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Influence of voxel size and point cloud density on crown cover estimation in poplar plantations using terrestrial laser scanning

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ABSTRACT Accurate estimates of crown cover (CC) are central for a wide range of forestry studies. As direct measurements do not exist to retrieve this variable in the field, CC is conventionally determined from optical measurements as the complement of gap fraction close to the zenith. As an alternative to passive optical measurements, active sensors like terrestrial Light Detection And Ranging (LiDAR) allows for characterizing the 3D canopy structure with unprecedented detail. We evaluated the reliability of terrestrial LiDAR (TLS) to estimate CC using a voxel-based approach. Specifically, we tested how different voxel sizes (ranging from 5-20 cm) and voxel densities (1-9 points/dm^3) influenced the retrieval of CC. Results were compared against benchmark values obtained from digital cover photography (DCP).

The trial was performed in hybrid poplar plantations in Northern Italy. Results indicate that TLS can be used for obtaining accurate estimates of CC, but the choice of voxel size and point density is critical for achieving such accuracy. In hybrid poplars, the best performance was obtained using voxel size of 10 cm and point density of 8 points/dm^3. The combined ability of measuring and mapping CC also holds great potential to use TLS for calibrating and upscaling results using coarser-scale remotely sensed products.

KEYWORDS: canopy photography, phase-shift laser scanner, forest structure, canopy gap fraction, voxelization.

Introduction

Canopy cover (CC), defined as the average proportion of ground surface covered by the vertical projection of tree crowns, is important in forestry and in land use - land change (LULC) analyses (Chianucci 2020) and is a key variable for accurate modelling of leaf area index using optical theory (Nilson 1999, Nilson and Kuusk 2004). In addition, CC is a major driver of forest reflectance, being therefore useful for calibration and validation of optical remote sensing data (Chianucci et al. 2016, Chianucci 2020, Tang et al. 2019). Accordingly, accurate in situ estimates of CC are central for a wide range of forestry studies.

Currently, the main challenges in quantifying CC are that no direct measurements exist to retrieve this variable in the field. While visual methods provide subjective and non-replicable measurements, optical methods have been more frequently used to derive this variable from gap fraction measurements (Chianucci 2020). So far, digital cover photography (DCP) was considered the best method to indirectly estimate CC from the complement of gap fraction measured at the zenith (Chianucci 2016, 2020). As an alternative to passive optical measurements, active sensors like Light Detection And Ranging (LiDAR) have become increasingly popular in the last two decades. In particular, Terrestrial Laser Scanning (TLS) has received strong attention for fast, robust and non-destructive measurements of forest attributes with increasing level of accuracy (Eitel et al. 2010, Grotti et al 2020, Stovall et al. 2018).

TLS is a ground-based laser scanning technology, which can provide detailed three-dimensional information to precisely depict forest structure in a non-destructive, objective, and reproducible manner. While the use of TLS for measuring tree horizontal and vertical forest stand attributes has been widely explored, additional outputs can also include three-dimensional reconstructions of individual tree structure (Côté et al. 2009, Puletti et al. 2019) or vegetation profiles (Ashcroft et al. 2014). In addition, TLS holds strong potential in retrieving canopy attributes like CC due to its ability to precisely measure both the horizontal and vertical tree crown structure and arrangement from the 3D point cloud.

After field acquisition, the point cloud can be used directly or transformed into spatial structures such as voxels (Hosoi and Omasa 2007). This procedure, which is needed to normalize the raw point cloud data, divides the 3D space in small equal boxes, called voxels (or volumetric pixels). Voxels are means to represent a three-dimensional space using a regular grid. The use of voxels facilitates complex and detailed spatial analysis and several previous studies have utilized them in the analysis of TLS data, particularly for canopy profiling (Hosoi and Omasa 2006, Gajardo et al. 2020, Soma et al. 2021, Xu et al. 2021) and particularly the retrieving of angular gap fraction (for a review, see Yan et al. 2019). After voxelization, each box is defined as "vegetation" depending on the number of points falling inside it (usually one). As demonstrated in previous studies on 3D modelling of forest canopies using TLS data, one important step involves the definition of voxel size, a second one the threshold to define a voxel as "vegetation" or not. Both scan resolution, point

