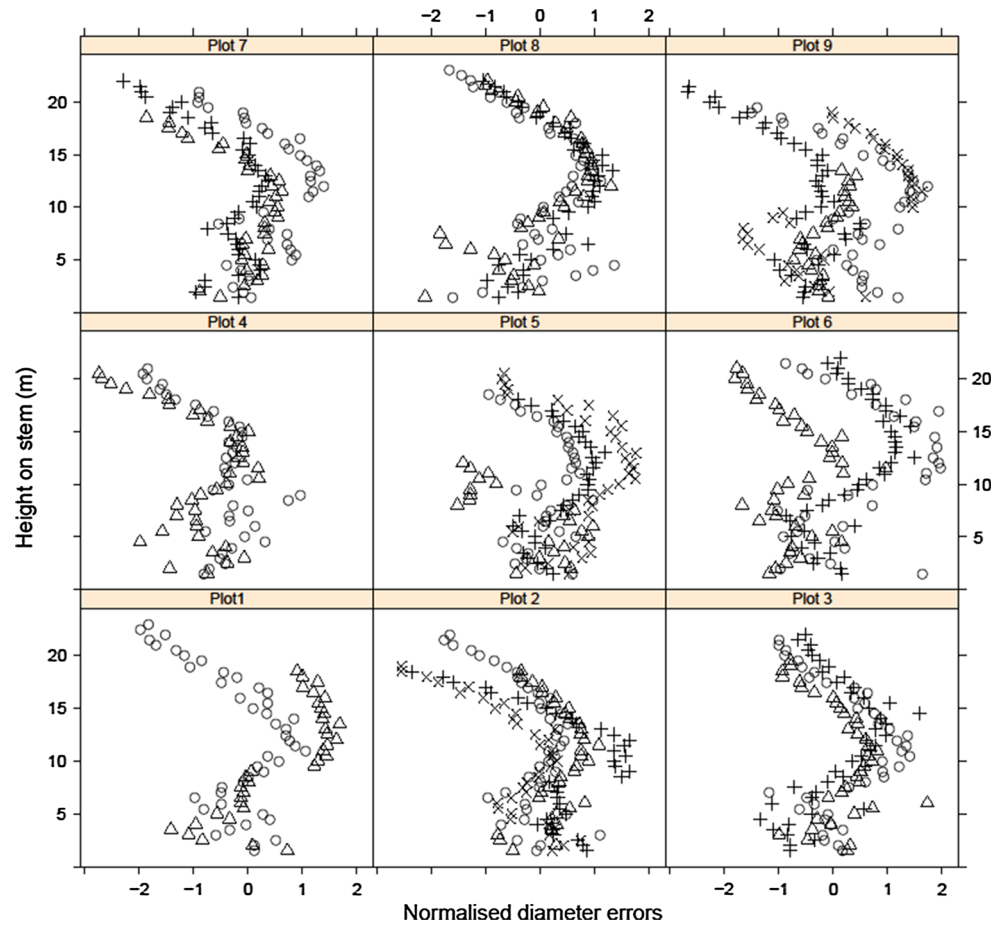
where h_m is mean tree height per plot, d is mean tree diameter per plot and DBH is diameter at breast height of trees for which height h is predicted.

To calculate plot and stand volume, an occlusion correction factor was used based on the number of trees counted per plot and the number of trees detected during automatic processing of DBH and volume by Autostem^{TM}. Total volume of trees per plot was computed based on the data obtained from trees visible to the scanner and corrected using the correction factor (Eq. 4).

$$TOT_{VOL} = CF \times VIS_{VOL} \qquad (4)$$

where TOT_{VOL} is the total volume of trees per sample plot, VIS_{VOL} is volume of visible trees to the scanner per plot and CF is correction factor for occlusion (Eq. 2).

Statistical analysis

The *lattice* library in R was used for plotting stem profiles, normalized scan errors, residual errors of DBH and diameter at 2.0 m, versus distance and slope (Sarkar 2008). The effect of pruning on the accuracy of diameter measurements was investigated at various heights on the trees (1.3,

2.0 m, and at every half-metre along the stem) using SAS (SAS Institute Inc., 2009).

