A tractor mounted scanning LIDAR for the non-destructive measurement of vegetative volume and surface area of tree-row plantations: A comparison with conventional destructive measurements

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Abstract

The use of a low-cost tractor-mounted scanning LIDAR (Light Detection and Ranging) system for make non-destructive recordings of the tree-row structure of different orchards and vineyards is described. Field tests consisted of several LIDAR measurements on both sides of the row, before and after defoliation of the selected trees. Summary parameters describing the tree-row volume and the total crop surface area seen by the LIDAR (expressed as a ratio with ground surface area) have been derived using a suitable numerical algorithm. The results for apple and pear orchards and a wine producing vineyard are shown to be in reasonable agreement with the results derived from a destructive leaf sampling method. Also, good correlation was found between manual and sensorial determination of vegetative volume of tree-row plantations. The *Tree Area Index*, TAI, parameter gave the best correlation between destructive and non-destructive (LIDAR) determinants of crop leaf area. The LIDAR system proved to be a powerful technique for low cost, prompt and non-destructive determination of volume and leaf area characteristics of plants.

Key words: 3D Plant structure, Leaf Area Index, LAI, Geometrical characteristics of plants, Non-destructive measurements, Tractor-mounted LIDAR, Tree structure, Vegetative volume.

Notation

- θ angular position of the vegetation surface intercepted by the laser beam
- r radial distance between the target intercepted point and the LIDAR position
- Z direction parallel to the tree row

I_o original beam intensity

$I(r)$ final beam intensity, after a distance r

α extinction coefficient, related with the leaf area density and leaf orientation.

1. Introduction

The measurement and structural characterisation of plants can be carried out by means of several detection principles, including image analysis techniques, stereoscopy photography, analysis of the light spectrum, infrared thermography, ultrasonic ranging and optical ranging; the last being applied to this study.

LIDAR (**Li**ght **D**etection **a**nd **R**anging) is a remote sensing technique based on the measurement of the time a laser pulse takes between the sensor and a target. LIDAR for vegetation studies usually uses a near-infrared radiation, although, sometimes, visible light is also used. This reflects off leaves, branches and other elements and is returned to the instrument. The elapsed time between the transmission of the pulsed laser beam and the reception of its echo, sometimes called time-of-flight, is used to measure the distance between the scanner and the surface of the reflecting object. In recent years, LIDAR sensors have been widely used for the measurement of environmental parameters, particularly for the characterisation of forest and agricultural systems (Ritchie et al.,1993; Nilsson, 1996; Wehr & Lohr, 1999; Lefsky et al., 1999; Harding et al., 2001; Holmgrena & Persson, 2004; Svetlana et al., 2004; Parker et al., 2004). Although the majority of these measurements are carried out through LIDAR sensors placed on aircraft or satellites, there is the option of using systems based on terrestrial or ground-based LIDAR sensors (e.g. Walklate et al., 2002; Tumbo et al., 2002; Wei & Salyani 2004; Van der Zande et al., 2006; Palacín et al., 2007). The advantages of ground-based LIDAR are that can be simple to operate and economic. In conjunction with multispectral sensors, LIDAR sensors can provide detailed three-dimensional information on land-cover. Moreover, they can induce fluorescence in plants allowing them to be used to monitor plant health on a large scale.

With regard to agriculture applications, Walklate et al., 2002, proposed a methodology for managing and computing laser sensor data to obtain several parameters related to geometric characteristics of apple trees (height, volume) and to some properties that define structural characteristics of trees (foliage density and foliage distribution). Subsequently, they evaluated the comparative performance of different pesticide deposition models by means of LIDAR field measurements of crop structure and leaf deposit for Cox apple trees with different combinations of rootstock, plantation density, age and growth stage.

Usually, the structural and geometrical parameters of trees, such us vegetative volumes and areas, are derived from the manual measurement of heights and widths and the destructive sampling of leaves. However, because destructive sampling is both slow and costly for fruit orchards, other alternative methods, such as robust cost-effective ground-based LIDAR scanning systems, have been used over the last 10 years. Since 1995, much effort has been addressed at the University of Lleida to the detection of the geometry and other structural parameters of plants –such as leaf area index (LAI)- by non-destructive methods based on the use of ultrasonic sensors and, more recently, terrestrial LIDAR scanners (Sanz et al., 2004). In order to determine the suitability of laser sensors to characterise fruit trees and vineyards, several parameters have been computed based on scanner data, and compared with foliage areas and plant volume by means of linear regression analysis. The procedures developed and the results obtained are presented in here.

