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Document downloaded from:

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The final publication is available at:

<https://doi.org/10.1007/s11119-016-9451-z>

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SHORT DISCUSSION

Setting the optimal length to be scanned in rows of vines by using mobile terrestrial laser scanners

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Abstract Mapping the leaf area index (LAI) by using mobile terrestrial laser scanners

(MTLS) is of significance for viticulture. LAI is related to plant vigour and foliar development being an important parameter for many agricultural practices. Since it may present spatial variability within vineyards, it is very interesting monitoring it in an objective repeatable way. Considering the possibility of using on-the-go sensors such as MTLS within an agricultural plot, it is necessary to set a proper length of the row to be scanned at each sample point for a reliable operation of the scanner. Three different row length sections of 0.5 m, 1 m, and 2 m have been tested. Data analysis has shown that models required to estimate LAI differ significantly depending on the scanned length of the row; the model required to estimate LAI for short sections (0.5 m) is different from that required for longer sections (1 and 2 m). Of the two models obtained, we recommend using MTLS for scanning row length sections of 1 m because the practical use of the sensor in the field is simplified without compromising the results (there is little variation in the model when the row length section changes from 1 m to 2 m). In addition, a sufficient number of sampling points is obtained to support a map of the

LAI. Linear regression models using as explanatory variable the tree area index, obtained from the data provided by the scanner, are used to estimate the LAI.

Keywords LiDAR · Mobile ground-based laser scanner · LAI estimate · Precision viticulture

Introduction

Several studies have been published on the use of mobile terrestrial laser scanners (MTLS) in viticulture (Rosell et al. 2009a, 2009b; Keightley and Bawden 2010; Llorens et al. 2011a; Sanz et al. 2013; Arnó et al. 2013). These studies focused on developing computational methods to characterize vineyards (canopy volume and leaf area) by using the data supplied by MTLS. An example of successful application of MTLS in vineyard is the possibility to estimate the leaf area index (LAI) by using simple linear regression models. Arnó et al. (2013) proposed this methodology in which, after processing the data supplied by the scanner, the tree area index (TAI) is obtained, and this index is subsequently used as the explanatory variable. The TAI was first proposed by Walklate et al. (2002) with the aim of applying it in apple orchards. The TAI was applied in viticulture later, and a detailed explanation of the process for calculating the TAI can be found in Arnó et al. (2013).

The operation mode of MTLS is well known for row cultivation. MTLS are used laterally along the rows and are positioned conveniently from the right or left side of the row to provide vertical scans of the vines. Each scan is the result of successively projecting the laser beam according to a predetermined scan resolution (typically between 0.25 and 1 degree). The influence of the scanning side has been discussed in

Arnó et al. (2015); they concluded that the results obtained are similar regardless of the scanned side. However, there are very few studies on the length of the row section to be scanned, and how this factor influences the quality of LAI estimates. The methodology developed by Walklate et al. (2002) and adapted by Arnó et al. (2013) consists of projecting n successive vertical scans in a vertical XY plane to analyse them jointly to determine the TAI. The combined number of scans depends on the scanned length of the row and the scanner horizontal resolution (function of update frequency and travel speed of the system), and it strongly affects the TAI estimation (Arnó et al. 2013). Additionally, when scanning an entire vineyard in a continuous way to create a map, longer scanned sections results in less and more separated TAI estimates and *vice versa*, since to obtain a single value of TAI it is necessary to scan a given length of the row and cumulate the scans performed in that length. Hence, there is a need to specify the optimal section length to be scanned and simultaneously meet the requirements to obtain reliable data and sufficient support (or number of geo-referenced data) within the plot in order to optimize the use of MTLs to map the LAI. A field test was conducted in *Vitis vinifera* L. cv. Syrah to clarify this issue.