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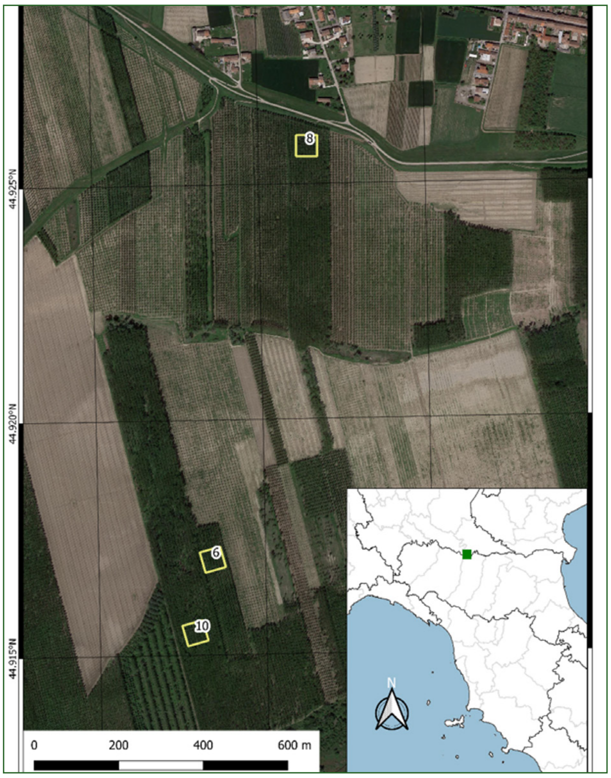
cloud registration, and voxelization affect the TLS processing chain. Hence, for reliable quantification of 3D forest structural indicators, understanding how voxel size and minimum number of points in each voxel influence the results is crucial (Soma et al. 2018, 2020, 2021, Zong et al. 2021).

In this study, we tested the ability of phase-shift TLS to estimate CC in poplar plantations with varying ages (ranging from 6 to 10 years of age). Specific objectives of this experiment were to quantify the impact of *(i)* voxel size (vox_{size}) and *(ii)* minimum number of points inside each voxel to classify it as "vegetation" (vox_{mnp}) on CC retrieval. Different configurations have been tested in terms of vox_{size} (with cubic voxels side ranging from 5 cm to 20 cm) and vox_{mnp} (from 1 to 9 points per voxel). To validate the results, TLS-derived crown cover was compared against values obtained from digital cover photography (DCP, Chianucci 2016), which is considered the benchmark method to estimate this variable in the field (Chianucci 2020).

Figure 1 - Study area location (green box) and three sites with stand age (yellow squares).



Material and methods

Definition of canopy cover

Traditional measures of canopy cover consider crowns as non-transparent envelopes, i.e. considering within- crowns gaps as part of the canopy; this is equivalent to the definition of crown cover by Macfarlane et al. (2007) and canopy cover by Rautiainen et al. (2005). Conversely, foliage cover (*sensu* Macfarlane et al. 2007) is considered as the complement of total gap fraction, taking into account both within- and between-crowns gaps; this is equivalent to the definition of effective canopy cover by Rautianien et al. (2005). For the remainder of the study, canopy cover and crown cover are used as synonym.

Study area

The trial was performed in July 2019 (leaf-on conditions) in three neighbouring stands of hybrid poplar plantations differing by age (6, 8 and 10 years of age) located in Viadana, Mantova, Northern Italy (Fig. 1). The inter-row tree spacing was 6 m, and intra-row spacing was 7 m. The plantations were established on flat and uniform terrain. In each plantation, a square 50 x 50 m plot was established, in which DCP and TLS measurements were performed as described in the next sections.

Digital Cover Photography

Sixteen DCP images were acquired along a grid of sampling points inside each 0.25 ha plot. Images were collected under overcast sky conditions using a digital Nikon D90 single-lens reflex camera equipped with fixed lens (AF Nikkor 50mm 1:1.8 D), following the protocols of Chianucci et al. (2020b) and Chianucci (2020) as described below. The images were acquired in raw (NEF) format. The camera was placed at about 1.3 m height and oriented upward. The camera was set in aperture-priority mode, with the aperture set to F10.0; the exposure was set to underexpose the image by one stop (REV-1) to improve contrast between sky and canopy pixels (Macfarlane et al. 2014).

