A Review of Methods and Applications of the Geometric Characterization of Tree Crops in Agricultural Activities.

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ABSTRACT

This paper presents the foundations and applications in agriculture of the main systems used for the geometrical characterization of tree plantations, including systems based on ultrasound, digital photographic techniques, light sensors, high-resolution radar images, high-resolution X-ray computed tomography, stereo vision and LIDAR sensors. Amongst these, LIDAR laser scanners and stereo vision systems are probably the most promising and complementary techniques for achieving 3D pictures and maps of plants and canopies. The information about the geometric properties of plants provided by these techniques has innumerable applications in agriculture. Some important agricultural tasks that can benefit from these plant-geometry characterization techniques are the application of pesticides, irrigation, fertilization and crop training. In the field of pesticide application, knowledge of the geometrical characteristics of plantations will permit a better adjustment of the dose of the product applied, improving the environmental and economic impact. However, it is still

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necessary to resolve several technological and commercial questions. The former include improving detection systems, especially with regard to developing software for the post-processing steps and improving the speed of calculation and decision making. Amongst the latter, it is essential to produce low cost sensors and control systems in order to facilitate large-scale deployment. Obtaining a precise geometrical characterization of a crop at any point during its production cycle by means of a new generation of affordable and easy-to-use detection systems, such as LIDAR and stereo vision systems, will help to establish precise estimations of crop water needs as well as valuable information that can be used to quantify its nutritional requirements. If accurate, this can provide valuable information on which to base more sustainable irrigation and fertilizer dosages. These would be able to meet crop needs and could also be used as part of specific management systems, based on prescription maps, for the application of variable quantities of water and fertilizers. The availability of measurement tools that allow a precise geometric characterization of plantations will also facilitate and enhance research aimed at developing better crop training systems that ensure an optimal distribution of light within the treetops and higher fruit quality. It is therefore of vital importance to continue devoting major efforts to the development of increasingly accurate, robust and affordable systems capable of measuring the geometric characteristics of plantations, which support the development of the different areas of a sustainable and precision agriculture.

Key words: Terrestrial Laser Scanning; LIDAR; Stereo vision; Ultrasonic sensors; Variable Application; 3D Real time applications; 3D Plant modelling.

1. Introduction

The structural aspects of a canopy are crucial at different levels (individual tree, crops, forest and ecosystems). The space occupied by tree foliage determines the potential for resource capture and for exchanges with the atmosphere (Phattaralerphong and Sinoquet, 2005). Plant structure influences most biophysical processes, including: photosynthesis, growth, CO_2-sequestration, and evapotranspiration (Li et al., 2002; Pereira et al., 2006), etc. At the forest level, structure plays a key role in processes involving exchanges of matter and energy between the atmosphere and terrestrial above-ground carbon reserves (Van der Zande et al., 2006).

Most of the work conducted to date has been related to forest areas (Lefsky et al., 2002; Parker et al., 2004; Maas et al., 2008; Kushida et al., 2009). However, in the field of agriculture, obtaining three-dimensional models of trees and plantations opens an immense and novel field of applications.

As far as agricultural crops are concerned, the geometric characterization of trees is both a relevant and complex task (Sanz et al., 2011a, b). It is relevant because tree canopy geometric characteristics are directly related to tree growth and productivity, and hence can be indicators for tree biomass and growth estimations, yield prediction, water consumption estimation, health assessment, and long-term productivity monitoring (Lee and Ehsani, 2009). Canopy characteristics supply valuable information for tree-specific management reducing production costs and public concerns about environmental pollution. Thus, there is a whole range of key agricultural activities including pesticide treatments, irrigation, fertilization and crop training which depend largely on the structural and geometric properties of the visible part of trees

It is a complex task because the thousands of elements that form trees (trunks, branches, leaves, flowers and fruits) are difficult to measure. There are essentially three reasons for this: (i) the large number of elements to consider, (ii) their location in a relatively small three-dimensional space, which implies that some elements will always be partially or totally hidden, regardless of the view angle adopted and (iii) the geometric complexity of all these elements (Zheng and Moskal, 2009). At present a number of research groups are conducting research into a variety of non-destructive techniques for the measurement of the tree canopy structural characteristics, such as volume, foliage and leaf area index. This can be achieved by different detection approaches, such as image analysis techniques, digital stereoscopy photography, analysis of the light penetration in the canopy, ultrasonic sensors and laser scanning techniques, among others.

The following sections will outline the main methods adopted for the geometric characterization of trees in the field and its application to four important crop management actions i.e. pesticide application, irrigation, fertilization and crop training.

2. Methods for the Geometric Characterization of Tree Crops

The structural and geometrical parameters of trees, such as vegetative volume and area are usually derived from manual measurements of height and width and the destructive sampling of leaves. However, as destructive sampling is both slow and costly for fruit orchards, other alternative remote methods have been used over the last 10 years. The measurement and structural characterisation of plants can be carried out remotely using several detection principles, including image analysis techniques, stereoscopic photography, analysis of the light spectrum, ultrasonic ranging and optical ranging (Rosell et al., 2009b).

The use of ultrasonic sensors (Giles et al., 1988; Zaman and Salyani, 2004; Zaman and Schumann, 2005; Solanelles et al., 2006), as well as digital photographs (Phattaralerphong and Sinoquet, 2005; Leblanc et al., 2005), laser sensors (Naesset, 1997a, b; Aschoff et al., 2004; Van der Zande et al., 2006; Rosell et al., 2009a, b), stereo images (Andersen et al., 2005; Rovira-Más et al., 2005; Kise and Zhang, 2006), light sensors (Giuliani et al., 2000), high-resolution radar images (Bongers, 2001) or high-resolution X-ray computed tomography (Stuppy et al., 2003) offers innovative solutions to the problem of structural assessment. Most of these approaches have proven incapable of describing the three-dimensional structure of a tree or canopy in a fast, repeatable and accurate way or have been associated with practical problems under field conditions (Van der Zande et al., 2006). The following paragraphs explain the main features of these sensors in more detail.

2.1 Radar systems

Most remote sensing techniques measure within the optical window of electromagnetic radiation where the influence of atmospheric conditions is high. Radar systems, on the other hand, measure within the microwave window and are relatively independent of atmospheric conditions. High-resolution radar images can be used to describe canopy structure in detail and over large areas. At present, the ways to measure the three dimensional structure of (components within) individual trees in detail are currently being developed and coupled to physiological models; however, the use of such methods is only feasible with small plants. At large scale levels, remote sensing data are used to describe differences in structure such as the roughness of the upper surface of a forest, which is an important structural parameter that indicates the distance from the forest to the macro-environment interface. Recently available high resolution radar images can be developed in such a way as to allow us to derive the relative heights of canopy surfaces. The introduction of high-spatial-resolution radar systems now permits the discrimination of forest types based on differences in canopy architecture. Radar systems with high spatial resolution (1 to 3 m) have recently become available for civil applications and can be used for the detection of individual tree crowns when they are large in comparison with the spatial resolution of the image and when they form part of the upper canopy, preferably for emergent trees (Bongers, 2001). However, this spatial resolution is still far from satisfactory resolution requirements of most agricultural applications (which range from several cm. to a few mm., depending on the target) and this means that any accurate measurement of the 3D characteristics of the canopy, such as its height and volume and the three-dimensional spatial model of its trees, remains unfeasible for the moment.

2.2 Medical and Industrial Adapted Technologies

On the opposite side from the viewpoint of spatial resolution are systems based on modifications of techniques commonly used in medicine and industry, such as high-resolution X-ray computed tomography (HRCT) or nuclear magnetic resonance imaging (MRI), among others. Both HRCT and MRI can provide non-invasive 3D visualizations of a wide variety of plant structures. In MRI, the water content of the objects examined is a crucial factor for determining pixel intensity, while HRCT is more suitable for ‘dry’ objects, such as dried plant parts, dry fruits and seeds and fossilized material because it can penetrate denser materials and depends on contrasts in overall density rather than on water content. However, HRCT cannot be used *in vivo* because the high-energy x-rays it uses could prove lethal. HRCT and MR techniques provide digital output which permits graphic 3D visualizations as well as accurate and reproducible quantitative measurements (Stuppy et al., 2003). At present, the main limitations of these techniques are that: (i) the largest specimens that can be scanned must not exceed about one metre in diameter or in height, which makes them inapplicable to most tree crops; (ii) the associated equipment is too expensive; (iii) their applicability to real field conditions is very difficult as is their integration with agricultural machinery; iv) in the case of HRCT, the powerful x-ray sources employed (up to 420 kV) imply a health risk to human beings.

2.3 Digital Photographic Techniques

Digital photographs can be used to reconstruct the 3D volume of an object by computer vision techniques (CVT). In CVT, a digital imaging camera receives light from the object surface and converts the light into electrical signals using a charge-coupled device (CCD) image sensor. CCD image sensors are solid state, silicon-based light sensitive devices that convert an optical image into an array of electrical signals, which are proportional to the intensities of the light from the surface. An analog-to-digital converter device converts the electrical signal into a digital data and the digitized imaging data are then stored in the computer (Chen et al., 2002). The photographic method was first developed for solid objects with well-defined opaque contours, but some work was also done on tree canopies. The silhouette area seen on each photograph, with photographs being taken in several beam directions (N, S, E, W, NE, etc.), is used to compute a solid angle, which is formed by the tree viewed from the camera location; this is a cone that includes the volume of the tree crown. The volume of the tree crown is therefore, estimated as the intersection of the different cones provided by a set of photographs.

Photographic methods for estimating individual tree dimensions and tree crown volumes also describe the canopy space as an array of 3D cubic cells that are considered to be semi-transparent. Tree crown volume is defined as the volume of the set of voxels (the 3D equivalent of a 2D pixel) containing phytoelements. This photographic method of reconstruction involves: (i) the estimation of canopy height and diameter from the location of the topmost, rightmost and leftmost vegetated pixels; (ii) the construction of a rectangular bounding box around the tree based on previously derived canopy dimensions; (iii) the division of the bounding box into an array of voxels; (iv) the division of each tree image into a set of picture zones. Each picture zone corresponds to the direction of a beam from the camera to the target tree, whose equation is computed from the zone location on the picture and from the camera parameters. After processing all the vegetated zones, voxels that have not been intersected by any beam are presumed to be empty and are removed from the bounding box. Estimations of crown volume can be refined by combining several photographs taken from different view angles (Phattaralerphong and Sinoquet, 2005).