Materials and methods

Because the scanner used is the same as in previous works (Arnó et al. 2013, 2015), the characteristics and mode of operation are not included in this paper. The sensor used in this study was the LMS-200 (SICK AG, Waldkirch, Germany) (Fig. 1), which provides a two-dimensional vertical fan-shaped scan when it is applied laterally from one side of the row. As the scanner is moved along the row in a tractor-mounted system, different vertical scans are finally obtained along the scanned length of the row. A point of known absolute coordinates is generated when the laser beam strikes the canopy. Vines

can be represented in 3D by combining the obtained information; this 3D representation of vines is known as a point cloud. However, calculating the TAI requires further processing of this point cloud. Specifically, all the scans in the scanned row section are projected into a vertical plane, and the overlapped points are then bound using a grid of polar cells as shown in Figure 1. The TAI is finally computed as the ratio between the density of leaf area detected by the scanner (which is proportional to the number of cells with interceptions and the points within each cell) and the ground area. Some assumptions are considered in the calculation process, such as the laser beam is transmitted within the canopy according to the Poisson probability model. A detailed explanation of the method and the mathematical expression of the TAI can be found in Arnó et al. (2013).

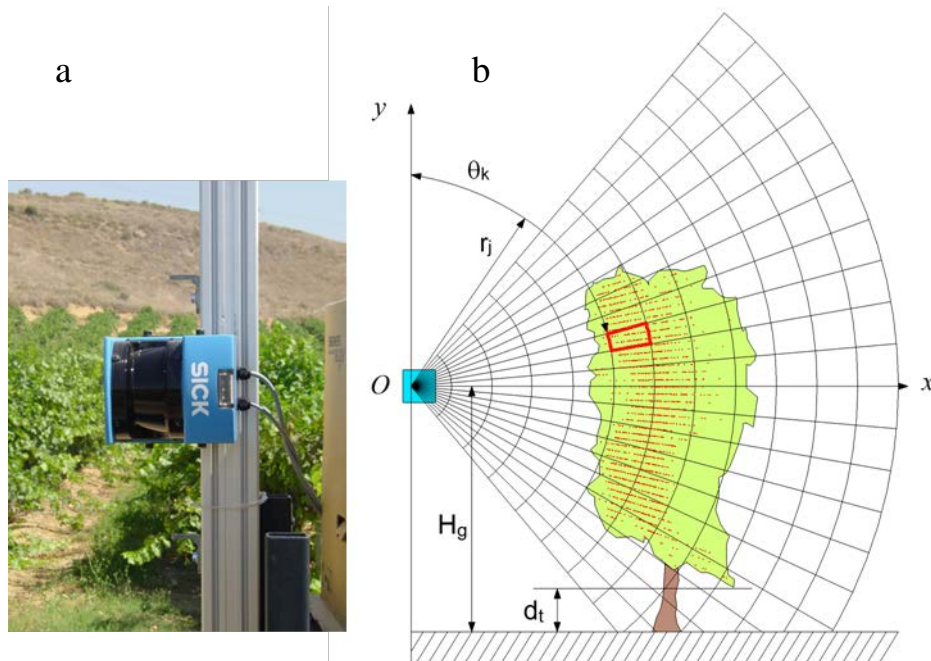


Fig 1 (a) Mobile terrestrial laser scanner used in the study (based on LMS-200, SICK AG, Waldkirch, Germany) (b) Projection of the point cloud on a two-dimensional grid of cells. A generic cell (marked in red) is defined by two coordinates, r_j is the distance from the MTLs, and θ_k is the angle in the clockwise direction. H_g is the height of the sensor from the ground, and d_t is the threshold distance to exclude points that are not within the canopy (Arnó et al. 2013, 2015)