Raw images were first pre-processed using the 'RAW2JPG' software (Macfarlane et al. 2014). The NEF format was converted to 12-bit linear (demosaiced), uncompressed portable grey map (*pgm*) format using the '*dcraw*' (Coffin 2011) functionality. The blue channel of the *pgm* image was selected and a linear contrast stretch was applied using the '*imadjust*' functionality of MATLAB's (MathWorks Inc., USA) Image Processing Toolbox. Images were then converted to 8 bits per channel and saved as JPEG files for subsequent analysis. A gamma adjustment was also applied to the raw images (Macfarlane et al. 2014). Finally, jpeg images were classified using a dual thresholding (two-corner method; Macfarlane 2011).

Once classified, the total gap fraction was also further classified into large between-crowns gaps and small, within-crown gaps. Gaps larger than 1.3% of the image area were classified as between-crowns gaps as proposed by Macfarlane et al. (2007). Crown cover (CC_{DCP}; *sensu* Macfarlane et al. 2007) was then estimated as the complement of large between-crowns gap, including within-crown gaps as part of the canopy:

(1) $$CC_{DCP} = 1 - \frac{NL}{NT}$$

where *NT* is the total number of pixels and *NL* is the total number of pixels located in the large gaps. The two-corner classification method and gap size classification were implemented using the 'DCP 3.15' software (Macfarlane et al. 2014). An example of a cover image that has been classified into canopy and sky pixels, with the sky pixels further classified into large, between-canopy gaps, is given in Figure 2.

Figure 2 - An example of a cover image that has been classified into between-crowns sky pixels (white), within-crown sky pixels (grey) and canopy (black). By knowing the number of these pixels, crown cover (CC) was estimated from the images using Equation 1 (see the text).

Terrestrial laser scanner data collection and processing

TLS data were acquired using a FARO Focus 3D × 130 (FARO Technologies Inc., Lake Mary, FL, USA). The instrument uses a phase-shift-based technology with a maximum range of 130 m and acquires data with an azimuth scan angle of 360°. It collects the x, y, and z coordinates and the intensity of laser returns with a scan ranging noise of ±1 mm (FARO 2013). A complete description of the instrument can be found in Giannetti et al. 2018.

The TLS device was set to acquire data with medium resolution and quality (1/5 resolution and 4× quality) for a total of 28.2 million pulses per scan. Time elapsed per scan was approximately 3 min. Scanning was repeated in five positions systematically distributed across the stand (similarly to Figure 1 in Puletti et al. 2019). Up to 12 white polystyrene registration spheres (14 cm diameter) were placed throughout each plot to aid in digital registration of individual scans, as described in the following section.

For each stand, individual scans were merged using the automatic registration algorithms included in Trimble Real Works® (TRW) software. The program joins overlapping redundant points to create one seamless 3D point cloud suited for the analysis. Details of the operation (settings, criteria, and thresholds) performed by the software are not declared nor accessible. For further details on pre-processing methods used in this experiment please see Puletti et al. 2019.

Vertical profiles of voxelized point clouds for TLS crown cover estimations

Point clouds were first normalized. The ground level was clearly detectable since shrubs and the herbaceous cover were absent. In order to reduce the huge dimension of registered point clouds (i.e. millions of points), we opted for a voxelization approach. For consistency with crown cover measured from digital photography (CC_{DCP}), CC_{TLS} considers all voxels as belonging to the canopy. Such process starts with the creation of vertical profiles at the stand level and then finds the local minima in the lower third of tree height (i.e. crown-base detection, Fig. 3). All "vegetation" voxels over that height were considered as canopy. Columns of voxels with any vegetation in them (representing tree stems) were considered as canopy gaps. CC_{TLS} estimation process ends with calculation of the percentage ratio of filled pillars over the total of pillars in the stand (Fig. 4).

Figure 3 - Example of vertical density profiles (Aschcroft et al. 2014) obtained by voxelization of 10-year-old stand with a voxel resolution of 10 cm and minimum number of points inside voxel equal to 7. The y-axis (Z) is the height from the ground, the x-axis (veg) represents the number of "vegetation voxel" at each Z. The height obtained with procedure described in par. *Vertical profiles of voxelized point clouds for TLS crown* cover estimations (2.9 m) was then used as cut-off to calculate the "canopy pillars" (see text for further details).

