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SHORT NOTE

Evaluation of an occlusion adjustment model for predicting hidden stems when using terrestrial laser scans in natural and plantation forests in Australia and USA

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Abstract

Terrestrial laser scanning (TLS) technologies are now being used to provide detailed forest inventory information at the tree or plot scale. A major problem to overcome when using TLS is occlusion by surrounding trees, lower branches and understorey. An occlusion adjustment model was evaluated in 24 stands in Oregon, USA and Australia. The model can be used to predict stand-level tree count densities with minimal errors, especially if an appropriate plot radius is selected. The optimal plot radius may be dependent on the stand-type in which the TLS is being undertaken. Other approaches are likely to be more appropriate if accurate stem counts are required at the individual plot level.

Keywords: Douglas-fir; eucalypts; poplar; radiata pine; stem occlusion; terrestrial laser scanning; tree count density.

Introduction

Forest managers need good metrics of the quantity, quality and location of timber resources within their forests to ensure that: (a) harvest and volume growth increments are balanced; (b) log products are optimally matched to markets; (c) wastage is minimised; and (d) the value of the forests are maximized at the time of harvest. New approaches to obtaining these metrics are being examined with the goals of increasing their accuracy and reducing their data gathering costs.

Airborne laser scanning (ALS), also known as aerial LiDAR, has been used since 2001 to describe forest structure over large areas. Airborne laser scanning can provide information on tree location within plots, tree height, crown dimensions of dominant trees and timber volume. However, ALS can only provide limited information under the canopy or at the tree scale. Terrestrial laser scanning (TLS) technologies have been implemented to provide detailed forest inventory information at the tree or plot scale (Thies & Speicker, 2004; Bienert et al., 2007).

Dassot et al. (2011) note that a major problem to overcome when using TLS is occlusion by surrounding trees, lower branches and understory. Something as simple as an accurate stem count can be difficult when far stems are hidden behind near stems. Murphy et al. (2010) reported that 0% to 46% of trees in 33 radiata pine plots in Australia were occluded when scans were gathered at a single TLS point in each plot. Occlusion rates were also found to be dependent on plot size. Stand density is a key factor that affects occlusion levels and tree description and can become a real problem in the case of plot inventories (Watt & Donoghue, 2005; Murphy, 2008).

There are a number of approaches that could be taken to overcome or reduce occlusion effects when using

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TLS for stem measurements and determining stem count density. These include:

- Taking multiple scans from different scan points that are geo-referenced to each other.
- Counting the number of stems that are hidden behind other trees and are inside the plot radius. A single point laser range finder could be used to measure distances to the hidden trees. This would also require the person measuring the plots to move around near the scanner site to locate "in" trees – similar in practice to the use of a relascope, a multi-use instrument for forest inventory.
- Predicting the number of trees hidden in the plot based on a measure of what can be seen.

Strahler et al. (2008), following Jupp et al. (2005), present a model for adjusting seen count estimates for the occlusion effect. The adjustment procedure is based on the assumption that the location of trees is randomly distributed. Strahler et al. (2008) comment that the random occlusion model "is not appropriate for a plantation where trees are spaced more regularly".

All of the above approaches have their limitations. The multiple scan approach will involve additional cost due to increased scan collection time and data processing time. The counting hidden stems approach introduces errors related to determining if stems near the plot boundaries are in or out. The occlusion adjustment model approach is unlikely to be accurate at the individual plot level, but may be less costly and have an "acceptable" level of accuracy at the stand level.

This technical note reports the results of a limited set of evaluations on the application of the occlusion adjustment model in non-plantation and plantation stands in Australia and Oregon, USA.

Materials and Methods

Occlusion Adjustment Model

A summary of the model used is given below. A more detailed introduction to the theory and adjustment procedures of this model is provided by Jupp et al. (2005).

The number of stems expected to be visible within a plot of radius (R) is:

$$N(\lambda, D_E; R) = N_0(\lambda, R)\, F(t)$$

where: $F(t) = 2/t^2\,(1 - e^{-t}[1 + t])$

and $t = \lambda D_E R$

and $D_E = \bar{D}\,(1 + C_V^2)^{1/2}$

and $N_0(\lambda, R) = \lambda \pi R^2$

In the above expressions λ is the true count density of stems (m^{-2}), D_E is the effective diameter of the stems, $\bar{D}$ is the mean diameter of the stems, C_V is the coefficient of variation of the stem diameters, and $N_0(\lambda, R)$ is the true number of stems within the plot.