The field test was conducted in a plot of *Vitis vinifera* L. cv. Syrah in Raimat (Lleida, Spain). The vineyard covers an area of 17.74 ha and was planted in 2002 in a 3 x 2 m pattern. Drip irrigation is applied by partial rootzone drying in vines trained in vertical shoot position. The rows are oriented north-south. To ensure full vegetation in the vineyard during the pass of the scanner, the test was performed at the growth stage 77 (berries beginning to touch) according to BBCH-scale (Meier 2001). Field methodology was similar to previous tests (Arnó et al. 2013, 2015); thus, five sampling sections of different vigour for five different rows were selected within the plot. Each sampling section was 2 m long and covered the distance between two consecutive vines (or distance between trunks). After scanning the sampling sections from both sides of the row (two replicate scans or passes from the left and two replicate scans or passes from the right side of the row), the vines were manually defoliated to measure the leaf area and the actual values of the LAI. The sampling sections were defoliated by separating the leaves of adjacent vertical vegetative strips of 0.5 m in length, allowing the generation of different LAI values within the same sampling section. Specifically, seven LAI values were obtained per section according to three different row lengths (4 values for strips of 0.5 m, 2 values for strips of 1 m, and a single overall value for the total section of 2 m). As the number of sampling sites (or sampling sections) was 5, a total of 20, 10, and 5 LAI values were obtained, corresponding to row lengths of 0.5 m, 1 m, and 2 m, respectively. In short, the latter are the three spatial supports evaluated to estimate the LAI.

A dummy-variable regression was proposed to assess whether the LAI estimation models differ according to the scanned lengths (0.5 m, 1 m, and 2 m). In fact, the aim of the paper is not finding a universal model to get the LAI in vineyard rows using a normalization by the length of row (e.g. per meter of row) but to compare three

different models, corresponding to three different sampling sections, to provide MTL users with the best option. The procedure was therefore based on the following model,

$$Y_i = \alpha + \beta X_i + \gamma_1 D_{i1} + \gamma_2 D_{i2} + \delta_1(X_i D_{i1}) + \delta_2(X_i D_{i2}) + \varepsilon_i \quad (1)$$

where Y_i is the LAI, X_i is the TAI, D_{i1} and D_{i2} are the dummy regressors for the polytomous explanatory variable '*scanned length of the row*', and $X_i D_{i1}$ and $X_i D_{i2}$ are the interaction regressors between the TAI and the '*scanned length of the row*'. The model for the intermediate length (1 m) was used as the reference model (baseline); the other models were compared with this reference model by using the dummy-variable regression and an adequate coding for each possible scenario. The analysis was performed using JMP® Pro 11.0.0 (SAS Institute Inc.), and the models obtained were as follows,

$$\text{Scanned lengths of 1 m } (D_{i1} = 0 \text{ and } D_{i2} = 0): Y_i = \alpha + \beta X_i + \varepsilon_i \quad (2)$$

$$\text{Scanned lengths of 2 m } (D_{i1} = 1 \text{ and } D_{i2} = 0): Y_i = (\alpha + \gamma_1) + (\beta + \delta_1) X_i + \varepsilon_i \quad (3)$$

$$\text{Scanned lengths of 0.5 m } (D_{i1} = 0 \text{ and } D_{i2} = 1): Y_i = (\alpha + \gamma_2) + (\beta + \delta_2) X_i + \varepsilon_i \quad (4)$$

Results and discussion

Figure 2 shows the three models obtained. In each case, the LAI was estimated from the TAI using a linear regression model. The approach was to estimate the LAI of the vineyard using the mobile terrestrial laser scanner from either side of the row, as demonstrated in Arnó et al. (2015). Besides the goodness of fit (R^2 between 0.67 and 0.73), a very interesting trend appeared in that the slope of the regression line increases as the scanned length of the row decreases. However, contrary to the expected result, the behaviour of the intercept of the regression line was just the opposite of that shown by the slope, and the model for the scanned lengths of 0.5 m was the only one with a negative intercept value.