Results

Stem profile

Diameter measurements along the stem at half-metre intervals were extracted from the point cloud data and compared with the field measurements. The summarized results, based on the processing of all felled trees in the nine plots, are depicted in Fig. 1. The diameter along the stem was estimated with low error values up to a height of c. 13–15 m, with slight differences between individual trees in each plot and between plots. The errors from 15 m upwards tend to indicate an underestimation of diameter values obtained using Autostem^{TM} compared with the manual measurements.

The output from Autostem^{TM} based on applying the circle fitting procedure indicated that up to the height of c. 15 m, the measurements were close to the values obtained using the conventional technique. The box plots in Fig. 2

Fig. 2 Standardized diameter errors (i.e. normalized error expressed as a proportion of conventional diameter) at different distance intervals from the scanner (*x*-axis) for the stem height classes (0–7.5, 7.5–15, 15–20 and 20–24 m) for the 27 felled trees in 2009. The *box plots* cover 50 % of the observations. The *dashed lines* cover 95 % confidence intervals and the open circles are outliers. The *black dots* represent the median
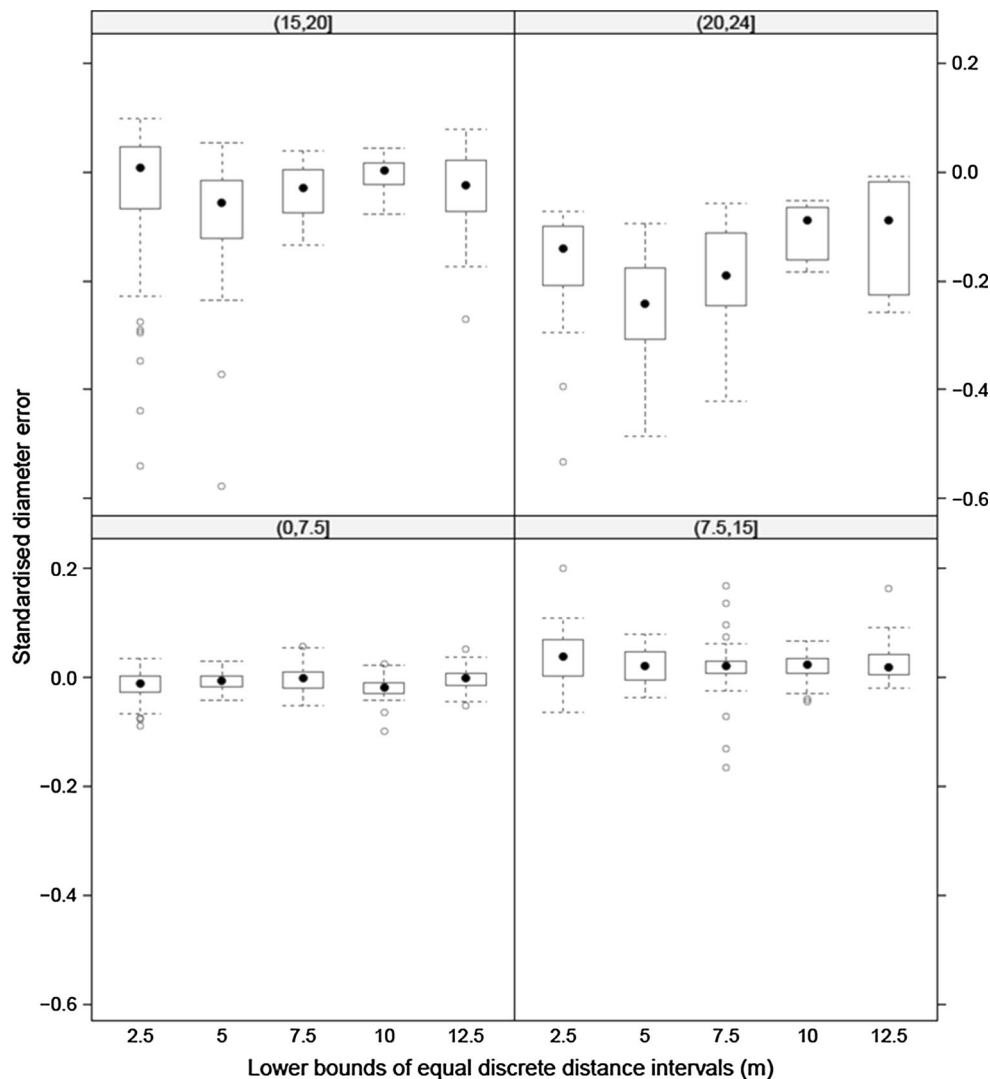
indicated that the normalized error is small in the panels for heights of 0–7.5 and 0–15 m. The confidence intervals in the panels for heights of 15–20 and 20–24 m are wider than in the panels for lower heights, and in the 20–24 m panel, the median error values are consistently negative.