2. Materials and methods

2.1 LIDAR scanner

The LIDAR scanner used in this experimental work was a low-cost general-purpose LMS-200 model (Sick, Düsseldorf, Germany) (Fig. 1), with accuracy of ±15 mm and 5 mm standard deviation in a range up to 8 m, a selectable angular resolution of 1º, 0.5º or 0.25º and a scanning angle of 180º (although the scanning angle reduced to 100º when the 0,25º resolution was selected). In this study, an angular resolution of 1º and a scanning angle of 180º were used.

The LMS-200 has a standard RS232 serial port for data transfer with a selectable rate selectable of 9.6, 19.2 or 38.4 Kbit s^{-1}. MATLAB 6.5 software (The Mathworks Inc, Natick, MA, USA) installed on a laptop was used for data acquisition and process support.

When the laser beam is intercepted by the surface of vegetation, from the reflected signal the sensor determines the angular position θ and the radial distance r between the target interception point and LIDAR position (Fig. 1). The sensor continuously measures distances at the selected angular resolutions. In this work, this carried out every degree in a 0º to 180º window. All this information represents the vertical outline (or slice) of the tree for the current position of the LIDAR. When moved along the rows, the LIDAR scanner supplied a cluster or cloud of plant interception points in polar coordinates (r,θ), according to reference system shown in Fig. 1.

Although the LMS200 LIDAR is a 2D laser scanner, the displacement of the laser sensor along the direction (Z) parallel to the row of trees at a known constant speed, and the use of software allows a three-dimensional (3D) graphic representation of the cloud of plants interception points to be developed, such that a non-destructive record of the tree-row structure of the crop can be obtained. Once the 3D cloud of points was obtained, efforts were focused on obtaining the geometrical and structural parameters of the tree and bush crops.

2.2 Field tests

The system was applied to characterise some common Spanish tree and bush crops. The species analysed were pear trees (*Pyrus communis* L. cv. ’Conference’ and ‘Blanquilla’), apple trees (*Malus communis* L. cv. ‘Golden’ and ‘Redchief) and vineyards (*Vitis vinifera* L. cv. ‘Cabernet Sauvignon’ and ‘Merlot’).

2.3 LIDAR measurements

Measurements were made using a tractor-mounted LIDAR system that traversed the crop in direction Z, parallel to the row at a known and constant speed (between 1 km. h^{-1} and 2 km. h^{-1}, depending on the crop), in a straight line, and at between 1m and 2m from the row axis, depending on the crop (Figs.1 and 2). The laser sensor was located, approximately, at half the maximum height of the trees (2.1 m, in the case of fruit trees and 1.6 m, in the case of vineyards). The exact location of each vertical slice along the tree row line (Z-axis) was determined from the known forward travel speed of the LIDAR which was kept constant during each trial. From each test, the accumulation of vertical slices corresponding to different positions along the tree-row line leads to the obtaining of a cloud of intersection points which is a 3D image of the structure of the row. Each field test consisted of several runs (measurements) with the LIDAR, on both sides of the row, as shown in Fig. 2, before and after the defoliation of the selected trees. This methodology was repeated four times coinciding with different growth stages of crops. In the field tests carried out with fruit trees and vineyards, a zone of 4 m and 2 m length, respectively, was scanned and later defoliated into four sections of 1 m and 0.5 m, respectively (Fig. 3). This procedure allowed the available sensor data to be compared with the 16 experimental values of crop leaf surface values obtained by manual measurements. As a result, 3D pictures of the crops could be rebuilt from the cloud of points obtained based on the laser scanner measurements, an example of which is shown in Fig. 4. Once the 3D pictures were built, several geometrical and structural parameters of the vegetation, such as volume and leaf area of trees, could be determined.