Since the number of trees visible within the plot [$N(\lambda, D_E; R)$] is known, and if it is assumed that $\bar{D}$ and C_V of the visible stems is representative of all stems within the plot, it is possible to back-calculate λ and hence the expected "true" number of trees within the plot [$N_0(\lambda, R)$].

Tree data

Data for evaluating the occlusion adjustment model was gathered by two methods; from real measurements in 52 TLS plots and from theoretical measurements in three mapped stands.

Fifty two randomly-located, circular TLS plots were established on flat ground in 21 stands in Australia and Oregon. A summary of the plot information is provided in Table 1. Plot radii ranged between 5.64 and 20.34 m. Species included radiata pine (*Pinus radiata* D. Don), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), Southern Blue Gum (*Eucalyptus globulus* Labill.), and hybrid poplars (*Populus* sp.). The Douglas-fir plots were established in non-plantation stands. All other plots were in plantation stands. All trees in the TLS plots were counted in the field and manually measured for diameter at breast height (DBH) at 1.4 m above the ground.

Analyses

TLS plots

The TLS scans were viewed manually using Scene software (FARO, FL, USA) to determine how many trees were "seen" and how many trees were "occluded" at a plane passing through DBH. The occlusion adjustment model describes the expected number of tree centre-lines that can be seen from the scanning position, with two levels of assessment. The first level included only those trees where both sides (left and right) could be viewed (hereafter referred to as "completely seen" trees). The second level included trees where at least one side of the tree plus half or more of the diameter could be viewed (hereafter referred to as "majority seen" trees). Trees that were completely hidden or had less than half of the diameter visible were classed as occluded. Comparisons between stem count density levels adjusted for occlusion and true count density were undertaken at the individual TLS plot level.

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TABLE 1: Summary data for Terrestrial Laser Scan and mapped stands.

Location	Species	Type[1]	No. of Stands	No. of TLS plots	Plot radius (m)	Stand age (years)	Average diameter breast height (mm) and range [in brackets]	Measured stocking (s ha^{-2})
TLS								
Oregon, USA	Douglas-fir	np	3	11	11.28	20 - 67	333 [71-668]	350 - 1000
Oregon, USA	Poplar	p	1	10	10.0	11	290 [177 – 378]	700 - 764
Western Australia	Southern Blue Gum	p	1	3	7.5	15	238 [125 - 341]	623 - 905
Western Australia	Radiata pine	p	4	16	5.64 - 20.34	18 - 33	383 [80 – 643]	115 - 1101
South Australia	Radiata pine	p	12	12	8.93 - 11.28	27 - 41	377 [201 – 538]	200 - 679
Mapped Stands								
Oregon, USA	Douglas-fir	np	2	-	-	68 - 100	477 [122 - 1432]	214 - 257
New Zealand	Radiata pine	p	1	-	-	30	483 [205 to 800]	211

[1] np = non planted; p = planted

Mapped plots

A computer program was written using Visual Basic language to randomly allocate plot locations within the three mapped stands. Plots were allowed to overlap each other but not extend beyond the stand boundary. Based on the known location and diameter of each tree, and simple geometry it was possible to determine the number and diameters of "completely" seen trees, "majority" seen trees, and occluded trees within a given plot radius. Four plot radii were evaluated for all three stands; 7.5, 10, 12.5 and 15 m. In addition, a 20 m plot radius was evaluated for the two Douglas-fir stands. Eight sampling intensities, based on percentage of the stands area, were evaluated for each plot radius evaluation; 1, 2, 3, 4, 7, 10, 15 and 30%. Each combination of plot radius and sampling intensity was repeated for 250 iterations. In total, over 90 combinations were evaluated for the three mapped stands. Comparisons between count density levels (adjusted for occlusion) and true count density were undertaken at the stand level. In addition, comparisons were made between the quadratic mean DBH of seen trees and all trees within the generated plots. Comparisons are based on smoothed data; for each "plot radius / sampling intensity" combination, the stand level averages were calculated using results from 250 iterations, which in turn were the calculated averages from individual plots. The number of individual plots was dependent on the sampling intensity and the plot radius.