2.3.1 Hemispherical Photography

Some authors have investigated the retrieval of canopy architectural parameters from digital hemispherical photography using off-the-shelf digital cameras with fish-eye lenses (Leblanc et al., 2005). This technique takes advantage of the sensor's linear response to light of these cameras to improve estimations of the gap fraction: (i) using the digital numbers of mixed sky-canopy pixels to estimate the within-pixel gap fraction and (ii) considering the variation in view zenith angle to take into account the sky radiance distribution and the canopy multiple scattering effects. As a result, some plant characteristics, such as the leaf area index (LAI) and the foliage element clumping index can be estimated with reasonable accuracy. These measurement systems make the assessment of plant geometry a complex and slow process which is not suitable for 3D real-time applications. Moreover, these systems do not allow us to obtain the 3D model of plants directly but by means of post-processing computing algorithms.

2.4 Light Sensors

There are commercially available portable light sensing instruments, so-called ceptometers, that measure the plant intercepted light from the above-canopy and below-canopy measured radiation and calculate the canopy photosythetically active radiation (PAR) interception (Fig. 1). PAR data can be used with other canopy parameters and climate data to accurately calculate the LAI non-destructively in real time and estimate diverse canopy processes like biomass production, radiation interception, energy conversion, precipitation interception, and evapotranspiration.

The use of light sensors to obtain the geometrical and structural characteristics of plants, such as their shape, size and the number of theoretical canopy leaf layers (leaf layer index, LLI), is based on monitoring the light–shadow windows of a tree via a grid system of light sensing sensors on the ground (Giuliani et al., 2000). The sensing system consists of an array of 48 light sensors set out horizontally and upwards in correspondence with cavities drilled into two aluminium bars (Fig. 2). The chosen light sensors are low cost phototransistors with spectral sensitivity in the 300–1100 nm waveband. The ground readings taken at each measurement over the day are used to project a digitized shadow image. Using image processing, the amount of intercepted radiations is calculated as the difference with respect to the corresponding incoming radiation above the canopy. Tree-crown size and shape are profiled via computer imaging by analysing the different shadow images acquired at various solar positions during the day.

This system has several practical limitations. With regard to measurement requirements, the use of the light scanner must be restricted to sunny and clear sky days and low wind-speed conditions as well as smooth ground-layer vegetation, which produce a ground canopy shade whose contours are sufficiently visible and stable. The readings are taken by moving the sledge scanner, step by step, from one side of the designated area to the other, so as to cover all the grid points to be monitored. A data set is recorded at each position, but the procedure makes the measurement process very time consuming. Furthermore, this system does not allow us to obtain a 3D model of plants directly, but by means of post-processing the shadow images acquired. Finally, this method is not suitable for real-time 3D applications.

2.5 Stereo Vision

Computer stereo vision implies the extraction of 3D information from digital images, as obtained by a CCD image sensor-based digital camera. A stereovision system can provide a three-dimensional (3D) field image by combining two monocular field images taken simultaneously using a binocular camera (Kise et al., 2005). The main advantage of stereoscopic vision over conventional monocular vision is its ability to detect ranges: distances between scene objects and the camera. Monocular cameras create planar images in which each pixel is the result of a two-dimensional projection of the 3D world.

Stereovision adds a third coordinate, or range, which completes the full localization of any point within a 3D Cartesian frame (Fig. 3). The natural outcome of a stereovision sensor is a 3D point cloud that renders the captured scene with a degree of detail proportional to the resolution of the acquired images. Every single point in the 3D cloud comes from a stereo-matched pixel and will be endowed with three coordinates that identify its exact spatial position (Rovira-Mas et al., 2006).

Stereo analysis links geometrical positioning information relating to objects to their real-world coordinates, presenting this information in the form of a 3D map. Stereo vision systems have not only provided distance measurements with a reasonable degree of accuracy but also support the acquisition of 3D image data for Geographical Information System (GIS) data bases (Lin et al., 2008). With regard to the accuracy of the measurement, Kise and Zhang (2008) found that the root mean squared (RMS) error between crop heights based on 90 points estimated from 3D field crop structure maps obtained with their stereo vision system and manually measured ground truth data was 0.04 m, with a maximum error of 0.09 m. This validation result proved that the 3D field mapping system developed in their research could provide centimetre-level crop plant height information with a high spatial resolution in the form of a panoramic field view. The possibility of rendering a 3D representation of a field scene provides an effective means of keeping track of the stages of development of vegetation, and also as a way of sensing those plant physical parameters that are important for production management, such as crop size and volume (Rovira-Mas et al., 2005). Stereovision systems can provide direct measurements of 3D vegetation structures and spectral information. In the case of agricultural systems, the additional dimension of the scene is critical for many agricultural applications such as observations of crop growth conditions, estimation of physical parameters, and also livestock 3D shape extractions (Kise and Zhang, 2008). However, stereo vision systems offer less accuracy than laser-based systems and need appropriate calibration and recording procedures. In addition, they are less effective under certain weather conditions and require further improvements if they are to be applied to dense area canopies. Unfiltered mismatches result in pixels showing erroneous stereo information that provides meaningless location-based data (Rovira-Más et al., 2008). Furthermore, agricultural fields and orchards are generally well illuminated and have rich texture patterns, which typically results in disparities in images when there is extensive coverage. In spite of the robustness of stereo cameras to adapt to lighting conditions, poor illumination results in a lack of texture and, consequently, in a weak disparity image, which produces only a sparse 3D cloud. When selecting a stereo sensor, one must consider the type of illumination expected and then opt for either pre-calibrated or changeable optics cameras. The former typically imply fixed optics with no possibility of adjustment and control, while the latter require careful calibration every time a lens is removed or the baseline is modified.

Another intricate problem relates to the size of the resulting 3D cloud. When several images are processed together, the magnitude of the data files grows considerably, complicating the handling and storage of 3D information. The problem becomes more critical when real-time processing is required. In these cases, the solution is often to process one image at a time and to delete it after the information has been extracted; but even in these situations, the time needed for stereo calculations can be determinant (Rovira-Mas et al., 2006). Even so, these aspects are gradually being improved so stereo vision is emerging as one of the preferred methods for the geometric characterization of tree crops.

2.6 Ultrasonic Sensors

Another type of system is based on the use of ultrasonic sensors (Fig. 4) to measure distances quickly and automatically. These sensors have three basic elements: an emitter of ultrasonic waves, a chronometer and a wave receiver. Their operation is based on determining the flight time of an ultrasonic wave from the point of emission to the point of detection after bouncing off an object.

The main advantages of ultrasonic sensors are their robustness and low price. Their main drawback is the large angle of divergence of ultrasonic waves. This limits the resolution and accuracy of the measurements taken and also requires the use of many units to cover a common agricultural scene (Rovira-Mas et al., 2005). Despite of this, ultrasound sensors are currently being used for the characterization of plant mass and give good results in certain scenarios. Several researchers used ultrasonic sensors to estimate the most relevant geometrical parameters of trees and tree crops i.e. height, width, volume and leaf area and compared them with manual measurements. They also investigated the effect of foliage density and tractor speed, developed software to create maps of volume in real time and investigated the influence of the space between rows of trees and their age on the volume of space that they occupied (Tumbo et al., 2002; Zaman and Salyani, 2004; Schumann and Zaman, 2005; Llorens et al., 2011).

2.7. LIDAR Sensors

Another detection principle, which is being used rapidly, is based on the LIDAR (Light Detection and Ranging) sensor technology, which allows 3D scanning of all types of objects. LIDAR laser technology, which is a non-destructive remote sensing technique for the measurement of distances, provides a relatively novel tool for generating a unique and comprehensive mathematical description of tree structure**.** The distance between the sensor and the target (e.g. a leaf or branch) can be measured by one of two methods: (i) measuring the time that a laser pulse takes to travel between the sensor and the target (*time-of-flight LIDAR*) or (ii) measuring the phase difference between the incident and reflected laser beams (*phase-shift measurement LIDAR).*

LIDAR sensors can be located on satellites and aircraft or carried by terrestrial means (Fig. 4). The main advantages of these sensors are their high speed and accuracy of measurement. LIDAR sensors facilitate the description of the geometric structure of trees. Their ability to very quickly (thousands of points per second) measure the distance between the sensor and the objects around it allows us to obtain 3D cloud points (x, y, z) which, by applying appropriate algorithms, makes it possible to digitally reconstruct and describe the structure of trees with high precision (Pfeifer et al., 2004; Rosell et al., 2009a, b). For these reasons, in spite of their limitation for dusty environments, LIDAR systems have turned out to be one of the most used sensors for the geometric characterization of tree crops.

The capacity of LIDAR to quantify spatial variations, which is an important aspect of vegetation structure, is a significant advance over some previous methods. LIDAR systems can be used to quantify changes in canopy structure at various time scales. They can provide detailed assessments of canopy growth and allocation responses to field experiments including fertilization, irrigation, soil warming and fumigation. Laser technology offers unique options in terms of the viewing angle and distance information needed to model canopy structure; hence, there is an emerging to thoroughly investigate LIDAR structural applications (Van der Zande et al., 2006).

Most of the work carried out to date has focused on forestry. However, 3D models may also be valuable for agricultural landscapes, with some applications being similar to those used in forest areas and others being specific to agricultural subjects. Due to their different characteristics, some techniques suitable for agricultural crops are difficult to apply to forest plantations. One basic difference relates to the accessibility to the zones of study for people and vehicles. Forest areas are often difficult to access for people and especially for vehicles. On the other hand, the transit of both people and machinery within agricultural plantations is guaranteed in most cases. This is highly relevant as it largely determines the kinds of instrumentation that can be used in each case. This explains the use of 3D LIDAR sensors in ground-based laser studies for forest applications. The main advantage of using these sensors is that they provide a 3D point cloud of the object being measured. However, the high cost of these instruments limits their use (Rosell et al., 2009a).

In agricultural applications, it is, however, possible to use two-dimensional (2D) terrestrial LIDAR sensors, which are much cheaper to use (Walklate et al., 2002; Palacín et al., 2007). 2D LIDAR sensors obtain a point cloud corresponding to a plane or section of the object of interest. The fact that these sensors only scan in one plane does not necessarily limit their scope to 2D perception (Rovira-Mas et al., 2006). Sensor position, when well-determined (for example, with a constant, known-speed, linear movement - that can be achieved easily in the case of agricultural plantations - or when using high precision GPS georeferencing), allows the recording of measurement results corresponding to different planes or cross sections of an object, generating a 3D point cloud. Rosell et al. (2009a, b) proposed the use of a 2D LIDAR scanner in agriculture to obtain 3D structural characteristics of plants (Fig.5). Their results, obtained for fruit orchards, citrus orchards and vineyards, showed that this technique could provide fast, reliable, and non-destructive estimates of 3D crop structure. They concluded that LIDAR systems were able to measure the geometric characteristics of plants with sufficient precision for most agriculture applications. The system developed made it possible to obtain 3D digitalized images of crops from which a large amount of plant information -such as height, width, volume, leaf area index and leaf area density- could be obtained.