Effect of distance, slope and pruning on diameter

A major interpretative feature of Table 3 is the statistically significant ($p < 0.05$) three-way interaction between distance, slope and actual diameter ($p = 0.0272$). This result was obtained from the analysis of all trees in the nine plots scanned in 2009 before and after removing lower branches up to a height of 6.0 m. The contour plots (Fig. 3) provide a graphical representation of this interaction. Even though pruning was seen not to be significant ($p = 0.8610$), the pruning effect seems to reduce scanner error (as shown by the positive coefficient for the unpruned data (Table 3).

Errors were significantly larger at 2.0 m than at DBH ($p < 0.0001$), and the difference was estimated to be approximately 0.5 cm (Table 3). The random plot effect was not significant ($p = 0.99$), indicating that the fixed terms in Table 3 adequately described the variability in the scanner error.

The error in diameter at various distances and slopes also propagates into errors of volume estimation (Fig. 4). Large values for the residual of volume can be observed at distances >12 m and for steep slopes (greater than ±15 %).

Occlusion

The numbers of trees per plot were obtained during the setting up of the plots. Occlusion percentage was calculated after automatic processing of the point cloud data using the Autostem[TM] software (Table 2). Based on a visual

Table 3 SAS output from the Eq. 1 model showing the effect of pruning, distance, slope and height along stem on the scanner-derived error for DBH and diameter at 2.0 m, for data of all trees in the nine plots scanned in 2009 before and after pruning

Effect	Dummy variables		Regression coefficient	Error	DF	t value	$p > |t|$
	Pruned	Heightonstem					
Intercept			2.0998	1.0294	8	2.04	0.0757
Heightonstem		2	0.5593	0.0994	1119	5.63	<0.0001
		1.3	0	–	–	–	–
Pruned	0		0.0174	0.0992	1119	0.18	0.8610
	1		0	–	–	–	–
Distance			−0.2255	0.0994	1119	−2.27	0.0234
Slope			0.2150	0.1049	1119	2.05	0.0407
Distance*slope			−0.0254	0.0108	1119	−2.35	0.0191
Actualdiam			−0.0556	0.0319	1119	−1.74	0.0821
Distance*actualdiam			0.0078	0.0031	1119	2.51	0.0124
slope*actualdiam			−0.0069	0.0033	1119	−2.08	0.0379
Distance*slope*actualdiam			0.0008	0.0003	1119	2.21	0.0272

The p value is SAS type-III, i.e. conditional on all other terms having been fitted