Plotting of data and statistical analyses were carried out using Microsoft Excel for both the TLS plots and the mapped stands. A binary variable was included in the regression analyses for testing the effect of stand type (plantation or non-plantation) on prediction errors. The effect of species was not evaluated using regression analysis since all Douglas-fir plots were in natural forests and all other species were in plantation forests. Means and standard errors for different species were calculated, however.

Stem locations were mapped in two non-plantation Douglas-fir stands in Oregon using ground surveying instruments and in one plantation radiata pine stand in New Zealand using aerial photographs and an analytical stereoplotter. The areas of the two Douglas-fir stands were 3.6 and 4 ha. The area of the radiata pine stand was 1.9 ha. Ages for the three stands ranged between 30 and 100 years. The DBH of each tree in all three stands was manually measured. A summary of the stand information is provided in Table 1.

Results

The mean error in the adjusted count density estimates for the TLS plots was +0.3% (3.7 s ha^{-2}) when adjustments were based on "completely" seen trees and +2.9% (20.3 s ha^{-2}) when adjustments were based on "majority" seen trees. Percentage errors ranged between -37% and +18% for "completely" seen tree adjustments and between -31% and +18% for "majority" seen tree adjustments. No clear pattern emerged with respect to species effects. Regression analyses showed that the size of the error was related to neither stand type nor true stem count density. It was, however, weakly related to the plot radius (Figure 1). Absolute errors were lowest for plot radii between 12 and 14 m.

Table 2 shows the summary statistics for the evaluations carried out using data from mapped

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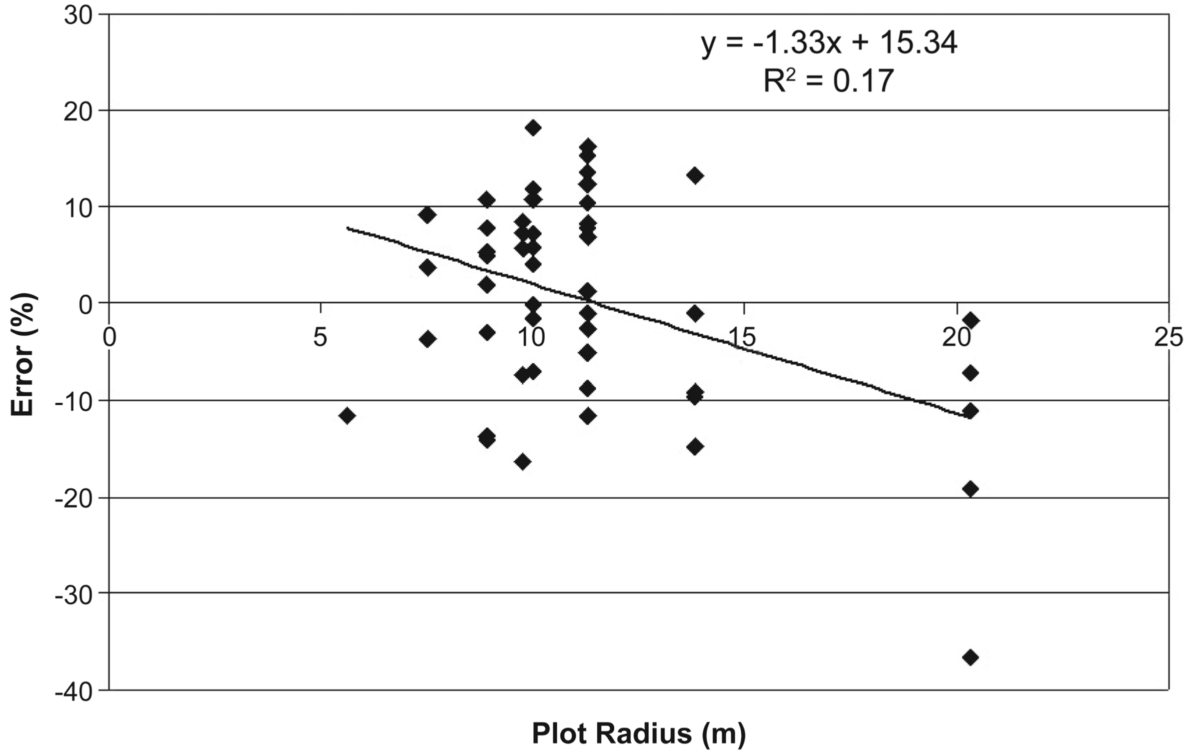