As regards the accuracy of the measurement, Palacín et al. (2007), who carried out real-time tree-foliage surface estimations using a ground laser scanner, concluded that the relationship between the external volume of the tree and its foliage surface could be considered linear with an average relative error of less than 6% in estimations for a complete grove, though trunks tended to cause instantaneous relative errors of up to 93% in the lower parts of trees. The same authors (Pallejà et al., 2010) analyzed the sensitivity of the tree volume estimates in the spatial trajectory of a LIDAR relative to different error sources. They demonstrated that the estimation of the volume is very sensitive to errors in the determination of the distance from the LIDAR to the centre of the trees (with errors up to 30% for an error of 50 mm) and in the determination of the angle of orientation of the LIDAR (with errors up to 30% for misalignments of 2%). They concluded that any experimental procedure for tree volume estimate based on a motorized terrestrial LIDAR scanner must include additional devices or procedures to control or estimate and correct these error sources. Wei and Salyani (2005) developed a laser scanner for measuring tree canopy characteristics and concluded that laser density measurements offered a good degree of repeatability, with an average coefficient of variation (CV) of less than 3% for three replications.

2.7.1. Flash LIDAR

Recently, a new technological generation of 3D LIDAR systems, called Flash LIDAR, has emerged, which will probably replace some of the present systems. Flash LIDAR are cameras that are much like 2D digital cameras in both their appearance and means of operation. They have 3D focal plane arrays with rows and columns of pixels but with the additional capacity to provide 3D "depth" and intensity. Each pixel records the time that the laser flash pulse from the camera takes to travel to the scene and to bounce back to the focal plane (sensor). A short duration, large area light source (the pulsed laser) illuminates objects in front of the focal plane as the laser photons are "back scattered" towards the camera receiver by the objects in front of the camera lens. This photonic energy is collected by an array of smart pixels, in which each pixel samples the incoming photon stream and "images" depth (3D) and location (2D), as well as reflective intensity. Each pixel has independent triggers and counters that record the flight time of the laser light pulse as it travels from the camera to the object(s). The physical range of the objects in front of the camera is calculated and a 3D point cloud frame is generated at video rates, this is currently possible at up to 60 frames/second (Advanced Scientific Concepts Inc., 2010). Compared with conventional 3D LIDAR systems, the main advantages of 3D Flash LIDAR systems are: faster measurement speed, smaller size and a much lower price, while maintaining good precision (to about a few mm).

2.8 Summary

In this section, many different sensing technologies and systems for the geometric characterization of tree crops have been reviewed. Based on the results and recommendations from these studies as well as the authors' own experience, Table 1 summarizes the operating principles and the main strengths and limitations of the exposed sensors and methods for the measurement of the geometrical properties of plants and crops.

3. Applications for Pest and Disease Control

Despite of the recent advances in the employment of different methods for defending crops against pests and diseases, the use of plant protection products (PPP) continues to be an essential strategy for addressing the qualitative and quantitative demands of the food market. In recent years, growing environmental awareness, together with social concern to preserve the health of people and animals, has led to important legislative measures to minimize risks associated with the use of PPP. For instance, consideration 11 of Directive 2009/128/EC, of the European Parliament and of the Council of 21 October 2009, established a framework for Community action to achieve the sustainable use of pesticides. It states that "research programmes aimed at determining the impacts of pesticide use on human health and the environment, including studies on high-risk groups, should be promoted at European and national level".

Adjusting the PPP dose to the structural and morphological characteristics of the vegetation is recognized at European level as an essential goal in the path towards reducing risks associated with the application of pesticides. The spraying equipment that is currently most used in fruit growing is hydraulic and air-assisted. This offers greater product penetration into the vegetation and produces a uniform deposition within tree canopies. The use of new technologies allows us to detect the structural characteristics of vegetation and thereby to select and apply more appropriate broth volumes. These techniques can also be used to achieve an acceptable control of air speed and flow and the most appropriate orientation of the air outputs, thereby reducing the risks associated with the use of PPP. Their application can also help to reduce the amount of product that reaches, and pollutes, ground, air and/or surface water. The development of automatic equipment capable of making a variable rate application, according to the characteristics of the vegetation, has proved a good solution for saving PPP and reducing the risk of environmental contamination. This requires the use of sensors capable of quickly, accurately and reliably identifying these characteristics, such as ultrasonic sensors (Giles et al., 1988; Escolà et al., 2001; Moltó et al., 2001; Solanelles et al., 2006; Llorens et al., 2010) or detection systems based on LIDAR sensors (Walklate et al., 1997, 2002; Sanz et al., 2004; Rosell et al., 2009a, b; Sanz et al 2011a, b).

3.1 Application doses and geometric characterization of tree crops

The choice of the most appropriate application doses of PPP is a fundamental consideration in modern agriculture. The value afforded to the environment today is not the same as it was several years ago. Choosing the dose to apply in each treatment is a difficult task because it is necessary to consider opposing interests. On the one hand, the dose must be sufficient to control the pest in all parts of the plant and on the other it should be as small as possible so as to cause little or no environmental impact. The geometric characterization of trees provides fundamental data that can be used to minimize the environmental impact of the application of pesticides.

The most common expression of the application dose that appears on the labels of existing products involves the amount of product applied per unit of ground area occupied by the crop ($l \cdot ha^{-1}$). This method is appropriate in the case of boom sprayers for the treatment of low-growing crops, where the target is uniform, parallel to the ground and located just below the boom. In contrast, the application of plant protection products to tree crops is made at the treetop level with the assistance of air. Under these conditions, the deposition of the product on trees, following the recommended dose given on the product label (RDPL), will vary according to tree size. To alleviate this problem and ensure the effectiveness of the product, manufacturers tend to increase the margin of error in the RDPL (Russell, 2004).

Different mathematical models are used to express the application doses of PPP to be applied to tree crops (Table 2). These models require different sets of information to calculate the number of litres per hectare required to complete the application. The information that each model requires has a direct effect on its ease of use and accuracy of application. The most common way of expressing the dose is the expression [1] in Table 2. The volume applied per unit area ($l \cdot ha^{-1}$) is a function of the flow from the nozzle ($l \cdot min^{-1}$), the speed ($km \cdot h^{-1}$) and the working width (m).

If the width of distribution is taken as the distance between rows, the volume of application is set exclusively in accordance with the area of the field, without taking into account the size of the vegetation. However, adopting this dosing system may lead to problems of overdosing in fields of low-growing vegetation. This increases problems of waste and product misuse or, conversely, problems of under dosing associated with greater vegetative development and inadequate infestation controls. This practice is not consistent with what is known as crop adapted spraying (Felber, 1997), which consists of maintaining constant product quantity per unit area of vegetation ($mg \cdot cm^{-2}$).

Knowledge of the geometrical and structural parameters of tree rows allows this model to be adjusted to reduce variations in deposition on different tree crops. Along these rows, Morgan (1964) recognized the need to adjust the dose according to the height of the trees in question. Koch (1993) adjusted RDPL according to wall surface vegetation, changing the horizontal target of the soil for the vertical target of the vegetation (Pergher and Petris, 2008). Byers et al. (1971) were the first to use TRV (Tree Row Volume) as a parameter for adjusting the rate of application. Walklate et al. (2002) determined an imaginary distribution width, a, as a function of the geometric and structural parameters obtained with a LIDAR measurement system, such as TAD (Tree Area Density), TAI (Tree Area Index), or LIF (Light Interception Flux model).

Another much more accurate model, but which requires information that is difficult to estimate, is the optimal coating model, expression [2] in Table 2, which is based on obtaining a level of coating (impact per unit area) that is suitable for the requirements of the product to be applied and the pest. The combination of the density of impacts (droplets $\cdot$ cm^{-2}) with the droplet volume (assuming that it adopts a spherical shape), along with a knowledge of the leaf surface to be treated, allows us to determine the theoretically optimal dose for spraying (Gil, 2005). The value obtained from the expression [2] in Table 2 corresponds to the amount that, theoretically speaking, would need to be distributed in order to guarantee an application efficiency of 100%. This situation, which involves a total absence of losses, is evidently impossible to achieve, so the model requires the introduction of a correction factor that would allow the amount of product lost to be quantified during the process of pesticide application. The application of this model requires a geometric characterization in order to estimate the LAI. This model, based on the expression [2], has been implemented in DOSAFRUT (2011). DOSAFRUT is a tool for determining the appropriate application rate (l/ha) for the specific conditions under which the treatment will take place (characteristics of the orchard, meteorology and spray). Currently, this tool is appropriate for all spray treatments applied in intensive apple and pear orchards at any vegetative stage except leaf fall and during the winter break. DOSAFRUT is most useful in implementing national action plans under Directive 2009/128/EC (COM, 2009).

3.2 Measurement of plant material

Thanks to recently developed technology, precision agriculture is currently helping to extend the methods currently being used in relation to pesticide treatments. This raises the potential for developing more precise PPP applications that comply with the environmental guidelines set out by the European Union (COM, 2009) and a number of other countries.

In this section we refer to various studies being conducted with ultrasonic sensors and LIDAR sensors, as they seem to be the most promising with respect to target-sensing pesticide application.

The performance of a prototype electronic sprayer was first tested by Giles et al. (1988). The system was based on ultrasonic range transducers mounted on an orchard air-blast sprayer. Subsequent applications focused on interrupting the spray output when there was no vegetation (Gil et al., 2007). In the field of variable application of pesticides in citrus orchards using ultrasounds, Moltó et al. (2001) designed a prototype machine that, applied one of two different doses according to the shape of the trees concerned: a higher doses at the centre of the tree, and lower doses to its outer parts. In this case, ultrasonic sensors determined the locations of these two zones (centre and exterior).

Based on initial work by Rosell et al. (1996) and Escolà et al. (2001) Solanelles et al. (2006) developed a prototype for an electronic control system based on ultrasonic sensors and proportional solenoid valves. This system allowed the authors to constantly vary the pesticide doses applied to the tree in accordance with the size of the vegetation. The aim of this prototype was to precisely apply the required amount of spray liquid and to avoid over dosing. In recent trials with vineyards Llorens et al. (2010) achieved a mean saving of 58% in the volume applied with the variable rate method and achieved good leaf deposits. The main disadvantages of ultrasonic sensors are their low resolution and accuracy; this implies that many units are required to cover a common agricultural scene.