2.4 Manual measurements of volume and leaf area of trees

To compare with the LIDAR results, the volumes and leaf areas of trees were measured manually. Firstly, several representative trees were chosen. The measurement of the volume of a tree began with the measurement, in a plane perpendicular to the row containing the trunk axis, of the maximum tree height and the height of their bare trunk. Subsequently, by subtracting both previous heights, the height of the foliated part of the tree was calculated. Next, the foliated part was divided into zones of 500 mm high and variable widths (Fig. 5). The width of the vegetation corresponding to each 500 mm height was measured both in the perpendicular plane of the trunk and in the perpendicular plane halfway between two consecutive trunks. The zones situated at the same height of both perpendicular planes have, in general, different trapezoidal sections. The area of each trapezium was calculated by multiplying the mean value of the top and bottom widths by the corresponding height. After calculating the area of each trapezium, the mean cross-sectional area of a zone was calculated. Subsequently, the product of the mean cross-sectional area and the distance between two consecutive trunks allowed the approximate volume of each zone to be known. Finally, the volume of the tree was obtained by summing the volumes of each zone.

For leaf area measurements, trees were divided in several volumes, as shown in Fig. 3, and separately defoliated, in order to obtain as much information as possible about the distribution of leaves in the trees, and to look for correlations with the LIDAR results. Once in the laboratory, the one-sided projected area of the leaves was measured using a shadowgraphic measurement technique using the *Area Measurement System-Conveyor Belt Unit* (Delta-T Devices LTD, Cambridge, UK). As a result, the one-sided projected area of each volume was obtained.

3. Results and Discussion

3.1 LIDAR non-destructive tree- volume measurement

As far as tree-volume is concerned, manually determined and LIDAR obtained results are not identical but there exists a simple relationship between values as is shown for example, in Fig. 6 for a *Pyrus communis* L. cv. ’Blanquilla’ pear orchard. The differences come from the uncertainty that is inherent with the concept of the tree-volume and the method used for its calculation.

3.2 LIDAR non-destructive leaf area measurement

Two methods for determining leaf area were developed.

The first was based on the relationship between the LIDAR measured plant volume and its respective total foliar area measured manually; from which LAI can be obtained. As is shown in Fig. 7, in the case of pear orchards, there exists a simple relationship between both values.

In Fig. 8 the relationship between the foliar area of each tree sector and the respective calculated LIDAR volume is shown. This corresponds to the sectors of seven defoliated apple trees of different ages and vegetative stages. In spite of the heterogeneity of the trees, there is a good correlation between the LIDAR volume and the foliar area (coefficient of determination R^2=0.814).

The second procedure is based on Beer's law and its application, based on a method developed by Walklate et al. (Walklate *et al.*, 2002; Sanz *et al.*, 2005) According to Beer's law, the transmission of a beam of light through a plant is attenuated exponentially: $I(r)=I_o e^{-\alpha r}$, where I_o and $I(r)$ are the original and the final values of beam intensity, respectively, and α is an extinction coefficient related to the leaf area density and leaf orientation. Among the several computed parameters proposed by Walklate (Walklate et al., 2002), the tree area index (TAI), formulated as the ratio between crop detected area and ground area, was chosen because of its superiority for predicting the leaf area index, LAI.

This parameter was calculated for a variable number of accumulated scans (slices), corresponding to defoliated crop sections of 4 m, 2 m or 1 m length. For more reliability, the results presented in Fig. 9 are based on TAI (calculated from LIDAR non-destructive measurements) and experimental LAI (measured by manual destructive sampling) obtained from 1 m crop sections (64 samples). It should be pointed out that the area measurements derived from these two sampling methods are physically different. In fact, manual destructive sampling gives scalar measurements of leaf area (expressed as a one-sided projected area) while LIDAR non-destructive sampling of the optical range interception probability distribution gives a vector measurement of the total vegetative area seen by the scanning LIDAR beam, and that this includes leaves, branches and other supporting structures found in the orchard or vineyard.

The models fitted to pear orchard data showed that an acceptable degree of variability (almost 75%) was explained by geometric and structural parameters. For example, the canopy volume calculated slice by slice (discriminated volume) proved to be a good predictor of LAI in both the pear and apple orchards (R^2=0.8422 and 0.814, respectively). In vineyards the same parameter also had a high correlation (R^2=0.8058) despite being lower than structural parameters such as TAI (R^2=0.9194). The good correlation between the volume and area in the tree-row would appear to imply that area-density is approximately constant. This may because growers tend to prune the orchards and vineyards to obtain good light penetration into the crop.