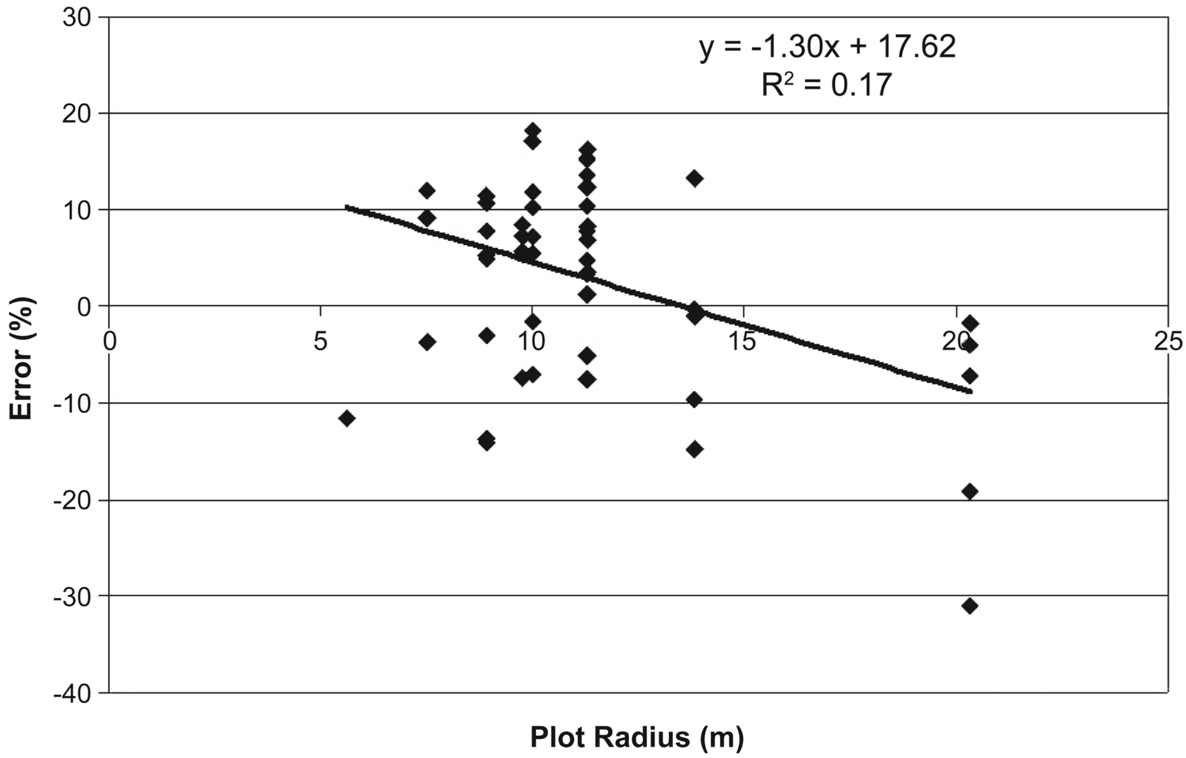

FIGURE 1: Relationship between errors in stocking estimates and plot size for occlusion model adjustments based on "completely" seen trees (top) and "majority" seen trees (bottom) in TLS plots. Note that all of the non-plantation plots had radii of 11.28 m.

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TABLE 2: Prediction error (%) summary statistics for mapped stands based on "completely" seen and "majority" seen tree occlusion model adjustments.

Statistic	**"Completely" seen trees**		**"Majority" seen trees**	
	Stocking	**Quadratic Mean DBH**	**Stocking**	**Quadratic Mean DBH**
Minimum	-8.5	-0.8	1.8	0.0
Maximum	4.0	0.5	16.4	1.1
Mean	-2.0	0.1	5.9	0.4
Standard error	0.4	0.02	0.4	0.03
Number of scenarios evaluated	92	92	91	91

stands. Adjusted count density was underestimated by 2% for the analyses based on "completely" seen trees and overestimated by 6% for the analyses based on "majority" seen trees. On average, the quadratic mean DBH of seen trees was generally within 1% of the calculated quadratic mean DBH of all trees within the stands (average error of 2 mm).