The angle of divergence of LIDAR sensors is much smaller than that of ultrasonic sensors. The higher resulting resolution means more measuring points which, in turn, provides a more accurate representation of the vegetation. It also implies a greater ability to penetrate vegetation. Measuring trees with LIDAR and ultrasonic sensors must take into account the impossibility of measuring distances to elements that are hidden behind others. In order to optimize PPP treatments, Walklate (1989) and Walklate et al. (1997) began a mathematical development to determine the structural parameters of tree crops based on data supplied by a LIDAR measurement system. Walklate et al. (2002) subsequently completed this mathematical development, enabling it to estimate the TAI and TAD, among other parameters. This whole mathematical development is based on measuring distances from one side of the row of trees using the LIDAR system. Using LIDAR to undertake the geometrical characterization of apple trees in the United Kingdom, Walklate et al. (2002) compared different volumetric models of leaf deposition ($l \cdot m^{-2}$) for pesticide treatments. This paper demonstrates the importance of the geometric characterization of fruit trees for the application of PPP.The comparisons have been limited to models in which the deposition on the leaves can be expressed as [1] in Table 2.

Depositions on leaves (Dose (l•m^{-2})) are a function of three variables: the flow rate delivered through the nozzles (Q (l•min^{-1})), the speed of the tractor (v (km•h^{-1})), and a length value (a (m)), or length-scale (according to the author), which is a function of the structural parameters of the tree crop. The different functions for the calculation of a use different structural parameters or combinations thereof (distance between rows, vegetation height, cross-sectional area, surface density of the tree, etc.). Using different ways to obtain a imply using different models to determine the deposition.

Comparisons between different models were evaluated by measuring the deposition of product on the leaves of apple trees. The equipment used was a hydropneumatic sprayer (Model TC 1082 by Hardi International A/S) with 8 conical nozzles and an axial fan. Ten trials were conducted over a three-year period (1997-1999) in plantations with small trees and medium and large plantation patterns. They were conducted with different rootstocks, at different planting densities, different ages, and at different vegetative stages. Linear regression analysis between the deposition of the product and the calculation functions of a led to the results shown in Table 3.

For the determination of a using a model which only depends on the width between the rows, the variation in deposition was explained by 9% of the variation in the measurements ($R^2 = 0.089$). This is a very low value and one that confirms what was otherwise quite easy to predict: it is necessary to take into account the geometric characterization of the trees. For the model based on the assimilation of the crop to a vertical plane wall (Koch, 1993;

Pergher and Petris, 2008), the determination of *a* depends on the height of the plant wall that is to be treated. For the model based on the assimilation of the crop to a wall of cylindrical surface, the determination of *a* depends on the square root of the cross-sectional area. For the model using the TRV the determination of *a* depends on the surface of the cross section and the distance between rows.

Other models based on estimations of the surfaces of leaves, branches and fruits, using a model of light transmission that follows a local poisson distribution gave better results (TAI, TAD and LIF). For the model that uses the TAI, defined as the entire surface of the tree projected in the direction of the laser beam divided by the total area of soil, the determination of *a* depends on the estimation of TAI from LIDAR data. For the model using the TAD, defined as the entire surface of the tree projected in the direction of the laser beam divided by the volume occupied, the determination of *a* depends on the estimation of TAI, the distance between rows and the cross-sectional area. For the model using the LIF, which is an optical analogy for the deposition of droplets on the crop, the determination of *a* depends on the estimation of LIF from LIDAR data. The paper concludes that TAD is the best parameter for determining the application doses for pesticide treatments on apple trees.

In the case of TAD, the following three points need to be considered: (i) the TAD is the result of a mathematical function which uses information obtained by LIDAR that has not been checked against actual measurements of vegetation (leaf, branch, and fruit surfaces). (ii) The TAD is derived from LIDAR data of only one side of the row of apple trees. There are already studies of geometric characterization of tree crops that use LIDAR information from both sides (Sanz et al., 2011b). (iii) The TAD is a mathematical function whose calculation requires a value for the volume occupied by the plants. This volume is not an objective parameter and therefore its value can vary considerably according to its definition. For example, in the case of an isolated tree, the volume obtained from a simple ellipsoidal model is much greater than that obtained by the immersion of the same tree in a water tank. However, the results of this study showed the importance of the density of the different elements that constitute a tree in determining application doses for PPP.

Continuing with the previous work and looking for easy solutions for the determination of pesticide doses for tree crops without the use of LIDAR sensors, Walklate et al. (2003) present a system to allow farmers to determine application doses for any vegetative stage of the tree. The first version was designed for apple plantations in the United Kingdom. The system is based on a set of pictograms, obtained with a LIDAR from various plantations. Each pictogram shows a homogeneous group of apple trees (5-10 trees) with various different amounts of foliage. Each pictogram corresponds to a specific adjustment factor, CAF (Crop Adjustment Factor), which depends on the TAD calculated using LIDAR data (Walklate et al., 2002). The maximum value (1) of CAF is for orchards in full vegetative development, with maximum foliage and the maximum TAD. In plantations with the same separation between rows the pre-flowering stages typically have CAF values of between ¼ to ½. In stages after flowering with leaves, values range from ½ to 1. With this system, the farmer has to derive the CAF factor from the pictogram that most closely resembles the situation corresponding to their apple plantation. The product of the reference dose (the dose used with extreme leafiness) with the value of CAF obtained from the pictograms gives the dose to be applied to a specific plantation at the present stage. Walklate et al. (2006) state that it is necessary for companies trading in PPP to clearly inform about the reference crop and the reference conditions in which the RDPL is effective. Standardizing these conditions would prove very useful for making dose adjustments.

The system of pictograms is a major advance but it is not generic enough for the large number of different situations that can occur in orchards (different species and varieties, crop training systems and vegetative stages), so further work is required to find an equally simple but more generic system.

3.3 Variable application

Despite the use of management and training systems that seek to establish an area or volume of vegetation which is as uniform as possible, the structure of modern fruit and citrus orchards and vineyards, etc. is often characterized by high degrees of heterogeneity. This, together with the presence of gaps (areas free from vegetation) of varying proportions, which depend on vegetative stage, greatly affects the quality and efficiency of PPP applications.

Areas free from vegetation offer the most favourable paths along which the products applied can escape, with consequent increases in losses due to drift (Doruchowski and Holownicki, 2000). In some cases, the percentage of product that does not reach its target may be as high as 80% of the total product applied (Holownicki et al., 2000). This, together with the high cost of pesticide applications in relation to overall production costs (between 30 % and 42% of production costs for olives and citrus in Spain, according to Moltó et al. 2001), has encouraged the development of systems to improve the efficiency of applications. The introduction of electronic systems in the development of new equipment has made it possible to reduce operational and environmental costs through an increase in quality (Llorens et al., 2010).

By using plant detection systems, variable dose application techniques (Table 4) continuously adjust the applied flow rate to the characteristics of specific crop areas. In the case of spraying with tunnel systems, product savings are the result of substantial product recovery (Planas et al., 2002). Variable applications may lead to significant savings by limiting the total quantity of product applied. It is necessary to improve our knowledge and use of systems capable of characterizing vegetation (depth, height, leaf area density, etc.) in order to adapt and modify application doses in line with detected changes and in real time (Gil, 2005). The objective pursued, whether using map-based systems, sensor systems working in real time, or both in conjunction, is to optimize the application of PPP in the area of vegetation being treated. This optimization must be both qualitative and quantitative and consists of continually adjusting the doses and the parameters that determine the quality of deposition, which include such factors as drop size and air flow (Escolà et al., 2001; Rosell et al., 2004; Gil et al., 2007).

In recent years, different research groups have developed prototypes based on the variable application principle. Applying a crop adapted variable application system with ultrasonic sensors and proportional solenoid valves, Solanelles et al. (2006) reported liquid savings of 70%, 28% and 39% in comparison to conventional applications in olive, pear and apple orchard respectively. Gil et al. (2007) and Llorens et al. (2010) with similar systems adapted to vineyards achieved average savings of 58% compared to the conventional constant rate application systems, with similar or even better PPP depositions on leaves. Escolà et al. (2007) boarded a LIDAR based electronic characterization system in a sprayer prototype in order to adjust the dose rate in a continuous variable rate real-time mode (Fig. 6). Compared with conventional systems, the tests of the prototype, performed in *Pyrus communis* L. Cv. ´Conference´ orchards, resulted in PPP volume savings of 44,33%. Doruchowsky et al. (2009) developed a spray application system for sustainable plant protection in fruit growing that can automatically adapt spray and air distribution according to the characteristics of the target, to the level of crop disease and to the environmental conditions. Their Crop Adapted Spray Application (CASA) system consists of three sub-systems: (i) Crop Health Sensor (CHS), based on a spectral sensor that analyses light reflected from leaves in the bandwidth 400- 1600 nm, (ii) Crop Identification System (CIS), based on a new ultrasonic sensor that delivers real time data on target characteristics such as tree canopy width and density, and (iii) Environmentally Dependent Application System (EDAS), which identifies the environmental circumstances i.e. wind velocity/direction, orchard boundary, and sensitive areas such as surface water, sensitive crops, public areas, etc, and adjusts application parameters according to the wind situation and sprayer position in relation to sensitive areas. Nozzles can be altered to adjust droplet size. These authors, as well as Pai et al. (2009) have designed different systems for the adjustment of orchard sprayer air output in order to optimize the spray distribution and minimize spray losses.

4. Irrigation Application

Water is a critical resource in agriculture and the need for irrigation at each point in the production cycle is essential for plant health and optimum productivity. A lack or excess of water causes problems. If there is insufficient water, water stress occurs, which affects productivity. On the other hand, an excess of water results in disease, nutritional disorders and/or root suffocation, etc.

Calculations of irrigation needs must distinguish between two different scenarios: design and management. In the case of design, seasonal series should be studied to identify periods of peak demand in terms of probabilities of occurring. In the case of management, interest focuses on the need for water in real time (Vellidis et al., 2008). In 1950, it was estimated that fewer than 100 million hectares of cropland were irrigated throughout the world. This area is now about 260 million hectares. This is equivalent to less than 17% of the total area of the Earth's land surface, but 40% of the area dedicated to food and fibre production (Fereres and Evans, 2006).

Irrigation is the largest consumer of fresh water on earth. Irrigation consumes an estimated 20% of total available freshwater and two thirds of the total volume intended for human use. In general, the increasing demand for water from all sectors (agricultural, municipal, industrial and recreational uses, etc.) means that significant improvement are required in the management of irrigation water in order to optimize the use of this limited resource that is essential for life. One proposed improvement implies changing the emphasis from maximizing production per unit area to maximizing production per unit of water consumed (Fereres and Evans, 2006).