Since there was a significant variability of foliage distribution along row trees, it probably should be recommended that geometric parameters are calculated on the basis of individual slices because using discriminated volumes improved the predictions for both pear orchards and vineyards. Nevertheless, a minimum number of slices is required to apply the principles of laser beam attenuation and Beer’s law.

Conclusions

The developed LIDAR-based measurement system proved to be a valuable tool for the measurement of the physical and structural characteristics of plants, such us tree volume, leaf area density and LAI. LIDAR sensors can detect canopy structure differences and predict foliage density if adequate crop parameters are obtained from sensor data. Although there are differences between orchards concerning reliability of prediction models, the measurement of canopy volume (Discriminated Volume) predicts LAI satisfactorily for the crops tested (apple trees, pear trees and vineyards). However, Tree Area Index, TAI, was shown as the better predictor for some specific crops.

The system developed could be used in precision agriculture for implementing two site-specific management techniques for the variable-rate application of crop production inputs: *map-based* and *sensor-based.* The ability of LIDAR sensors for measuring, in a rapid and non-destructive way, the crop leaf area, the tree-row volume and other crop parameters, makes this system a new and promising tool to be used as support for the decision making related to the optimisation of pesticide treatments for crop protection and other crop management practises. Also, this system could be an interesting tool for researchers interested in the characterisation of vegetation and its evolution with time.

Acknowledgements

This research was funded by the CICYT (Comisión Interministerial de Ciencia y Tecnología, Spain), under Agreement No. AGL2002-04260-C04-02.

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Figure Captions

Fig. 1. LIDAR system for field test in vineyard (left) and pear orchards (right), also showing polar (distance, r, and angle, θ) and cartesian (x,y,z) coordinates reference systems.

Fig. 2. Scheme of field tests (left) and a vineyard defoliated zone (right).

Fig. 3. Left: Top and front views of the distribution of the defoliation boxes for fruit trees. Right: Top, front and side views of the distribution of the defoliation boxes for fruit vineyard.

Fig 4. Different views, depending on the position of the observer, corresponding to an apple orchard, obtained from the three-dimensional digital model extracted from the LIDAR measurements.

Fig. 5. Segmentation of a tree in zones for the manual measurement of its volume.

a) A drawing of a tree-row showing three selected trees with their trunk and intermediate cross sections, A and B, respectively. The maximum tree heights (A_i, B_i) and the height of their bare trunks (a_i, b_i) are also shown. b) Cross-section of a tree in a plane perpendicular to the tree-row direction, in the trunk (left) and halfway between two consecutive trunks (right). The different widths corresponding to each 500 mm. height divisions are also shown. c) Cross-section of each division zone in a plane perpendicular to the tree-row direction, in the trunk, *Ti*, (left) and halfway between two consecutive trunks, *ti*, (right).

Fig. 6. Manually (x) vs LIDAR (y) measured volume of *Pyrus communis* L. cv. ’Blanquilla’ pear trees. The regression formula obtained was: y = 0.6187 x – 0.0103.

Fig. 7. Total foliage tree area (x) versus LIDAR measured volume (y) of *Pyrus communis* L. cv. ’Blanquilla’ pear trees. The regression formula obtained was: y = 0.1234 x + 0.0689.

Fig. 8. Results corresponding to a plantation of apple trees (*Malus communis* L. cv. ‘Golden’). *a*) Cloud of points generated by the LIDAR sensor. *b*) Generation of global volume from the cloud of points. *c*) Calculation of the volume of a single slice *d*) Correlation between LIDAR measured volume (y) and leaf Area (x); the regression formula obtained was: y = 0.1064 x + 0.0712.

Fig. 9. Leaf Area Index (LAI) prediction by means of linear regression analysis of geometric and structural parameters in vineyards. The regression formula obtained was: LAI = 1.3011 TAI – 0.2325.