Fig. 3 Contour plots of DBH error (conventional vs. scanned) as a function of the slope (in %) from the plot centre to individual trees (x-axis) and the distance (in m) from the scanner (y-axis), for four DBH classes
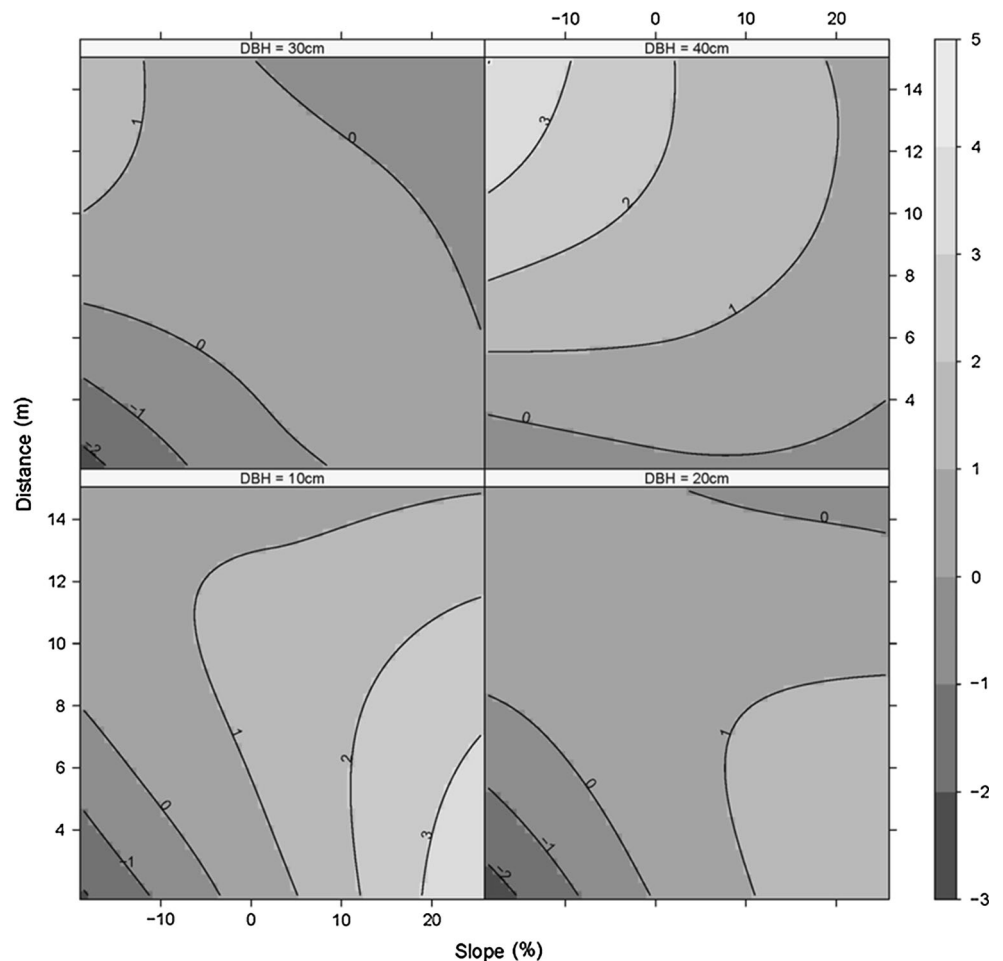
inspection of the point cloud data, it was determined that all undetected trees missing from the Autostem[TM] output were either partly or completely occluded. There was no difference in the numbers of occluded trees before and after pruning. High numbers of trees per plot were recorded in plot 7; however, the occlusion was low in this plot, especially in 2009. The occlusion percentage was high in plots 1 and 5 in 2007 and in plot 1 in 2009. The average
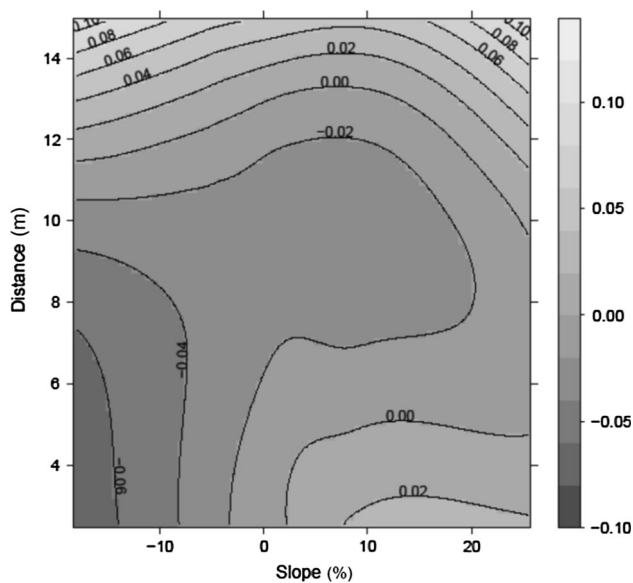
Fig. 4 A contour plot of tree volume error (conventional vs. scanned), as a function of the slope (in %) from the plot centre to individual trees (x-axis) and the distance (in m) from the scanner (y-axis)

occlusion percentage for the seven plots was 19.3 and 13.1 % for the data acquired in year 2007 and 2009, respectively. The mean difference in stocking per plot between the 2 years was 9.5 %. The removal of four to five sample trees in year 2007 resulted in the reduction in occlusion by 6.2 %.

Estimating volume increment

Using repeated scanning and field measurements in years 2007 and 2009 in the same seven plots, we investigated the possibility to monitor tree and forest volume increment. Only trees present in both 2007 and 2009 were included in this analysis.