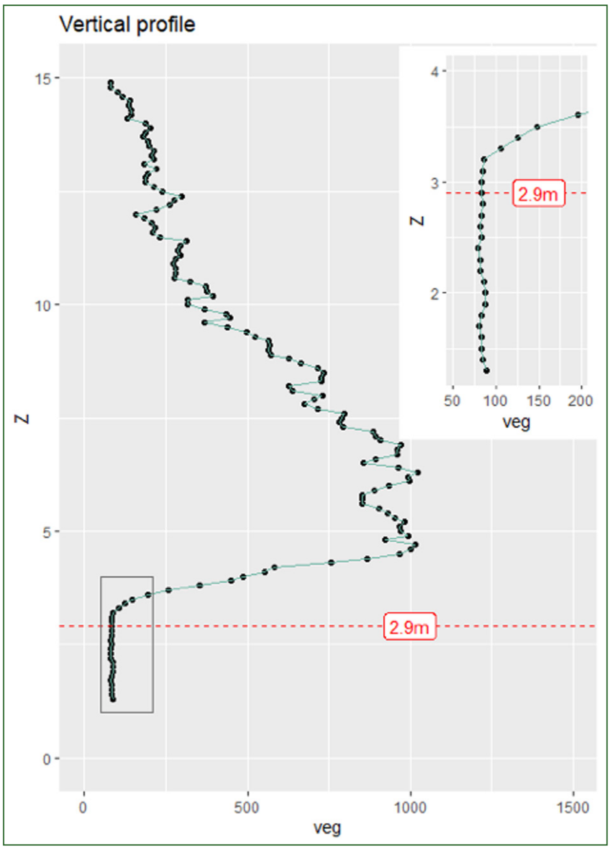
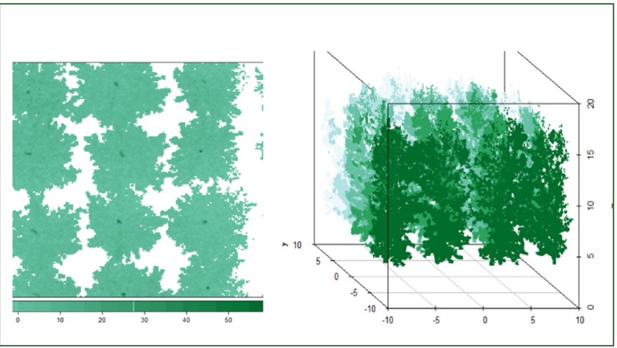


Figure 4 - On the left, the two-dimensional canopy cover estimated using the procedure described in par. *Voxel site and threshold.* Colour is proportional to the number of "vegetation" voxels in the pillar. On the right a three-dimensional representation of voxel-canopy centroids. Both figures refer to 6-years-old stand, voxel size 10 cm, and minimum number of points inside voxel equal to 7.



Voxel sizes and thresholds

Four different cubic voxels sizes were used: *v005* (side = 5 cm, volume = 0.125 dm^3), *v010* (side = 10 cm, volume = 1 dm^3), *v015* (side = 15 cm, volume = 3.375 dm^3) and *v020* (side = 20 cm, volume = 8 dm^3).

Traditional application of voxelization in forest ecosystems uses different voxels size and a minimum number of points inside each voxel to classify it as "vegetation" (vox_{mnp}) always equal to 1 (see e.g. Cifuentes et al. 2014). However, despite this is a reasonable assumption under an operational point of view, this approach leads to comparing different densities (i.e. different number of points per unit volume). To evaluate the effect of vox_{mnp} on crown cover estimates, we tested nine different densities, from 1 to 9 points/dm^3. Voxels with a density higher than the specified threshold were classified as "vegetation". In the end, 108 different combinations (9 thresholds × 4 voxel sizes × 3 stands) were considered. The overall effect of all the combinations on TLS-derived crown cover estimates (CC_{TLS}, see par. 2.3.1) was calculated for each stand.

Comparison of CC between DCP and TLS

The relative deviation (RD%) was used as a measure of performance for evaluating the differences, in percentage, between the TLS-derived estimates of crown cover and the benchmark CC_{DCP} values obtained from DCP.

Results

CC_{DCP} ranged between 0.37 to 0.63 in stands aged 6 years (0.49 ± 0.09), between 0.72 to 0.95 in stands aged 8 years (0.85 ± 0.07) and between 0.66 to 0.95 in stands aged 10 years (0.82 ± 0.07) (Fig. 5).

Registered point clouds were composed of 10.3, 94.9, and 144.3 million points in 6-, 8-, 10-year-old stands respectively, reduced to 8.5, 39,5, and 59.1 million points after cropping the plot area. The process attained a very low plot-level registration error, and TRW achieved a high-precision scan placement with mean tension value in single point clouds registration process of 3.1 mm (sd = 0.9 mm, max = 3.9 mm).