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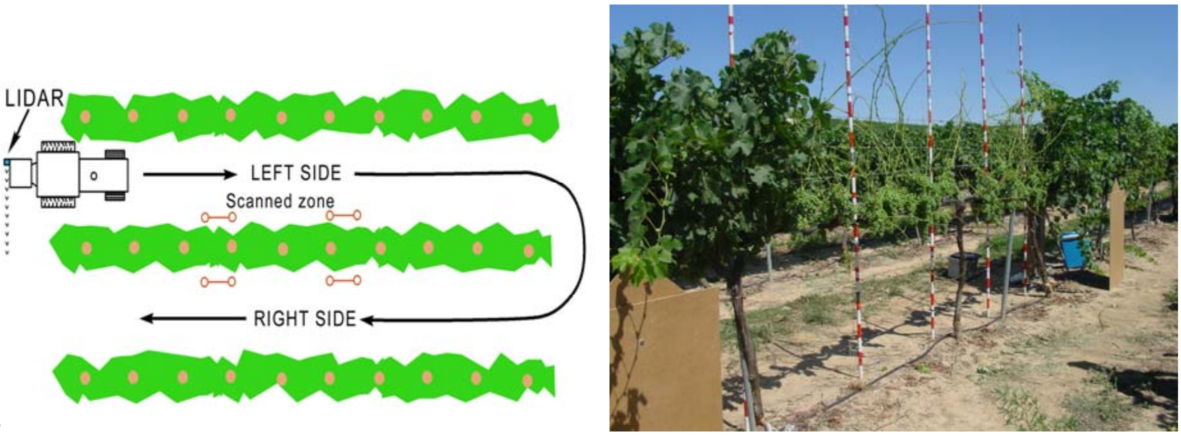

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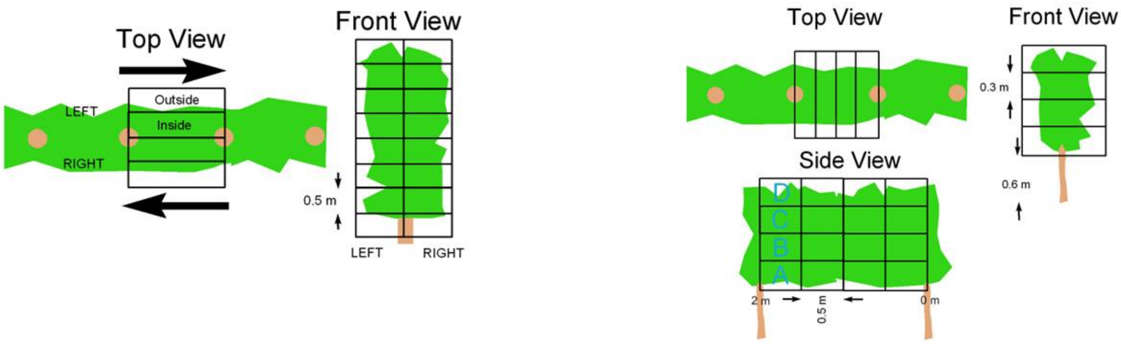

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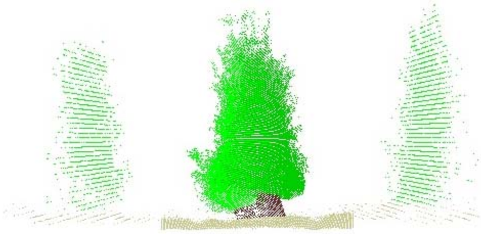