The mean volumes per hectare (extrapolated from mean plot values) in 2007 and 2009, using Autostem[TM], were 288.52 and 362.99 m³, respectively (Table 4). These increased to 332.32 and 417.98 m³, respectively, when a correction factor (Eq. 4) was used to account for the occluded trees. The mean volumes per hectare computed using the conventional method were 305.29 m³ in 2007 and 384.54 m³ in 2009 when only the trees visible to the scanner were included, and 386.32 and 465.47 m³ in 2007 and 2009, respectively, when all trees in the plots were included. The mean differences between the volume increments derived using the conventional method and Autostem[TM] over the 2 years period were 6.0 % (or 4.77 m³ ha⁻¹), based on the trees visible to the scanner, and 8.1 % (or 6.96 m³ ha⁻¹) when including a correction factor (AS) and using data for all trees in the plots (FF) (Table 4).

Comparisons of DBH and volumes calculated for individual trees were performed using trees felled for validation of diameter measurements along the stem. For most of the trees, the DBH estimates were very close, but for a few of them the differences were greater than ±2.0 cm. The volumes derived from Autostem[TM] and from the form factor method were compared to the values calculated based on 50-cm-long stem sections and showed an overall difference of 22 and 11 %, respectively. For most of the trees, the estimates are very similar, but for some trees the differences were >0.200 m³, especially when the Autostem[TM] estimates are compared to those obtained using the other two methods. In most cases, the volume differences appear to be caused by differences in DBH estimates, but errors in tree height estimation add to the number of trees with noticeable volume estimate differences.

Discussion

Stem profile

The stem profile result obtained in this study showed a decline of accuracy at heights >15 m (Figs. 2 and 3). However, the interpolation and extrapolation techniques used have resulted in an improvement in accurate values up to a height of 15 m on the stem compared with the values obtained without interpolation. This is partly due to the use of interpolation techniques implemented to estimate diameters for the regions that were occluded by branches in the tree canopy. Nugent et al. (2009) reported that although Treemetrics technology provides vastly more tree information than more traditional inventory approaches, it is not guaranteed to provide a complete picture of each tree. Readings for some sections of a tree may be missing due to occlusion by branches or other trees. They found that this becomes increasingly common the further up the tree the readings are sought due to the effects of denser branching and the limitations of the laser at increased distances.

A similar study conducted by Henning and Radtke (2006) to accurately measure upper-stem diameters that were difficult to evaluate without destructive or labour intensive methods found that diameter measurements assessed using TLS point clouds were on average within a few millimetres of calliper measurements. They reported that the decline in the accuracy of the measurements occurred above 10 m along the main stem. They attributed the loss of accuracy at points higher than 10 m in their study mainly to the reduced numbers of surface points in bole slice sections at such heights, due to the scanner's finite angular step width and the increased distance from the instrument to bole surfaces high aboveground. The other factors mentioned to contribute to this reduction are

Table 4 Volume (m³) per tree, plot and hectare (for 2007 and 2009), derived from point cloud data using Autostem™ software (AS) versus calculated volume using form factors (FF): (a) volume excluding and including occluded trees; (b) volume differences as estimated by the two approaches (i.e. AS and FF) in 2007 and 2009, and growth from 2007 to 2009

(a)

2007

Plot	AS			FF			
	Occlusion excluded		Occlusion adj/plot	Occlusion excluded		Occlusion included	
	Per tree	Per plot	Per plot	Per tree	Per plot	Per tree	Per plot
1	0.739	19.944	24.758	0.835	22.541	0.822	31.252
2	0.750	23.991	27.519	0.768	24.578	0.706	32.492
3	0.705	21.139	24.983	0.764	22.923	0.722	30.309
4	0.670	21.448	23.340	0.685	21.927	0.652	24.120
5	0.734	22.032	26.038	0.767	23.008	0.763	29.771
6	0.586	22.279	25.892	0.637	24.223	0.653	28.073
7	0.634	22.820	24.450	0.650	23.388	0.651	29.958
Mean vol/plot	0.688	21.951	25.283	0.729	23.227	0.710	29.425
Mean vol/ha		288.519	332.320		305.296		386.763