The CC_{TLS} agreed with the range of estimates from DCP in 8- and 10-years plantation (Tab.1); largest variability in TLS was found in the 6 years old plot, where CC_{TLS} ranged between 0.10 to 0.74; the lower performance was found in the vox_{size} = 5 cm.

Best configuration between voxel sizes and minimum number of points are v010 7 points, v010 8 points and v005 1 point respectively for 6-, 8- and 10-year-old plots. At higher voxel sizes and lower number of points, CC_{TLS} is higher than CC_{DCP}.

Figure 5 - Boxplots of crown cover estimated from DCP according to the plantation age.

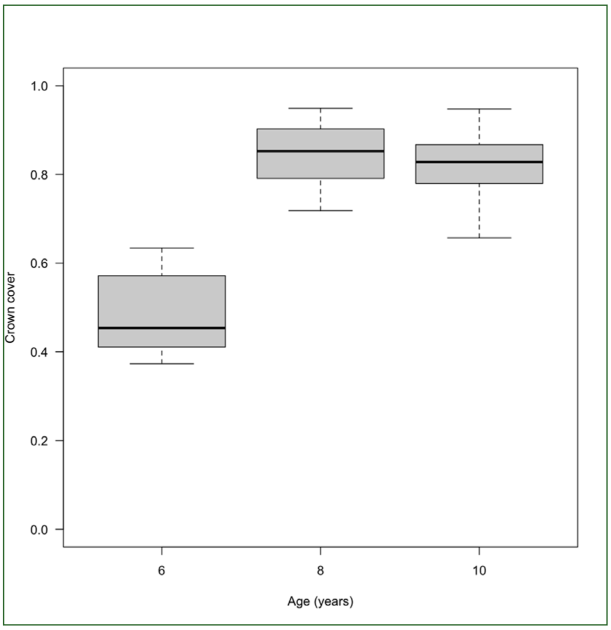


Figure 6- Boxplot of relative deviation (as percentage, y-axis) of canopy cover estimates.

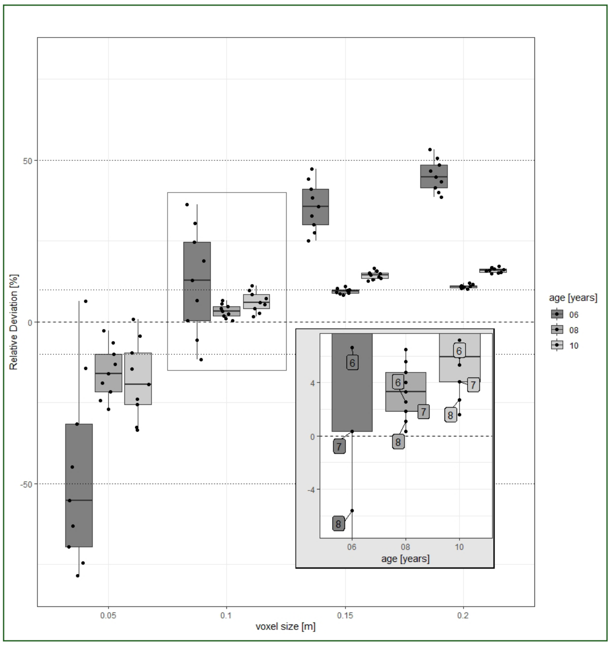


Table 1 - Relative deviation values (as percentage) and threshold densities (i.e. minimum number of points per voxel expressed in number of points per dm³) for each combination. For example: for vox_{mnp} equal to 8 (see row 8) the number of points dm^{-3} is 8.0 when the voxsize is 10 cm (8 points over 1 dm³) while is 1.0 when the voxel size is 20 cm (8 points over 8 dm³).