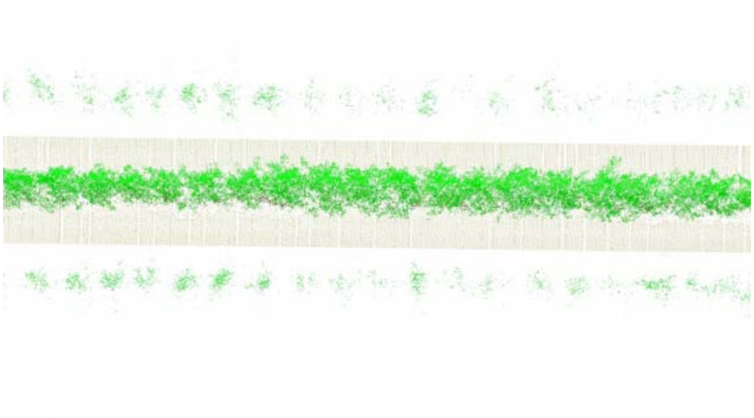

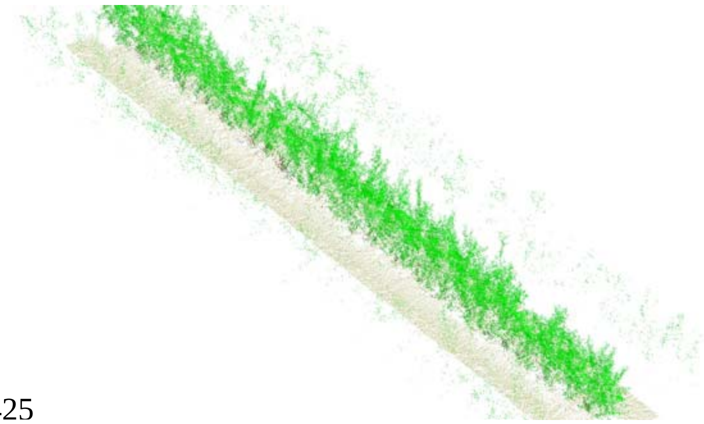

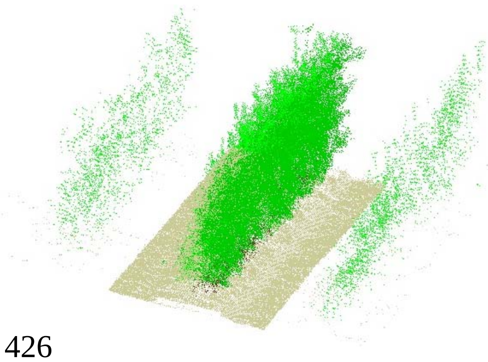

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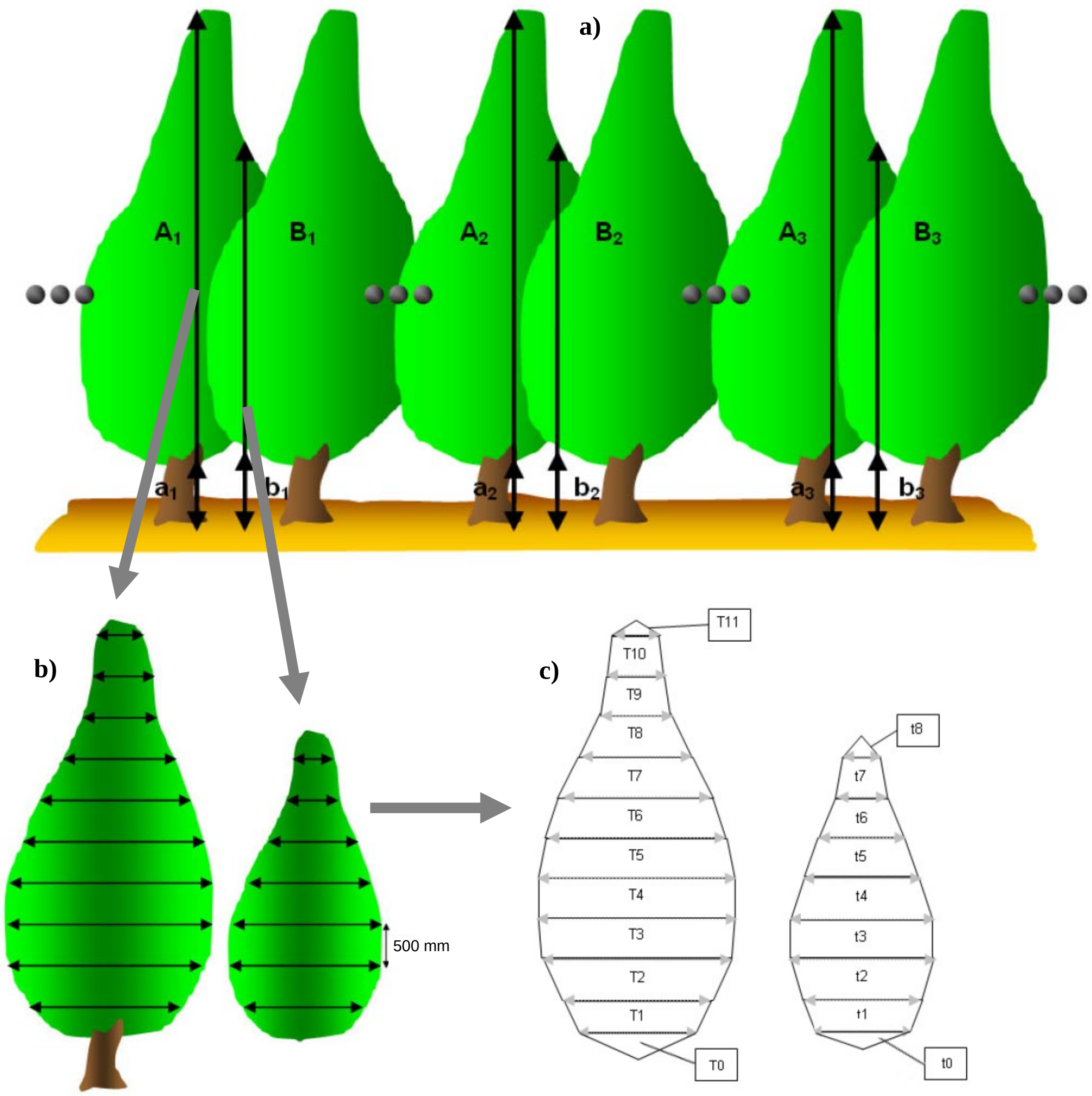