2009

Plot	AS			FF			
	Occlusion excluded		Occlusion adj/plot	Occlusion excluded		Occlusion included	
	Per tree	Per plot	Per plot	Per tree	Per plot	Per tree	Per plot
1	0.923	25.857	32.099	0.995	27.857	0.876	37.658
2	0.870	28.723	32.947	0.880	29.056	0.767	38.341
3	0.779	26.471	31.284	0.857	29.55	0.776	35.678
4	0.754	25.633	27.895	0.786	26.735	0.714	29.280
5	0.865	27.666	32.696	0.930	29.760	0.850	36.561
6	0.746	27.618	32.097	0.782	28.922	0.714	34.249
7	0.746	31.346	33.585	0.793	33.308	0.708	36.121
Mean vol/plot	0.812	27.616	31.800	0.861	29.256	0.772	35.413
Mean vol/ha		362.991	417.985		384.543		465.466

(b)

2007 Volume estimate differences

Plot	FF occlusion excluded–AS occlusion excluded		FF occlusion included–AS occlusion adjusted
	Per tree	Per plot	Per plot
1	0.096	2.597	6.494
2	0.018	0.587	4.972
3	0.059	1.784	5.326
4	0.015	0.480	0.779
5	0.033	0.976	3.733
6	0.051	1.944	2.181
7	0.016	0.568	5.509
Mean vol/plot	0.041	1.276	4.142
Mean vol/ha		16.777	54.442

2009 Volume estimate differences

Plot	FF occlusion excluded –AS occlusion excluded		FF occlusion included–AS occlusion adjusted
	Per tree	Per plot	Per plot
1	0.071	1.999	5.560
2	0.010	0.333	5.394
3	0.079	2.684	4.395
4	0.032	1.101	1.385
5	0.065	2.094	3.865
6	0.035	1.304	2.153
7	0.047	1.962	2.536
Mean vol/plot	0.049	1.640	3.612
Mean vol/ha		21.552	47.481

Growth (2009–2007)

Plot	AS occlusion excluded		AS occlusion adjusted	FF occlusion excluded		FF occlusion included	
	Per tree	Per plot	Per plot	Per tree	Per plot	Per tree	Per plot
1	0.185	5.913	7.340	0.160	5.316	0.053	6.406
2	0.121	4.732	5.427	0.112	4.478	0.060	5.849
3	0.0074	5.331	6.301	0.093	6.231	0.054	5.370
4	0.084	4.185	4.555	0.101	4.807	0.062	5.161
5	0.130	5.633	6.658	0.163	6.752	0.087	6.790
6	0.160	5.339	6.205	0.144	4.699	0.061	6.177
7	0.112	8.526	9.135	0.143	9.920	0.057	6.162
Mean vol/plot	0.124	5.666	6.517	0.131	6.029	0.062	5.988
Mean vol/ha		74.472	85.665		79.246		78.704

that smaller stem diameters present smaller surfaces to be scanned, resulting in fewer surface points for arc-centre estimation, and that obstructions from branches and foliage reduce the number of data points available to characterize bole surfaces at such heights.

Effect of distance, slope and pruning on diameter

As the distance increases, the accuracy of the tree diameters retrieved from the point cloud data decreased. This could be explained by the fact that the quality of point cloud data received by the scanner, on which the circle fitting algorithms are based, gets poorer at greater distances. Lovell et al. (2011) also found the highest accuracy of diameter measurements at close ranges. Treemetrics have introduced a policy to work with more but smaller plots (i.e. 10 m radius) to reduce the problems associated with scan distance.

Another contributor to error is the Autostem™ determination of the location of the foot of the tree. Based on this location, the software might determine the DBH location at a higher or lower position than the exact DBH location where the manual measurements were taken. Based on visual assessments of the processed point cloud data, these differences were in almost all cases <10 cm and should therefore not lead to large errors in DBH values. The reason for errors in the DBH location could be errors associated with determining the DTM by the Autostem™ software on sloping ground, resulting in incorrect DBH positions, with the majority of the estimates at negative slopes showing lower values of DBH compared with those of manually measured DBH. It appears, however, that different systematic errors were associated with trees located uphill and downhill from the scanner, indicating specific tree and ground intersection determination problems for the two situations.

Another reason for the differences between uphill and downhill measurements is the effect of slope on the angle of incidence, which determines the point cloud density. Aschoff and Spiecker (2004) found that on the downhill side of a steep plot there are far fewer scan points than on the uphill side, contributing to a lower accuracy of derived parameters for trees in that position.