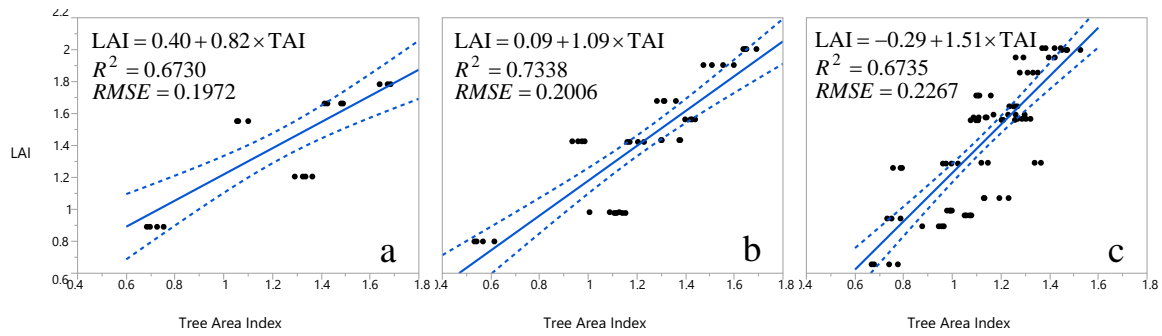


Fig 2 Linear regression models for estimating LAI in a vineyard according to the scanned length of the row: (a) 2 m, (b) 1 m, and (c) 0.5 m

As shown in Figure 1, the point cloud was projected onto a grid of cells in a plane orthogonal to the direction of the scanner's movement. The influence of the scanned length on the LAI estimation models can be interpreted by analysing Figure 3, where the obtained point clouds and their projections are shown for three different tests corresponding to each of the three evaluated lengths. As expected, a larger number of points was obtained when the scanned length increased because the sensor provided an increased number of scans (the horizontal scanning resolution remained the same), and this increased the likelihood of intercepting vegetation. High values of TAI correspond to a large number of intercepted points spread over a large cross-sectional area. Therefore, and in accordance with Figure 3, the TAI decreases as the scanned length decreases because of the reduced number of points and the reduced projected area of the polar grid occupied cells. In such cases, the regression coefficient should be increased to properly estimate the LAI. The remaining question is whether the models are significantly different.

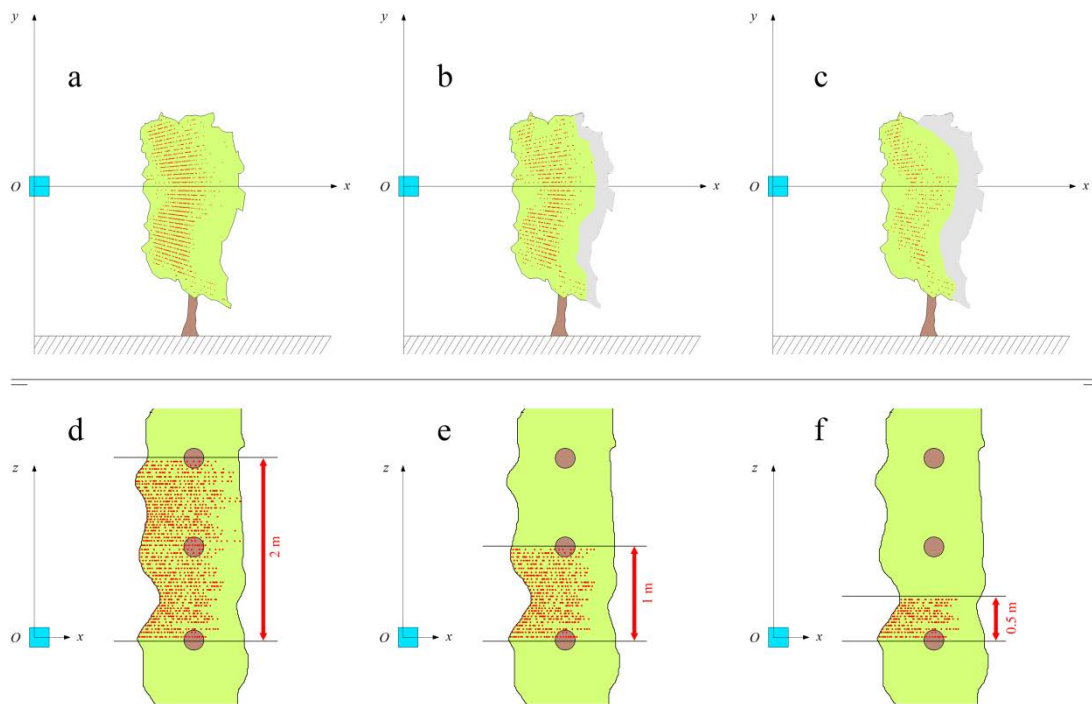


Fig 3 Projected point clouds for three different scanned lengths of the row: (a) 2 m, (b) 1 m, and (c) 0.5 m. The shaded area indicates the progressive reduction of the cross-sectional area of the canopy. Simulated scans along the row in the Oxz plane (bird's eye view) are shown for the three scanned lengths: (d) 2 m, (e) 1 m, and (f) 0.5 m. By decreasing the scanned length of the row (2 to 0.5 m), there are fewer points that intercept and penetrate the canopy. As a result, the cross-sectional area occupied by these points decreases (area seen in the Oxy plane), and therefore the cross-sectional area not intercepted by the laser beam (shaded area) increases.