Applying all the water that a crop requires is not always the best strategy for irrigation. The practice of subjecting the crop to controlled water stress at certain points in the production cycle has been shown to not only considerably reduce water consumption without losses in overall productivity but even, in some cases, to help increase fruit quality (Mpelasoka et al., 2001; Goldhamer et al., 2006; Leib et al., 2006). This agricultural practice has significant advantages, but requires extremely accurate risk scheduling, which in turn requires a thorough understanding of crop performance in real time both in terms of geometrical characterization and physiological behaviour.

The best way to know the water needs of a crop is to measure the water balance using lysimeters (Scott et al., 2005). These instruments monitor changes in weight produced by evaporation and transpiration in a cultivated area. The main drawback of this technique, which is considered the most accurate approach, is the cost of manufacturing, installing and maintaining the equipment required. For this reason, the use of lysimeters tends to be limited in practice to research and to helping to calibrate other cheaper methods of estimating evapotranspiration.

Studies of irrigation in tree crops are limited by the absence of proper tools for the geometric characterization of vegetation. Given this gap, researchers use variables that in some way represent, or are a result of, the size and structure of the vegetation in question. These variables include the overall size of the treetops, the surface section of the trunk and branches of shaded areas, trunk sap flow, and leaf area, etc. Differences in the size and shape of treetops relate to differences in transpiration (Cohen et al., 1987). A precise geometrical characterization of crops at any point during the production cycle may help to establish precise estimations of crop water needs.

4.1 FAO Penman-Monteith Method

Before referring to studies that relate the geometrical characteristics of vegetation to irrigation requirements, we should briefly examine the method traditionally used to determine the water needs of crops: the Penman-Monteith method. This method is a standard reference in studies on irrigation. It is based on the determination of reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) from meteorological data and crop coefficients. The first publication on the calculation of ET_c using the Penman method was that of Doorenbos and Pruitt (1977) in FAO Irrigation and Drainage Nº. 24, and was entitled "The needs of water on crops". A review of this method began in 1990 and in 1998 "Crop Evapotranspiration: Guidelines for the determination of the water requirements of crops" was published in FAO Irrigation and Drainage Nº56. In this paper new procedures for calculating evapotranspiration using the Penman-Monteith method were presented (Allen et al., 1998). The procedures set out in this guide can be used to determine the water requirements of crops, both with and without irrigation, for both natural and agricultural vegetation.

The ET_o is the rate of evapotranspiration from a reference surface. The ET_c is defined as the evapotranspiration of any crop when it is free from disease, well fertilized, cultivated in large fields under optimum soil and water conditions, and reaches maximum production according to the prevailing climatic conditions. The ratio ET_c / ET_o can be experimentally determined and is known as the crop coefficient (Kc), so $ET_c = Kc \bullet ET_o$. As a result of differences in the geometric structure of plants, leaf anatomy, stomata characteristics, aerodynamic properties, albedo, and cultivation practices, etc, crop evapotranspiration differs from reference evapotranspiration under the same conditions

4.2 Studies that relate irrigation with the geometric characterization of tree crops and vines

Several research studies relate the calculation of water needs for irrigation with aspects of the geometrical characterization of trees and vines. In the past, efforts to determine water needs were mainly focused on arable crops and, to a lesser extent, on tree crops and vineyards. The publication of Doorenbos and Pruitt (1977), in FAO-24, was very relevant because it enabled a high degree of accuracy in the quantification of crop water requirements, while at the same time it was easy to use and explain to farmers. However, the information specifically relating to tree crops was based on relatively few scientific studies. Although the review by Allen et al. (1998), published in FAO-56, contributed some general improvements to the methodology, but did not foster any significant improvements in the determination of Kc in tree crops.

There are important differences between the Kc of arable and tree crops. In the first case, the Kc varies seasonally and variance is determined by phenological stage, easily observable, or simply relates to the initial, maximum and final values. The Kc of deciduous tree crops also varies seasonally, but it is affected by other factors such as the treetop structure, density of trees, pruning, thinning, irrigation method, wetted surface during irrigation, area covered by trees, and management of the soil surface, etc. In the case of fully-grown evergreen trees, such as olives and citrus, it is generally necessary to bear in mind the fact that, in addition to the above factors, trees are active throughout the year and therefore the duration of the irrigation campaign is longer (Orgaz et al., 2006).

Based on results from four experiments with four irrigated crops (apples, olive trees, vineyards and walnut trees), Pereira et al. (2006) demonstrated compliance with the following equation: $S = ET_o \cdot A_L / 2.88$ [3], where: S: flow of sap per day and plant ($l \bullet d^{-1}$ $plant^{-1}$); A_L: leaf area of the plant ($m^2 \bullet plant^{-1}$). The sap flow (S) was measured using the compensation heat-pulse technique in order to determine the daily scale. These experiments seemed to confirm that under appropriate irrigation conditions, transpiration per unit leaf area was very similar, despite the different sizes and structures of the tree canopies. Thus, when calculating the water requirements of these fruit crops, the crop coefficient (Kc) can be omitted, although the leaf area (A_L) must be known.

With the help of a lysimeter, in a study conducted over four seasons (1990-1993), Williams et al. (2003) conducted a study that identified the Kc of vines of the Thompson Seedless variety. Over the four seasons, the leaf area of the tested vineyards was also measured. It was observed that differences in water requirements in different years were related to differences in the vegetative growth of vines. One of the conclusions from the study was that Kc experienced a parallel evolution to leaf area. During the four seasons of testing, Kc was linearly related with leaf surface. Continuing the work of their previous study, Williams and Ayars (2005) conducted further research in which, using a lysimeter, they determined the crop coefficient (Kc) and water needs of a variety of vineyards (Thompson seedless) in the San Joaquin Valley (California) for 1998 and 1999 seasons. During the vegetative development over the two campaigns, the leaf surfaces of two vineyards were measured, the corresponding leaf area index (LAI) were calculated, and the shadows generated on the soil at solar noon were measured. The study concludes that, in the vines of the Thompson seedless variety, the surface area of the shadow beneath the vines and the leaf area exhibited a high degree of correlation with Kc, $R^2=0.95$ and $R^2=0.87$ respectively. It should also be pointed out in the conclusion that the linear relationship between the percentage of the shaded area and the crop coefficient (Kc) was very similar to those reported in other studies involving other crops. This could perhaps suggest a universal rule, but this must be confirmed by further studies. Ayars et al. (2003), in a 4 year long study, analysed the crop coefficient (Kc) of a late variety of peach (Prunus persica (L.) Batsch, cultivar O'Henry) using a lysimeter as their main tool. They also measured the interception of sunlight at solar noon using a ceptometer. One of the results obtained was a good correlation between the Kc and the interception of light at solar noon (R^2=0.86).

The ability to simulate the interception of light at the level of the individual tree or in aggregated tree plantations could be a useful tool for creating optimal agronomic designs to achieve high production, high quality fruits and minimum production costs. Along these rows, Green et al. (2003) validated a 3D model of radiation interception and evapotranspiration for two varieties of apple tree and reached the following conclusions: (i) transpiration is primarily influenced by leaf surface and stomatal resistance, (ii) interception of light is primarily influenced by leaf surface and by the optical properties of leaves, and (iii) when comparing the two varieties of apple tree, the shortest was the most compact and efficient for intercepting solar radiation and therefore needed higher doses of water per hectare to sustain productivity.

Goodwin et al. (2006) conducted a short 15–day experiment to observe the effect of water consumption (TWU, Tree Water Use) on progressively pruning the branches of an isolated peach tree (Prunus persica L. Batsch). TWU was measured at 15 minute intervals using 8 sap flow measuring sensors and applying the compensation heat-pulse technique. Pruning was carried out on 5 different days. About a fifth of the total leaf surface was removed in each pruning session. The total leaf surface corresponding to all the branches cut off was measured after each cut. The effective shaded area (EAS, Effective Area of Shade) was derived from digital photographs, image analysis software (ArcView GIS, ESRI, California, USA) and the fraction of PAR (photosynthetically active solar radiation) intercepted by a ceptometer in the shaded area. The coefficient of transpiration (K_{cb}) was calculated from the relationship between TWU and ET_o. The main conclusion was that K_{cb}

= 1.05 *EAS*. The transpiration of an isolated peach tree could therefore be calculated from the ET_o and the effective fraction of shade at the soil surface (EAS). The authors also noted that as pruning significantly changes the relationship between the root and leaf systems, it can modify the pattern of water consumption on unpruned branches.

In line with a study of water needs in olive plantations, Testi et al. (2006) presented and validated a model for simulating the daily evapotranspiration on olive plantations. This model separately calculates transpiration from trees, soil evaporation, and the evaporation of water intercepted by vegetation after rainfall. The calculation of transpiration makes use of weather variables and three additional variables that refer to the structure of the trees and their planting densities. These variables are: volume of trees per unit area, v ($m^3 \bullet m^{-2}$), leaf density, L_d: ($m^2 \bullet m^{-3}$) and tree density (trees • ha^{-1}). Leaf density varies according to tree size (Villalobos et al., 1995; Mariscal et al., 2000) and is estimated from v as follows:

$$L_d = 2 \quad [v < 0.5] \qquad L_d = 2 - \frac{0.8 \cdot (v - 0.5)}{1.5} \quad [v > 0.5] \qquad [4]$$

The volume occupied by the tree corresponds to the volume of the elliptically shaped envelope surrounding the tree. The findings of this study, based on olive trees, were: (i) the model effectively estimated evapotranspiration, (ii) this model constitutes an improvement over previous models as it separates the calculations of evaporation and transpiration and (iii) the model is an interesting tool for the simulation of water needs and for assessing the impact of such variables as location, structure and tree density.

Orgaz et al. (2006) continued previous work and sought an easy and practical way to calculate the water needs of trees in plantations. They presented a methodology based on the daily evapotranspiration simulation model of Testi et al. (2006) combined with the performance of monthly averages for climatological data taken over a period of 20 years and applied in different simulated scenarios. Their methodology proposed using a set of equations and empirical parameters to obtain the monthly crop coefficient (Kc) for olive plantations located in areas with climates similar to the Mediterranean climate of southern Spain (Andalusia). The ultimate goal of this study was to provide optimised irrigation scheduling. Calculation of monthly K_c is designed to be implemented with the minimum amount of easily obtainable data. With regard to data relating to crop characteristics, the variables used are: average volume of treetop per unit area ($m^3 \bullet m^{-2}$), tree density (trees • ha^{-1}) and the fraction of soil cover, equivalent to the ground level projection of the trees.