voxmnp	voxsize				overall
	5 cm	10 cm	15 cm	20 cm	
1	1.5% (8.0)	18.0% (1.0)	24.9% (0.3)	27.5% (0.1)	18.0%
2	-8.4% (16.0)	15.3% (2.0)	23.4% (0.6)	26.3% (0.3)	14.2%
3	-17.0% (24.0)	12.7% (3.0)	22.1% (0.9)	25.4% (0.4)	10.8%
4	-24.1% (32.0)	10.0% (4.0)	21.0% (1.2)	24.6% (0.5)	7.9%
5	-30.2% (40.0)	7.3% (5.0)	19.8% (1.5)	23.9% (0.6)	5.2%
6	-35.3% (48.0)	4.8% (6.0)	18.6% (1.8)	23.3% (0.8)	2.9%
7	-39.0% (56.0)	2.1% (7.0)	17.5% (2.1)	22.5% (0.9)	0.8%
8	-43.9% (64.0)	-0.6% (8.0)	16.4% (2.4)	21.8% (1.0)	-1.6%
9	-46.2% (72.0)	-3.2% (9.0)	15.3% (2.7)	21.2% (1.1)	3.2%

Relative differences between CC_{DCP} and CC_{TLS} are presented in Figure 6. The overall best configuration was obtained with a voxel size of 10 cm and 8 points (Tab. 1). CC_{TLS} values are relatively low in 8 and 10 years-old stands with small variations between point-per-voxel density. For the smallest voxel size (5 cm), the tendency is to underestimate crown cover measured by DCP, particularly in young plantations (6 years-old) and using higher values of vox_{mnp}. Voxel sizes bigger than 1 cm overestimate actual crown cover, despite for older stands the error is contained in reasonable values (less than 15%).

Discussion

The study demonstrated that TLS can be used to obtain a reliable estimation of crown cover in poplar plantations. In our comparison, the best results were obtained with a configuration of 10 cm of vox_{size} and 8 points per dm³ (Tab. 3). Usually, the number of points per voxel for defining a vegetated voxel is fixed at 1 (see for example Cifuentes et al. 2014). In TLS phase-shifts, this choice could generate an overestimation of the vegetated cells due to so-called ghost points (Cifuentes et al. 2014).

In our experiment, equal (or similar) point-voxel densities generated by different combinations of vox_{size} and vox_{mnp} have generated different relative deviations. For example, densities of 8 points per dm³ can be reached configuring the analysis using two different combinations: (a) vox_{size} = 5 cm; vox_{mnp} = 1; and (b) vox_{size} = 10 cm; vox_{mnp} = 8. The latter shows lower relative deviation absolute values (0.6% instead of 1.5%). Similarly, densities of 2 points per dm³ can be reached by three types of combinations (with vox_{size} = 10 cm; vox_{mnp} = 2 or with vox_{size} = 15 cm; vox_{mnp} = 6 and 7), but the one with vox_{size} = 10 cm obtained better performances. Our findings are comparable with results from other studies (see for example Cifuentes et al 2014) performed on intermediate mature forests.

As highlighted by other authors (see for example Cifuentes et al. 2014), such voxel-based techniques have a major constrain related to the so-called "ghost points", a specific behaviour of phase-shift TLS that makes the point cloud noisy around the edges of objects (Newnham et al 2012). Such effect is amplified when registering multiple scans, creating false objects, and leading bias results in canopy measurements. The proposed approach highlights how such drawback can be profitably overcome by fixing the vox_{mnp} threshold at higher densities. Concerning the weather conditions, as always required when scanning in forests, it must be windless, not extremely cold, and not rainy or foggy during scan acquisition.

While the produced estimates are broadly consistent with benchmarking values obtained from DCP, TLS possesses several further advantages which can enhance the tree crown structure characterization. Firstly, TLS can also provide 3D crown information, such as tree crown volume, which can complement and enhance 2D information available from traditional optical canopy cover measurements (Chianucci et al. 2020a). This non-destructive method also allows for an automatic crown volume determination of a tree, without introducing errors made by operators during measuring. To do this, the method needs that a complete 360° scan of the tree crown has to be captured, i.e. at least three scans are needed for each tree and a balanced and rational scan acquisition planning must be performed. Secondly, the combined ability of assessing and mapping crown cover (see Fig. 4) can further extend the applications of TLS beyond the scope of traditional tree inventory. For instance, given that crowns respond promptly to disturbance (Chianucci 2020), repeated crown measurements can be used to assess tree responses to thinning, the influence of different tree spacing and fertilizer trials, and to relate growth to soil moisture availability, which are critical factors in short-rotation plantations. Finally, the spatially explicit nature of TLS measurements allows better integration with different remotely sensed sensors, which can be used in combination with TLS. In this line, crown cover maps from TLS can be used for calibrating metrics obtained from coarser-scale products and upscaling results using larger-scale remotely sensed information.