Occlusion

The average occlusion percentages computed from the two scans in the same plots in years 2007 and 2009 showed a reduction from 19.3 to 13.1 %, caused by the opening of gaps due to the felling of sample trees for validation purposes. Based on the results obtained of the pruning analysis and on visual inspection of the point cloud data, it was obvious that all cases of occlusion were caused by stems

hiding others from the scanner and not by stems being hidden by low branches. Several studies followed different method to overcome occlusion (e.g. Strahler et al. 2008; Lovell et al. 2011; Yao et al. 2011). The radius of the scan plot can influence the occlusion percentage. The greater the radius of the scanned plots, the more chance for trees closer to the scanner to hide trees located further away. Reducing the plot radius could overcome this problem but will require more plots to obtain stand estimates with similar accuracy. Strahler et al. (2008) have compared ground-based LiDAR and traditional relaskop results and found that the effects of occlusion due to the single viewpoint of the LiDAR scanner resulted in a reduction in basal area and stem density by about 10 %. However, they reported that the use of a methodology proposed by Jupp et al. (2005), based on the number of trees counted to adjust the LiDAR results (as was done in this study), enabled them to find good agreement with the traditional results. The occlusion effects can also be accounted for by statistical methods designed specifically to avoid the need for manual counts (e.g. Lovell et al. 2003; Parker et al. 2004; Strahler et al. 2008). Another solution to occlusion is the acquisition of multiple scans from different positions in the plot and the analysis of these scan data either separately or in the form of a merged point cloud dataset (e.g. Henning and Radtke 2006; Hopkinson et al. 2004; Yao et al. 2011).

Estimating volume increment

The type of sensor used to acquire data to study the growth of trees and forest stands has changed as technology advanced, and the comparison of datasets can be difficult due to differences in the sensor type used (Hyyppä et al. 2008). In this study, the sensor and the software used to acquire and process the datasets were the same throughout and the differences in the assessed parameters can be attributed to the changes in the trees and stand over the study period.

The increment values over the 2-year period derived from scan data were lower than those obtained using the traditional method. A detailed investigation of trees where the two estimates were far apart indicated that some of those trees have irregular shapes with buttressing several metres up the stem, resulting in Autostem™ only including part of the point cloud data in the definition of the arc used for circle fitting. In addition, the circle fitting process for some partially hidden trees resulted in a significant underestimation of the diameter. Finally, some of the trees were not totally captured by the scanner as a result of crown cover. This is due to canopy shadow effects and incomplete sampling of the vertical plot profile as explained by Hopkinson et al. (2004). These diameter errors for a small number of trees resulted in volume errors

when Autostem[TM] results were compared to values obtained using the form factor and segment methods, while incorrect height estimates added to these differences in a few cases.

The overall difference between the TLS-derived and conventional volume estimates in 2007 was 5.5 %, between the two 2009 estimates 5.6 % and between the two growth estimates 6.2 %. The use of a simple correction factor for occlusion increased the overall differences between the Autostem[TM] derived volume and form factor derived volumes for 2007 to 14.1 %, for 2009 to 10.2 % and between the two growth estimates to 8.1 %. These findings for uncorrected volumes are similar to results in other studies. For instance, Hopkinson et al. (2004) found TLS-derived estimates of timber volume within 7 % of those calculated from manual field measurements. Even with the use of a simple correction factor to account for all trees in the plot, this study produced estimates that were within 8 % of the values traditionally used in the forest sector in Ireland.

Conclusion

Based on the result of this study, we are able to show that terrestrial LiDAR enables the acquisition of forest stand parameters, such as diameter, height stem profile and volume increment, with an acceptable accuracy when compared to estimates obtained by traditional means. The combined effects of slope, distance from the tree and tree size were analysed and revealed complex interactions between all factors. The multi-temporal terrestrial LiDAR data enabled accurate volume increment (growth) estimation.

One of the limitations of TLS is the restricted distance range over which tree and forest structural characteristics can be obtained. Occlusion by stems and crowns resulted in underestimation of the number of stems per plot and hence resulted in an underestimation of plot and stand volumes. Compared with the result based on the form factor method and only including the trees visible to the scanner, the Autostem[TM] volumes were consistently lower. The use of a simple correction factor, which is based on tree numbers and not on actual tree dimensions, to get total volume estimates for the plot, resulted in an increase in the difference between the volume obtained using the corrected scan data and the volume determined based on the form factor method for all trees in the plot. However, the trend in the differences between volumes determined using the Autostem[TM] and the form factor methods was consistent, resulting in relatively small increment estimation errors.

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