Regression analyses indicated that errors in the adjusted count density were not related to sampling intensity but were related to plot radius and stand type for adjustments based on both "completely" seen trees and "majority" seen trees (Tables 3 and 4). The relationships were stronger for "completely" seen tree adjustments (R^2 = 0.98; SE = 0.005) than for "majority" seen tree adjustments (R^2 = 0.18; SE = 0.035). The best regression models found for count density were:

$$\text{AdjC\_Ratio} = 1.035 + 0.036\,\text{PID} + 0.001\,\text{PID*Radius} - 0.006\,\text{Radius}$$

and

$$\text{AdjM\_Ratio} = 1.023 - 0.002\,\text{PID*Radius} + 0.003\,\text{Radius}$$

where AdjC_Ratio is the ratio between the adjusted count density and the true count density based on "completely" seen trees, AdjM_Ratio is the ratio between the adjusted count density and the true count density based on "majority" seen trees, PID is the binary variable for stand type (PID = 0 for the non-plantation stands and 1 for the plantation stand), and Radius is the plot radius (m).

For the mean plot radius (11.87 m), adjusted count densities would be over-estimated by 2% for the plantation stand and underestimated by 3% for the non-plantation stands. Absolute errors were lowest for "completely" seen tree adjustments for a 6 m plot radius in the non-plantation stands and 16 m radius in the plantation stand. Absolute errors always increased with increases in plot radius for the "majority" seen tree adjustments.

Discussion and Conclusion

The purpose of this study was to evaluate the application of an occlusion adjustment model to predict stand-level tree count densities with minimal errors in non-plantation and plantation stands. Evaluations were based on real tree-count measurements in TLS plots and theoretical tree-count measurements in mapped stands.

TABLE 3: ANOVA table for regression model relating the ratio of adjusted tree count density, based on completely seen trees, and true density to stand type and plot radius.

	df	**SS**	**MS**	**F**	**Significance F**
Regression	3	0.1043	0.0348	1429.1	1.68E-74
Residual	88	0.0021	2.43E-05		
Total	91	0.1065			

TABLE 4: ANOVA table for regression model relating the ratio of adjusted tree count density, based on majority seen trees, and true density to stand type and plot radius.

	df	**SS**	**MS**	**F**	**Significance F**
Regression	2	0.0239	0.0120	9.7	1.50E-04
Residual	88	0.1080	1.23E-04		
Total	90	0.1319			

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One of the variables in the adjustment model is the mean DBH of the trees in the plot. Since DBH measurements can only be gathered on visible trees, two implicit assumptions in using the model are that the DBHs of the visible trees are representative of all trees in the plot and they are measured accurately. The quadratic mean DBH of visible trees in the mapped stands, at the stand level, was essentially the same as the quadratic mean DBH of all trees in the stand. Hence the first assumption is a reasonable one to make.

The average errors tended to be less when adjustments were based on "completely" seen trees than on "majority" seen trees. This was not expected, since the occlusion adjustment model assumes only that the centre-line of the tree can be seen and a diameter obtained.

At the individual TLS plot level, errors in adjusted tree count density averaged +0.3% when adjustments were based on "completely" seen trees. This can be compared with average errors of +3.8% reported by Yao et al. (2011) in six non-plantation stands in north-eastern USA and -1.2% reported by Strahler et al. (2008) in a non-plantation stand in Australia. The range in errors for individual TLS plots was large (-37% to +18%) but was still smaller than reported by Yao et al. (2011) (-87% to 104%).

The occlusion adjustment model is based on random location of trees within a plot and is not derived for a plantation with systematic distribution of stems (Strahler et al., 2008). Errors were related to stand-type for the mapped stands but not for the TLS plots. The data from the mapped stands had less variability associated with it (averages for the stand were used) and a larger number of data points than for the TLS plot data. This difference in data type may have allowed a relationship in the mapped stand data to be teased out that was not evident in the TLS plot data. More research is needed on this issue.

Errors, for both the TLS plots and for the mapped stands, were related to the radius of the plots. The optimal radius to minimize absolute errors was 6 m for the non-plantation mapped stands and 16 m for the plantation mapped stand. Where stand-type had no impact, the optimum radius for the TLS plots was 12 to 14 m, which fell within the 6 and 16 m for mapped stands.