Conclusions

We demonstrated that TLS can be used to effectively estimate CC in poplar plantations following a voxel-based approach. From a practical viewpoint, we recommend a setup of vox_{size} = 10 cm and vox_{mnp} from 4 to 8 (depending on stand age) to achieve a compromise between the accuracy of CC estimates, the size of the scans and the associated processing-time, simultaneously reducing the issues of ghost points. In case of denser canopy conditions, we suggest setting vox_{size} = 10 and vox_{mnp} from 3 to 5. This would represent an optimal strategy in poplar plantations as those sampled in the study, which correspond to sparse to medium dense canopy conditions (the mean leaf area index in these plantations ranged between 0.3 to 2.3 m^2m^{-2}; Chianucci et al. 2021).

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References

Ashcroft M.B., Gollan J.R., Ramp D. 2014 - *Creating vegetation density profiles for a diverse range of ecological habitats using terrestrial laser scanning*. Methods in Ecology and Evolution 5: 263–272.

Chianucci F. 2020 - *An overview of in situ digital canopy photography in forestry*. Canadian Journal of Forest Research 50 (3): 227-242.

Chianucci F., Grotti M., Puletti N., Ferrara C., Giorcelli A., Coaloa D., Tattoni C. 2020a - *Non-destructive tree stem and crown volume allometry in hybrid poplar plantations derived from terrestrial laser scanning*. Forest Science 66 (6): 737–746. doi: https://doi.org/10.1093/forsci/fxaa021.

Chianucci F. 2016 - *A note on estimating canopy cover from digital cover and hemispherical photography*. Silva Fennica 50: 1. doi: https://doi.org/10.14214/sf.1518

Chianucci F., Disperati L., Guzzi D., Bianchini D., Nardino V., Lastri C., Rindinella A. Corona P. 2016 - *Estimation of canopy attributes in beech forests using true colour digital images from a small fixed-wing UAV*. International journal of applied earth observation and geoinformation 47: 60-68.

Chianucci F., Marchino L., Bidini C., Giorcelli A., Coaloa D., Chiarabaglio P., Giannetti F., Chirici G., Tattoni C. 2021 - *Dataset of tree inventory and canopy structure in poplar plantations in Northern Italy*. Annals of Silvicultural Research 46 (1) (93-97) doi: http://dx.doi.org/10.12899/asr-2177

Cifuentes R., Van der Zandeb D., Farifteha J., Salasc C., Coppin P. 2014 - *Effects of voxel size and sampling setup on the estimation of forest canopy gap fraction from terrestrial laser scanning data*. Agricultural and Forest Meteorology 194: 230–240. doi: http://dx.doi.org/10.1016/j.agrformet.2014.04.013

Coffin D. 2011 -dcraw: *Decoding raw digital photos in Linux*.

Côté J., Widlowski J., Fournier R.A., Verstraete M.M. 2009 - *The structural and radiative consistency of three-dimensional tree reconstructions from terrestrial lidar*. Remote Sensing of Environment 113: 1067–1081.

Eitel J.U., Vierling L.A., Long, D.S. 2010 - *Simultaneous measurements of plant structure and chlorophyll content in broadleaf saplings with a terrestrial laser scanner*. Remote Sensinf of Environment 114 (10): 2229–2237.

FARO 2013 - *User Manual FARO Laser Scanner Focus 3D*. [Online]. Available: https://doarch332.files.wordpress.com/2013/11/e866_faro_laser_scanner_focus3d_manual_en.pdf [2018, September 1]

Gajardo J., Riaño D., García M., Salas J., Martín M.P. 2020 - *Estimation of Canopy Gap Fraction from Terrestrial Laser Scanner Using an Angular Grid to Take Advantage of the Full Data Spatial Resolution*. Remote Sensing 12 (10): 1596.

Giannetti F., Puletti N., Quatrini V., Travaglini D., Bottalico F., Corona P., Chirici G. 2018 - *Integrating terrestrial and airborne laser scanning for the assessment of single-tree attributes in Mediterranean forest stands*. European Journal of Remote Sensing 51: 795–807.

Grotti M., Calders K., Origo N., Puletti N., Alivernini A., Ferrara C., Chianucci F. 2020 - *An intensity, image-based method to estimate gap fraction, canopy openness and effective leaf area index from phase-shift terrestrial laser scanning*. Agricultural and Forest Meteorology 280: 107766. doi: 10.1016/j.agrformet.2019.107766

Hosoi F., Omasa K. 2007 - *Factors contributing to accuracy in the estimation of the woody canopy leaf area density profile using 3D portable lidar imaging*. Journal of Experimental Botany 58: 3463–3473.