In one way or the other, the previously mentioned studies highlight the importance of quantifying the plant size i.e. leaf surface (Pereira et. al, 2006; Williams et. al, 2003; Williams and Ayars, 2005; Green et. al, 2003; Goodwin et. al, 2006),shaded area (Williams and Ayars, 2005; Green et. al, 2003; Goodwin et. al, 2006; Orgaz et. al, 2006), interception of sunlight (Ayars et. al, 2003; Goodwin et. al, 2006), volume (Testi et. al, 2006; Orgaz et. al, 2006) and leaf density (Testi et. al, 2006;). In the case of estimating leaf area, the main problem encountered is the lack of quick, easy, cheap and non-destructive methods to make an accurate estimate of the variable in question.

A number of leaves clustered like a deck of cards transpire much less than the same number of leaves separated by a distance of 1m. However, in nature, we find neither the first nor the second case. The first case cannot create leaves that photosynthesize because light does not reach them. In the second case, all the leaves photosynthesize, but there is a high cost in branches that is not compensated by all the leaves conducting photosynthesis. Trees, and plants in general, try to optimize the production of leaves by distributing them so as to capture the maximum amount of light possible and obtain the maximum photosynthetic performance at the minimal cost.

5. Application to Fertilization

Adding a deficitary plant nutrient generally leads to an increase crop yield which offsets the cost of adding extra fertilizer. However, above certain concentrations, the increase in crop yield associated with additional extra nutrients declines. In fact, above a critical concentration, the costs associated with adding extra fertilizer are not offset by improvements in crop yield.

Programming the fertilization of a crop involves deciding which products should be applied, how to apply them, and in what quantities and at what times. All these decisions are intended to carry nutrients to the different parts of the plant in order to ensure the appropriate development of both the plant and the final harvest while at the same time minimizing the environmental impact of fertilization (Coates et al., 2006; Alva et al., 2008). The number and complexity of the processes involved in the transportation of nutrients make organizing an appropriate fertilization programme a rather difficult task.
Poor scheduling of fertilization leads to deficiency or to over-fertilization (Legaz and Primo, 1988; Navarro, 2003; Monge et al., 2007; Raese et al., 2007; Bravdo, 2009; Fernández-Escobar et al., 2009a). Poor plant nutrition produces a reduction in the harvest and, in many cases, in the size and quality of the fruit. On the other hand, excessive fertilization can entail a range of adverse consequences, such as loss of fruit quality, nutritional imbalance due to antagonism with other elements, alterations in the physical and chemical characteristics of the soil, environmental pollution and reduced profitability of the crop.

There are several commonly used methods for programming fertilization and each has its advantages and disadvantages (Sánchez and Curetti, 2009). The most widespread is the Critical Value (CV) method. Macy (1936) presented the concept of the critical concentration of nutrients, establishing the requirement of a minimum concentration of certain elements in the leaves in order to produce a good crop. Ulrich (1948) defined the critical level of nutrients as the concentration range below which plant growth is limited compared with plants with a higher nutrient level. The CV approach provides only an indication of adequacy or deficiency at a single point in time, but it does not provide any specific information on the most appropriate rate of fertilizer application or on its timing.

Another approach is the Nutrient Budgets method, which is based on determining the demand for plant nutrients at every moment in the production cycle. This requires an assessment of the extractions (outputs) and contributions (inputs). The former are associated with such factors as plant growth, fruit harvest (yield), pruning, loss of nutrients through runoff, and leaching etc. The latter relate to land reserves, contributions with water, cover crops, and fertilization etc. It is also necessary to assess the timing of the different demands, to observe and quantify the growth of flowers, fruits, branches and leaves, to estimate reserves and their movements within the plant, and to consider the weather conditions etc. (Muhammad, et al., 2009; Sánchez and Curetti, 2009). Making a geometric characterization during the productive cycle of trees provides an important part of the information required for programming fertilization according to this second method.

A precise geometric characterization of the trees in question is necessary in any research work which seeks to quantify vegetative growth in different fertilization situations (Rufat et al., 2004; Zaman et al., 2005; Dehghanisanij et al., 2007; Fernandez et al., 2009b; Rather et al., 2009; Schumann, 2010). In the scientific literature, there are several references to studies that have investigated the variable application of fertilizers in fruit orchards in terms of crop yields, leaf nutrients, soil nutrients etc. (Salazar and Lazcano, 2003; López et al., 2004). However, very few studies have taken into account the geometric characterization of the trees in order to determine fertilizer needs; amongst other reasons, this is because of the difficulty involved in obtaining accurate measurements.

Zaman et al. (2005), using ultrasonic sensors and a Differential Global Positioning System, calculated the citrus canopy volume and then generated maps for the variable rate application of nitrogen (site-specific applications of Nitrogen). The results of this study indicated that N rates should be calculated considering tree size. Moreover, because many extraneous factors (e.g., rootstock, soil series) can modify tree size, N consumption is only partially dependent on age. Variable rate applications of N ranged from 135 to 270 kg ha^{-1} y^{-1} as opposed to the grower's uniform rate of 270 kg N ha^{-1} y^{-1}. As a consequence a 38% to 40% saving in granular fertilizer was achieved for the studied grove when a variable rate of N was applied on a per-tree basis. At present, similar research is being conducted in Lleida (Spain) in studies of deficitary irrigation and nitrogen fertilization in which one of the pieces of information being used is the geometric characterization of tree test blocks using a LIDAR-based sensor system (Pascual et al., 2011; Rosell et al., 2009a,b).

6. Application to Crop Training

Increases in fruit production per unit area obtained by increasing planting densities have resulted in major changes in the design and management of fruit plantations. This has implied the need to study the behaviour of different training systems for each variety in order to find the one best suited to the agroclimatic conditions of each region. This should facilitate rapid entry into production and guarantee fruit quality and a rapid return on investment.

The top of a fruit tree is a complex system, because it is dynamic and changes shape and function according to its phenological state, cultivation practices and environmental conditions. It is therefore important to understand these processes in order to determine the best means of training and pruning to maximize production. In fruit plantations, the amount of light intercepted by a tree depends on tree density, orientation, size, tree shape and LAI (Robinson and Lakso, 1991).

In red apples, light levels of less than 50% of incident radiation reduce the colour due to a lower concentration of anthocyanins and a higher concentration of total flavonoids (Proctor and Lougheed, 1976; Awad et al., 2001). Besides the reduction in colour formation due to the reduced availability of light, several authors working with red apples have reported a reduction in size, soluble solids content and starch content (Seeley et al., 1980; Robinson et al., 1983; Tustin et al., 1988; Campbell and Marini, 1992). On the other hand, high exposure to solar radiation can cause a condition known as sunscald. This damage has been reported by many authors in various crops (Wade et al., 1993; Dodds et al., 1997; Yuri et al., 2000; Raffo and Iglesias, 2004), causing major economic losses which depend on the climatic characteristics of each season. In apple trees, leaf structure varies according to location on the plant and exposure to light (Faust, 1989). Jackson and Palmer (1977) found that apple leaves that develop in the shade have larger surface areas but are thinner. Barden (1974, 1977) also reported less developed palisade tissue and lower specific weight (mg • cm^{-2}), net photosynthesis rates and rates of transpiration. Leaves that grow exposed to the light achieve the maximum rate of photosynthesis with a 45-55% rate of incident light, while those growing inside the cup do so with lower rates of around 30% of incident light. When values of incident light do not reach these percentages, the rate of leaf photosynthesis is reduced, producing fewer photoassimilates (Faust, 1989). Raffo et al. (2006) confirm that light intensity decreases as it reaches the interior of the cup. Small trees therefore present a smaller canopy volume and have a lower proportion of leaves receiving less than 30% of incident light. This favours a good differentiation of floral buds which improves the setting, colour and soluble solids content of fruit (Doud and Ferree, 1980; Raffo et al., 2006).

The appropriate training of fruit trees is essential to ensure a suitable distribution of light within the treetops. This also helps to prevent the appearance of shady areas and areas with excessive radiation and helps to ensure fruit quality and quantity. There are many works that study the different training systems, but few are using 3D geometric characterization tools for conducting these studies. Below are some references to recent researches studying the relationship between light interception and the 3D shape of trees.

A simplified method for building 3D mock-ups of peach trees is presented in Sonohat et al. (2006). The method combines partial digitizing of tree structure with reconstruction rules for non-digitized organs. Reconstruction rules make use of allometric relationships, random sampling of shoot attribute distribution and additional hypotheses (e.g., constant internode length). The method was quantitatively assessed for two training systems (tight goblet and wide-double-Y), at a range of spatial scales. For this purpose, light interception properties of reference and reconstructed mock-ups were compared. The proposed method could therefore be used to make 3D tree mock-ups usable for a range of some, but not all, light computations. Because the simplified method allows large time savings, it could be used in virtual experiments requiring large numbers of replicates, such as comparative studies of tree genotypes or training systems.

Light models for vegetation canopies based on the turbid medium analogy are usually limited by the basic assumption of random foliage dispersion in the canopy space. The objective of Sinoquet et al. (2005) was to assess the effect of three possible sources of non-randomness in tree canopies on light interception properties. For this purpose, four three-dimensional digitized trees and four theoretical canopies - one random and three built from fractal rules - were used to compute canopy structure parameters and light interception

In the study conducted by Potel et al. (2005), three groups of six 13-year-old individual plants of apple cv. Golden Delicious trained under vertical axis, drilling and Ycare were subjected to digital imaging in 2004 and 2005. Through a method of measurement developed by the INRA (Centre of Clermont-Ferrand, France), it was possible to obtain an exact 3D reproduction of the trees. Light was analysed using the silhouette to total area ratio for each shoot, obtained by simulation, which characterized precisely the distribution of light in the tree. The results highlight the importance of the annual conditions in the evolution of leaf area. The illumination of the potential fruiting points becomes insufficient when the LAI exceeded 3, which was the case for all the systems in 2005. The value LAI recorded for the drilling system was particularly high (4.3) and the consequences of shading were particularly perceptible, with a reduction of 53% in generative shoot illumination.

Simple models of light interception are useful to identify the key structural parameters involved in light capture. Sinoquet et al. (2007) developed such models for isolated trees and tested them with virtual experiments. Light interception was decomposed into the projection of the crown envelope and the crown porosity. The latter was related to tree structure parameters. Virtual experiments were conducted with 3D digitized apple trees grown in Lebanon and Switzerland, with different cultivars and training. The digitized trees allowed actual values of canopy structure (total leaf area, crown volume, foliage inclination angle, variance of leaf area density) and light interception properties (projected leaf area, silhouette to total area ratio, porosity, dispersion parameters) to be computed, and relationships between structure and interception variables to be derived. The projected envelope area was related to crown volume with a power function of exponent 2/3. Crown porosity was a negative exponential function of mean optical density, that is, the ratio between total leaf area and the projected envelope area. The leaf dispersion parameter was a negative linear function of the relative variance of leaf area density in the crown volume. The resulting models were expressed as two single equations. After calibration, model outputs were very close to values computed from the 3D digitized databases.