Table 1 shows results of the dummy regression. It is to be noted that the models are not significantly different except for that based on scanned lengths of 0.5 m where a regression line with a large slope was found. Again, this result seems reasonable given the little difference between projected areas corresponding to lengths of 1 m and 2 m (Fig. 3). This finding may be important in optimizing the use of MTLs under field conditions. Focused on obtaining maps of the LAI in vineyard (Llorens et al. 2011b), the user of this technology requires not only a reliable model but, also, a model that can be reliably applied although the scanned length of the row can vary within certain limits. Under field conditions, it is very difficult to maintain a constant scanned length

for all sampling points. A single model that covers a range of scanned lengths from 1 m to 2 m is ideal for simplicity and because the number of sampling points with scanned data will be sufficient for building a map of the LAI of a vineyard. Moreover, the 1 or 2 m long sampling sections do not necessarily need to coincide with the position of the trunks, as vineyards are usually trained in trellis continuous systems. In conclusion, using MTLS on lengths of 0.5 m is not ideal.

Table 1 Statistical analysis of dummy-regression models for LAI estimation in a vineyard for different scanned lengths of the row (2 m, 1 m, and 0.5 m)

Model	Term	Estimate	Standard error	<i>t</i> ratio	<i>p</i> > <i>t</i>
LAI-1 m (baseline)	Intercept (α)	0.0888	0.1439	0.62	0.5380
LAI-1 m (baseline)	X_i (β)	1.0908	0.1146	9.52	<0.0001
LAI-2 m	D_{i1} (γ_1)	0.3110	0.2379	1.31	0.1933
LAI-0.5 m	D_{i2} (γ_2)	-0.3748	0.1941	-1.93	0.0555
LAI-2 m	$X_i D_{i1}$ (δ_1)	-0.2714	0.1866	-1.45	0.1483
LAI-0.5 m	$X_i D_{i2}$ (δ_2)	0.4241	0.1614	2.63	0.0096*

*Significant coefficient compared to the baseline.

Another issue that requires further analysis is the intercept of the regression line. Ideally, a negative intercept is expected to better fit the model in the case of using MTLS in leafless vines ($LAI = 0$) as there is a possibility that the laser beam impacts the woody structure. However, this effect can probably be different for leafless vines that have different woody structures (Arnó et al. 2013). Table 2 shows the resulting models of the regression analysis. The intercept reached a positive value but remained close to zero in both models. On the other hand, it is interesting to note that the TAI underestimates the actual values of LAI by almost 10% in one case, and by a little more than 50% in the other case, as happened in similar studies for the same lengths (Arnó et al. 2013). This highlights the importance of using appropriate regression coefficients to prevent deviations that may be important if the scanned length of the row is reduced. Moreover, further studies are required to refine the models considering the effect of the

cultivar or the training system on the intercept and slope of the regression lines obtained for lengths of 1–2 m.

Table 2 Regression models for estimating leaf area index in a vineyard (*cv.* Syrah) using different scanned lengths of the row

Type of scanned length	Regression model
1 m to 2 m	$LAI = 0.09 + 1.09 \times TAI$
0.5 m	$LAI = 0.09 + 1.51 \times TAI$

TAI: Tree Area Index

Acknowledgements

The authors acknowledge funding from the Spanish Ministry of Science and Education (OPTIDOSA research project, AGL2007-66093-C04-03) and the ERDF (European Regional Development Fund). The agreement with Codorníu allowing the use of the vineyard in Raimat is also acknowledged.

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