Hosoi F., Omasa K. 2006 - *Voxel-based 3-D modeling of individual trees for estimating leaf area density using high-resolution portable scanning lidar*. IEEE Transaction on Geoscience and Remote Sensing 44: 3610 3618.

Macfarlane C. 2011 - *Classification method of mixed pixels does not affect canopy metrics from digital images of forest overstorey*. Agricultural and Forest Meteorology 151: 833-840.

Macfarlane C., Ryu Y., Ogden G.N., Sonnentag O. 2014 - *Digital canopy photography: Exposed and in the raw*. Agricultural and Forest Meteorology 197: 244-253.

Macfarlane C., Grigg A., Evangelista C. 2007 - *Estimating Forest leaf area using cover and fullframe fisheye photography: thinking inside the circle*. Agricultural and Forest Meteorology 146 (1-2): 1-12.

Newnham G., Armston J., Muir J., Goodwin N., Tindall D., Culvenor D., Püschel P., Nyström M., Johansen K. 2012 - *Evaluation of terrestrial laser scanners for measuring vegetation structure*. In: *"CSIRO Sustainable Agriculture Flagship"* Manuscript ID: EP124571 [Online]. Available: https://publications.csiro.au/rpr/pub?pid=csiro:EP124571 [2013, December 10].

Nilson T. 1999 - *Inversion of gap frequency data in forest stands*. Agricultural and Forest Meteorology 98: 437-448.

Nilson T., Kuusk A. 2004 - *Improved algorithm for estimating canopy indices from gap fraction data in forest canopies*. Agricultural and Forest Meteorology 124 (3-4): 157-169.

Puletti N., Grotti M., Scotti R. 2019 - *Evaluating the Eccentricities of Poplar Stem Profiles with Terrestrial Laser Scanning*. Forests 10(3): 239. Doi: https://doi.org/10.3390/f10030239

Rautiainen M., Stenberg P., Nilson T. 2005 - *Estimating canopy cover in Scots pine stands*. Silva Fennica 39 (1): 137–142. http://dx.doi.org/10.14214/sf.402.

Soma M., Pimont, F. Durrieu S., Dupuy J.L. 2018 - *Enhanced measurements of leaf area density with T-LiDAR: Evaluating and calibrating the effects of vegetation heterogeneity and scanner properties*. Remote Sensing,10 (10): 1580.

Soma M., Pimont F., Allard D., Fournier R., Dupuy J.L. 2020 - *Mitigating occlusion effects in Leaf Area Density estimates from Terrestrial LiDAR through a specific kriging method*. Remote Sensing of Environment 245: 111836.

Soma M., Pimont F., Dupuy, J.L. 2021 - *Sensitivity of voxel-based estimations of leaf area density with terrestrial LiDAR to vegetation structure and sampling limitations: A simulation experiment*. Remote Sensing of Environment 257: 112354.

Stovall A.E.L., Anderson-Teixeira K.J., Shugart H.H. 2018 - *Assessing terrestrial laser scanning for developing non-destructive biomass allometry*. Forest Ecology and Management 427: 217-229.

Tang H., Song X.P., Zhao F.A., Strahler A.H., Schaaf C.L., Goetz S., Huang C., Hansen M.C., Dubayah R. 2019 - *Definition and measurement of tree cover: A comparative analysis of field-, lidar-and landsat-based tree cover estimations in the Sierra national forests, USA*. Agricultural and Forest Meteorology 268: 258-268.

Xu Y., Li S., You H., He Z., Su Z. 2021 - *Retrieval of Canopy Gap Fraction From Terrestrial Laser Scanning Data Based on the Monte Carlo Method*. IEEE Geoscience and Remote Sensing Letters. doi: https://doi.org/10.1109/LGRS.2021.3061540

Yan G., Hu R., Luo J., Weiss M., Jiang H., Mu X., Xie D., Zhang, W. 2019 - *Review of indirect optical measurements of leaf area index: Recent advances, challenges, and perspectives*. Agricultural and forest meteorology 265: 390-411.

Zong X., Wang T., Skidmore A.K., Heurich M. 2021 - *The impact of voxel size, forest type, and understory cover on visibility estimation in forests using terrestrial laser scanning*. GIScience & Remote Sensing: 1-17.