The above exposed studies make it clear that the availability of measurement tools that allow a precise geometric characterization of the plant material, as shown in Fig.7, will facilitate and enhance the work of researchers in tree crop training systems.

7- Conclusions

The analysis of the different existing detection systems to characterize the 3D structure of tree plantations shows the existence of several aspects that limit the use of most of the systems under field conditions, remaining, finally, a small group of sensors suitable for this purpose. Laser scanners and stereo vision are direct competitors and are probably the most promising and complementary techniques for achieving 3D maps of plants and canopies, although ultrasonic sensors remain an attractive option for certain applications. In fact, the possibilities of combining sensors for this purpose are innumerable. In the near future, it is highly likely that we will see a notable advance in this field of research with increased use of the new generation of Flash LIDAR sensors, capable of measuring 3D structures of plants in real time and at a moderate cost compared to alternative detection systems. As regards agricultural applications, the chapter dedicated to the application of PPP has demonstrated the importance of knowing the density of the different elements of a tree for the correct determination of the application rate. It has also been highlighted the usefulness of using pictograms to facilitate the quantification of the density of the plantations. However, it has become clear that there is still a long way to be done and both the geometric characterization of crops as well as variable application techniques must be improved. The coordinated use of multiple sensors, the development of new real-time data processing algorithms and the simplification of crop adaptable application systems are objectives for the future of this research line. The studies that relate irrigation with the geometric characterization of tree crops and vines highlight the importance of quantifying the plant size i.e. leaf surface, shaded area, interception of sunlight, volume, and leaf density. Also, a precise geometric characterization of trees is necessary in any research work which seeks to quantify vegetative growth in different fertilization situations. In the scientific literature, there are several references to studies that have investigated the variable application of fertilizers in fruit orchards in terms of crop yields, leaf nutrients, soil nutrients etc. However, very few studies have taken into account the geometric characterization of the trees in order to determine fertilizer needs; amongst other reasons, this is because of the difficulty involved in obtaining accurate measurements. Therefore, obtaining a precise geometrical characterization of a crop at any point during its production cycle by means of a new generation of affordable and easy-to-use detection systems, such as LIDAR and stereo vision systems will help to establish precise estimations of crop water needs as well as valuable information that can be used to quantify its nutritional requirements. If accurate, this can provide valuable information on which to base more sustainable irrigation and fertilizer dosages. These would be able to meet crop needs and could also be used as part of specific management systems, based on prescription maps, for the application of variable quantities of water and fertilizers. The appropriate training of fruit trees is essential to ensure a suitable distribution of light within the treetops. This also helps to prevent the appearance of shady areas and areas with excessive radiation and helps to ensure fruit quality and quantity. Many research works are being conducting about the different training systems, but few are using 3D geometric characterization tools for conducting these studies. The availability of measurement tools that allow a precise geometric characterization of the plant material will facilitate and enhance the work of researchers on tree crop training systems.

Therefore, in the near future, the evolution and development of new sensors devoted to the geometric characterization of tree crops will enable significant and much needed advances in optimizing the use of PPP, fertilizers and water in agriculture as well as increase in production and quality by improving training systems. It should be borne in mind that the benefits of this work affect millions of cultivated hectares and therefore impact directly on the society and the environment in which we live. It is therefore of vital importance to continue devoting major efforts to the development of increasingly accurate, robust and affordable systems capable of measuring the geometric characteristics of plantations, which support the development of the different areas of a sustainable and precision agriculture.

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FIGURES

Fig. 1. Photography of an AccuPAR Ceptometer, model LP-80 (Decagon Devices, Inc.) showing the 84 cm. length sensing probe consisting of 80 light sensors.

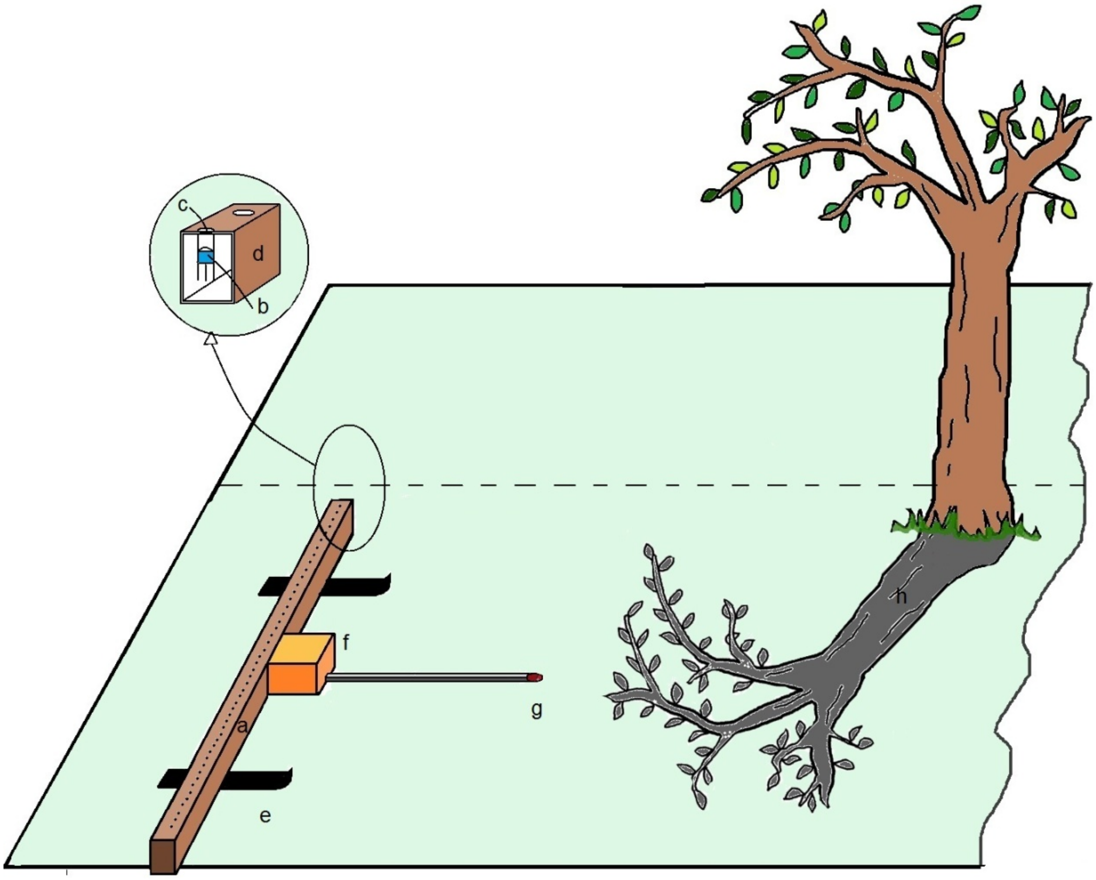

Fig. 2. Light sensor scanner for monitoring the light-shadow windows of plants. a) bar with light sensors; b) light sensor (NPN silicon phototransistor); c) Teflon® layer; d) aluminium frame; e) sledge; f) data logger and multiplexer; g) push-button; h) plant shadow projection (adapted from Giuliani et al., 2000).

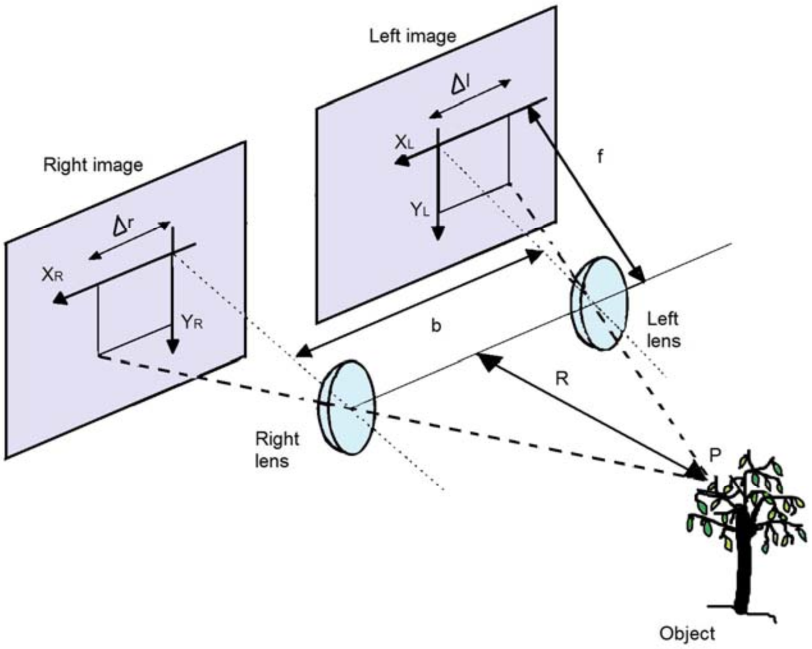

Fig. 3. Illustration of the basic geometrical variables involved in the determination of the 3D spatial coordinates of a point P by stereovision techniques: b, baseline and distance from the two camera's lenses centres; f, lens' focal length; R, range; P, transformed point; Δr, horizontal position of point P in the right stereoimage; Δl, horizontal position of point P in the left stereoimage. The distance R of the sensed point to the camera can be calculated as $R = \frac{bf}{dw}$, where d is the disparity value, d = Δl-Δr, and w is the size of the pixel in mm. Known R, the 3D spatial coordinates of the sensed point, P, can be calculated using similar geometrical relationships (adapted from Rovira-Mas et al., 2005).

Fig. 4. Ultrasonic and LIDAR sensors mounted on a tractor.