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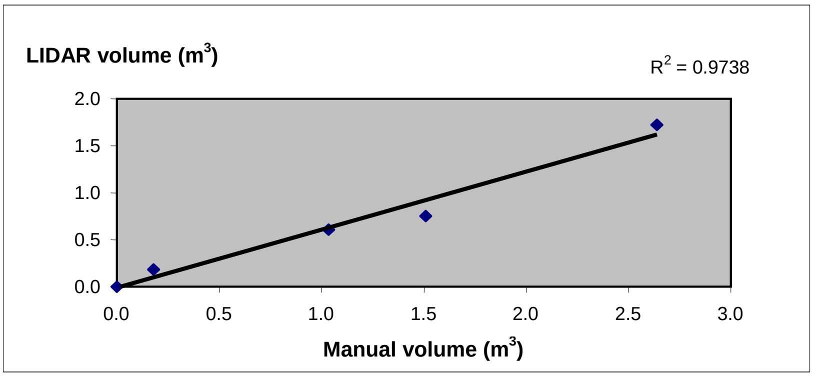

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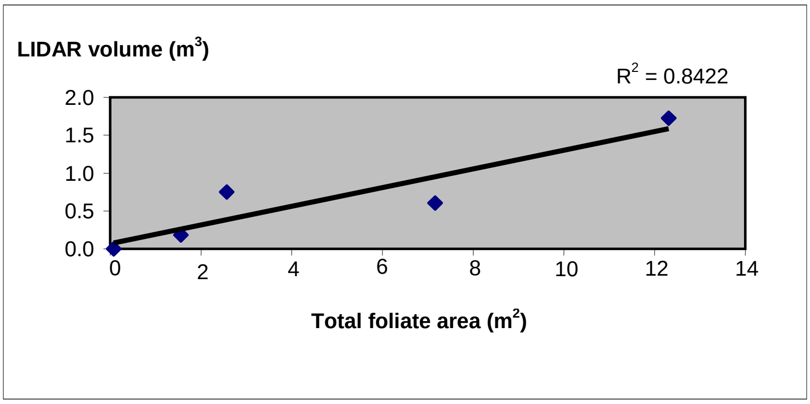