There are a number of limitations to this study. Firstly, although the range in stocking levels in the TLS plots and mapped stands was large, the highest stocking levels in this study were low compared with those studied by others. Yao et al. (2011), for example, evaluated the occlusion adjustment model in stands ranging between 1042 and 3341 s ha^{-2}. The model should be evaluated in a wider range of stockings. Secondly, three quarters of the stands in which the study was undertaken were plantation stands. The model is not considered to be appropriate in these stands. However, large differences in error rates for plantation stands were not observed; possibly because all of the plantation stands had had at least one thinning which may have reduced, at least to some extent, the systematic layout of the trees. The model should be evaluated in additional non-plantation stands. Finally, the model assumes that occlusion is due to the trunks of other trees in the plot. The model should be modified, in a way not yet determined, to include occlusion from branches and shrubs; these could be a significant problem in young, open-grown stands in particular.

Despite these limitations, the authors conclude that the occlusion adjustment model can be used with TLS to predict stand-level tree count densities with minimal errors, especially if an appropriate plot radius is selected. The optimal plot radius, which minimizes absolute errors in stem count density estimates, may be dependent on the spacing and spatial pattern of trees in the stand-type in which the TLS is being undertaken. Other approaches, such as scanning from multiple points within a plot and manually counting hidden stems, are likely to be more appropriate if accurate stem counts are required at the individual plot level. Further studies should be undertaken to evaluate the existing occlusion model in a wider range of stand types, and stem count densities and to develop a model that accommodates a wider range of occlusion sources.

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References

Bienert, A., Scheller, S., Keane, E., Mohan, F., & Nugent, C. (2007). Tree detection and diameter estimation by analysis of forest terrestrial laserscanner point clouds. In P. Rönnholm, H. Hyyppä, & J. Hyyppä (Eds.), *Proceedings of the ISPRS Workshop 'Laser Scanning 2007 and SilviLaser 2007, Espoo, Finland,* (pp. 50-55). Retrieved 22 December 2011, from http://www.isprs.org/proceedings/XXXVI/3-W52/ final_papers/Bienert_2007.pdf.

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

Dassot, M., Constant, T., & Fournier, M. (2011). The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. *Annals of Forest Science, 68,* 959-974.

Jupp, D. L. B., Culvenor, D., Lovell, J. L., & Newnham, G. (2005). *Evaluation and validation of canopy laser radar (LIDAR) systems for native and plantation forest inventory.* (CSIRO Marine and Atmospheric Research Papers, Number 020). Canberra, Australia: CSIRO.

Murphy, G. (2008). Determining stand value and log product yields using terrestrial LIDAR and optimal bucking: a case study. *Journal of Forestry, 106,* 317-324.

Murphy, G., Acuna, M. A., & Dumbrell, I. (2010). Tree value and log product yield determination in radiata pine (*Pinus radiata*) plantations in Australia: comparisons of terrestrial laser scanning with a forest inventory system and manual measurements. *Canadian Journal of Forest Research, 40*(11), 2223-2233.

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., & Bozkin-Morris, W. (2008). Retrieval of forest structural parameters using a ground-based lidar instrument (Echidna®). *Canadian Journal of Remote Sensing, 34,* 426-440.

Thies, M., & Spiecker, H. (2004). Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. In: M. Thies, B. Koch, H. Spiecker, & H. Weinacker (Eds.), *Laser-Scanners for Forest and Landscape Assessment. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36, 8/W2,* (pp. 192-197). Retrieved 22 December 2011, from http://www.isprs.org/proceedings/XXXVI/8-W2/THIES.pdf.

Watt, P. J., & Donoghue, D. N. M. (2005). Measuring forest structure with terrestrial laser scanning. International *Journal of Remote Sensing, 26,* 1437-1446.

Yao, T., Yang, X., Zhao, F., Wang, Z., Zhang, Q., Jupp, D., Lovell, J., Culvenor, D., Newnham, G., Ni-Meister, W., Schaaf, C., Woodcock, C., Wang, J., Li, X., & Strahler, A. (2011). Measuring forest structure and biomass in New England forest stands using Echidna ground-based lidar. *Remote Sensing of Environment, 115*(11), 2965-2974. doi:10.1016/j.rse.2010.03.019

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