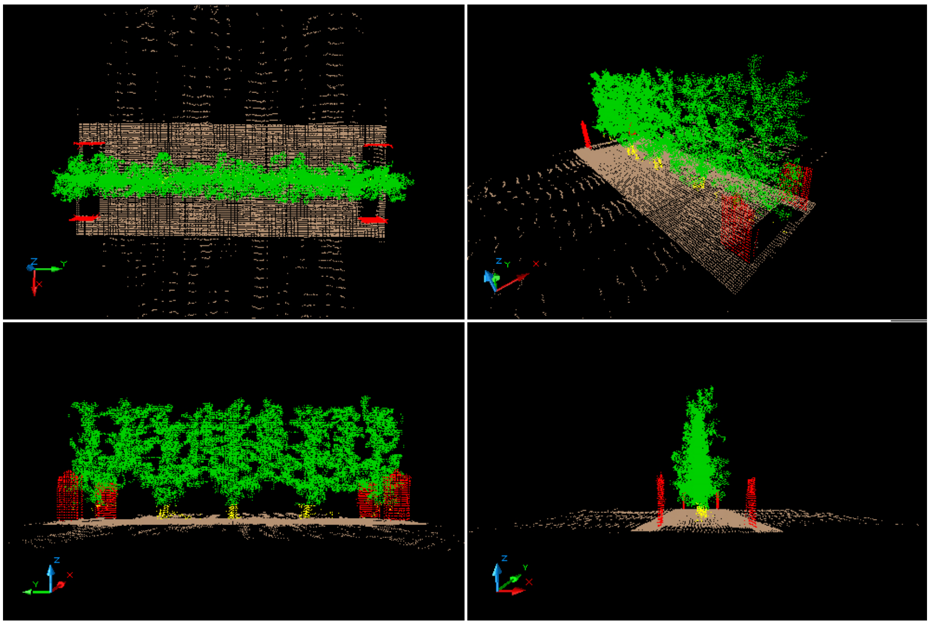

Fig. 5. Different views of the 3D structure of the pear orchard shown in the picture above obtained with a terrestrial LIDAR system (Rosell et al., 2009a).

Fig. 6. Variable dose Sprayer equipped with ultrasonic and LIDAR sensors for the electronic characterization of tree crops. This prototype automatically adjusts the applied dose rate in a continuous variable real-time mode accordingly to the crop geometry information supplied by the embedded sensors.

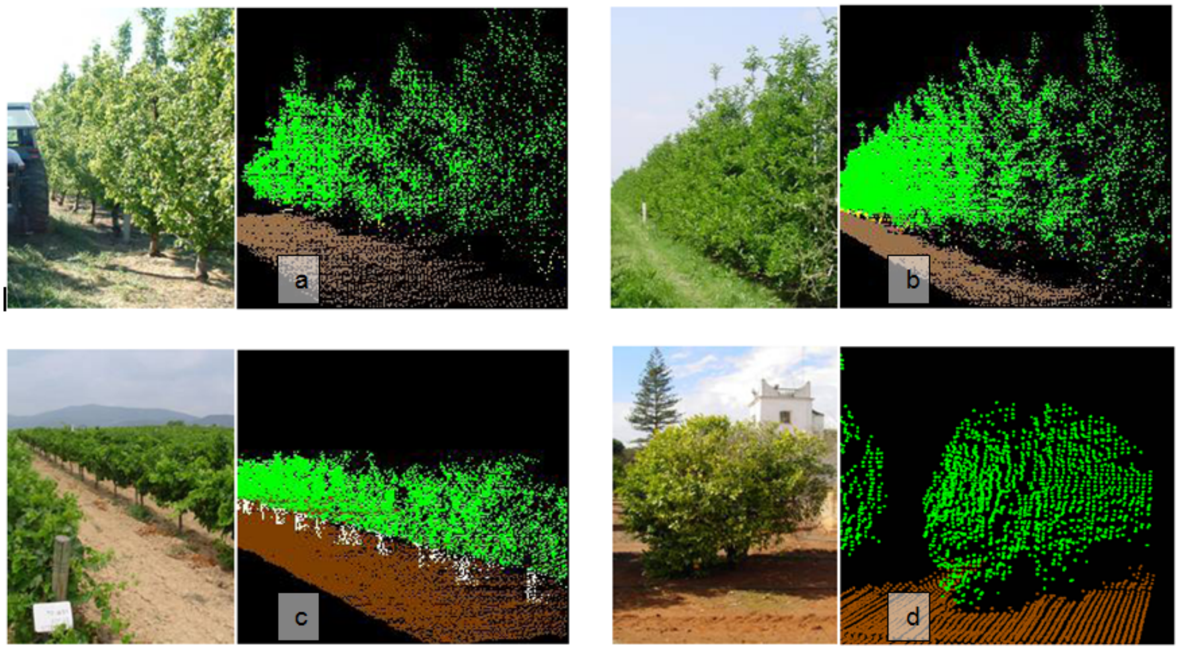

Fig. 7. Pictures of different crop training systems and their corresponding 3D images obtained by a LIDAR system: pear trees (a), apple trees (b), vineyards (c) and citrus trees (d) (Rosell et al., 2009a).

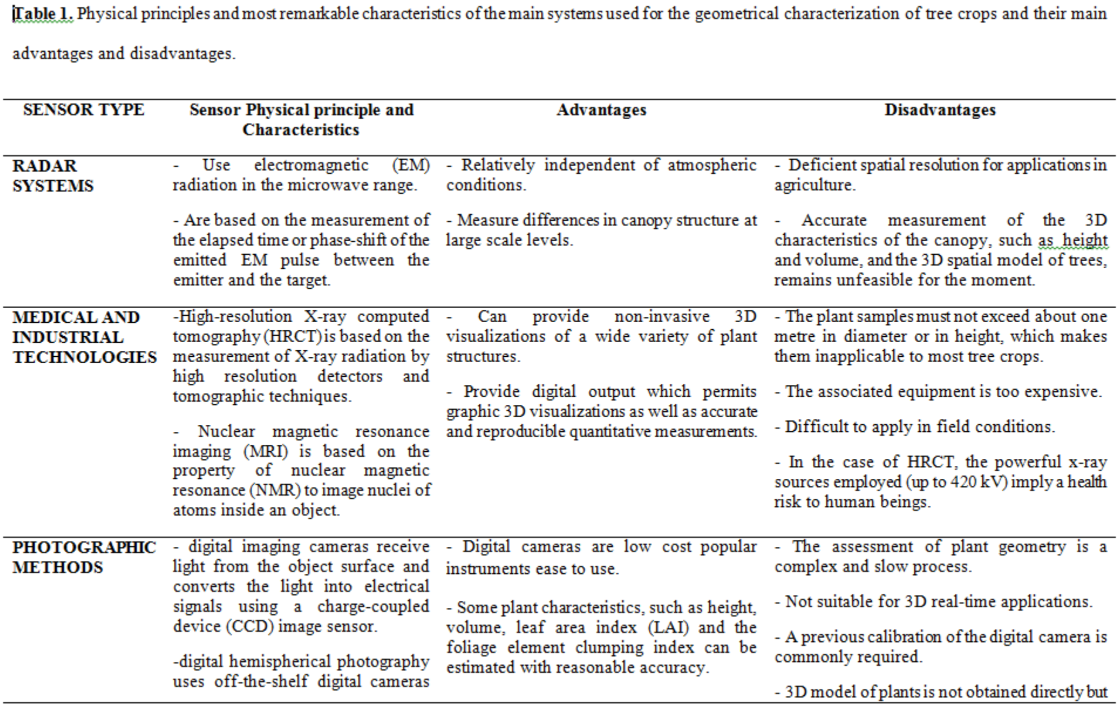

Table 1. Physical principles and most remarkable characteristics of the main systems used for the geometrical characterization of tree crops and their main advantages and disadvantages.

SENSOR TYPE	Sensor Physical principle and Characteristics	Advantages	Disadvantages
RADAR SYSTEMS	- Use electromagnetic (EM) radiation in the microwave range. - Are based on the measurement of the elapsed time or phase-shift of the emitted EM pulse between the emitter and the target.	- Relatively independent of atmospheric conditions. - Measure differences in canopy structure at large scale levels.	- Deficient spatial resolution for applications in agriculture. - Accurate measurement of the 3D characteristics of the canopy, such as height and volume, and the 3D spatial model of trees, remains unfeasible for the moment.
MEDICAL AND INDUSTRIAL TECHNOLOGIES	-High-resolution X-ray computed tomography (HRCT) is based on the measurement of X-ray radiation by high resolution detectors and tomographic techniques. - Nuclear magnetic resonance imaging (MRI) is based on the property of nuclear magnetic resonance (NMR) to image nuclei of atoms inside an object.	- Can provide non-invasive 3D visualizations of a wide variety of plant structures. - Provide digital output which permits graphic 3D visualizations as well as accurate and reproducible quantitative measurements.	- The plant samples must not exceed about one metre in diameter or in height, which makes them inapplicable to most tree crops. - The associated equipment is too expensive. - Difficult to apply in field conditions. - In the case of HRCT, the powerful x-ray sources employed (up to 420 kV) imply a health risk to human beings.
PHOTOGRAPHIC METHODS	- digital imaging cameras receive light from the object surface and converts the light into electrical signals using a charge-coupled device (CCD) image sensor. -digital hemispherical photography uses off-the-shelf digital cameras	- Digital cameras are low cost popular instruments ease to use. - Some plant characteristics, such as height, volume, leaf area index (LAI) and the foliage element clumping index can be estimated with reasonable accuracy.	- The assessment of plant geometry is a complex and slow process. - Not suitable for 3D real-time applications. - A previous calibration of the digital camera is commonly required. - 3D model of plants is not obtained directly but

Table 2. Two different mathematical models to express the application doses of PPP in tree crops.

Dose Expression	Nomenclature
$Dose = \frac{Q \cdot 600}{a \cdot v}$ [1]	Dose: volume of application (l • ha^{-1}) Q: flow rate (l • min^{-1}) a: width of distribution (m) v: speed (km • h^{-1})
$Dose_t = 2 \cdot LAI \cdot D_i \cdot 4/3 \cdot \pi \cdot (d/2)^3 \cdot 10^{-7}$ [2]	$Dose_t$: Theoretical volume or dose to be applied (l • ha^{-1}). LAI: Leaf area index (dimensionless). D_i: Optimal density of impacts per unit area.(droplets/cm^2) d: Average diameter of the applied droplets, expressed as the volume median diameter, VMD (μm).

Table 3. R^2 of linear regression analysis between the deposition of the product and the calculation functions of *a*.

Model that uses:	**R^2**
Width between the rows	0.089
Height of the plant wall	0.347
Square root of the cross-sectional area	0.373
Surface of cross section and the distance between rows	0.434
Tree Area Index	0.626
Tree Area Density	0.780
Light Interception Flux	0.520

Table 4. Techniques for variable dose PPP application systems.

Varying the speed of the treatment machine
Varying the flow from the nozzle
Varying the flow from the nozzle and also automatically changing it for others with higher or lower flow rates
Varying the amount of the active substance injected into the carrier substance, which is usually water, just before the emitting nozzle (Ess et al., 2001a; Humburg, 2003)
Using modulated spraying nozzle control (MSNC) (Ess et al., 2001b)