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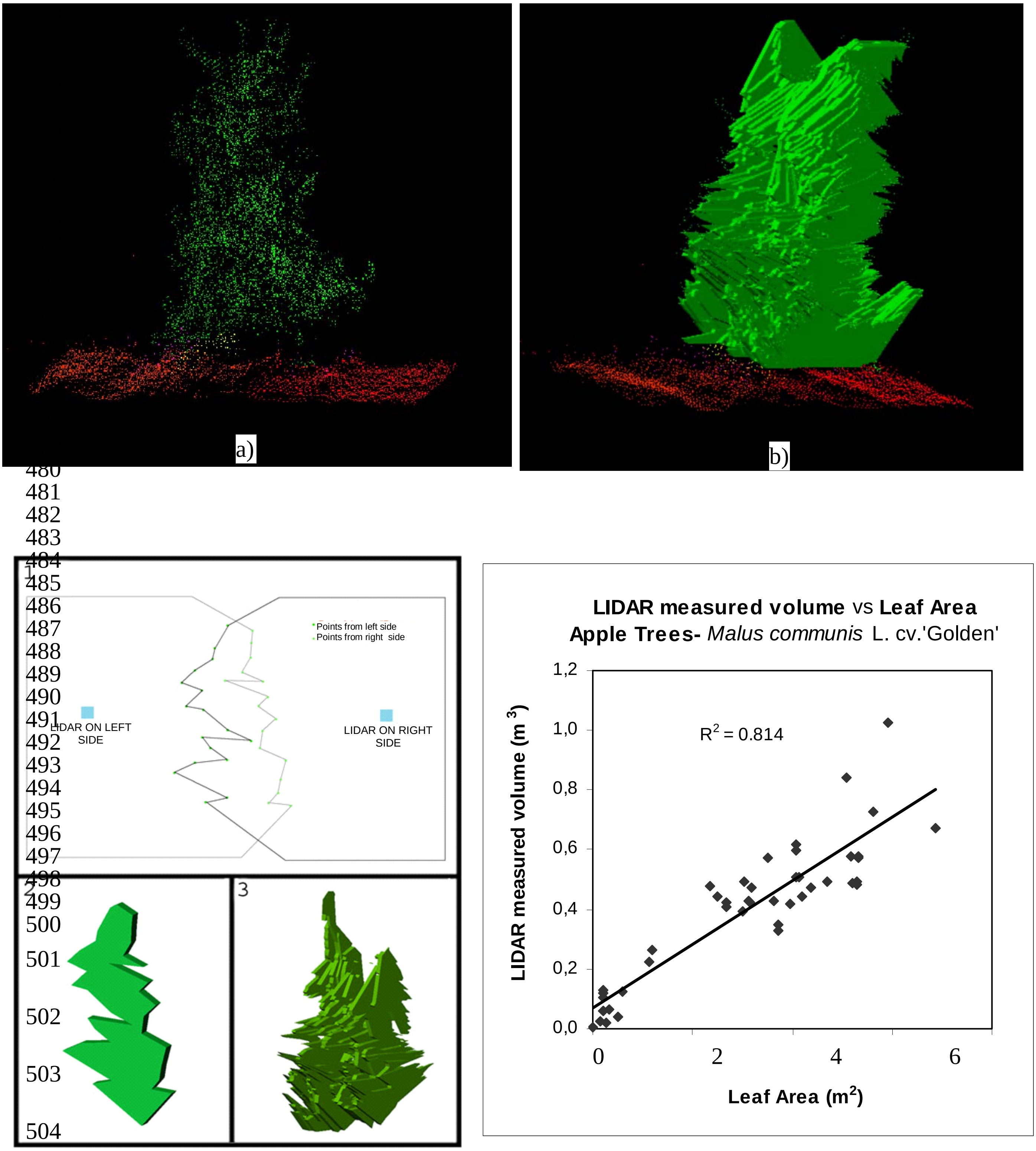

c) d)

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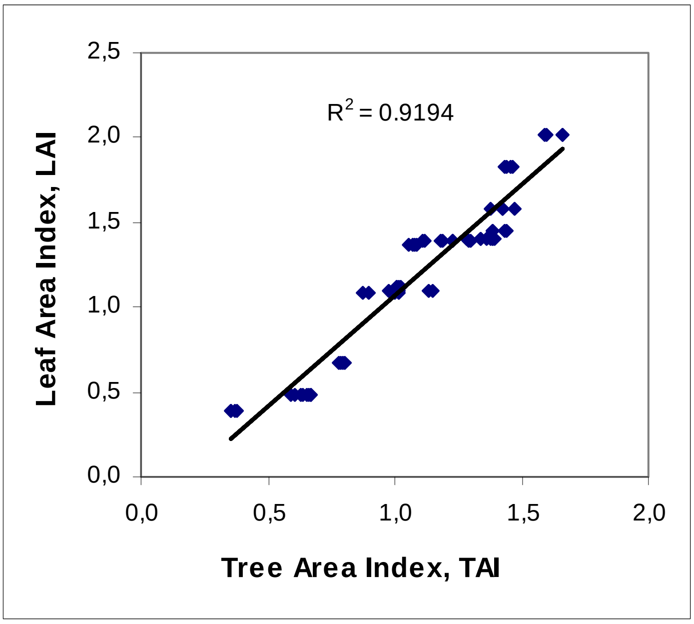

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