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Improvement of spray application process in greenhouse tomato crop: assessment of adapted spraying technologies and methods for canopy characterization

Jordi Llop Casamada

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PhD Dissertation

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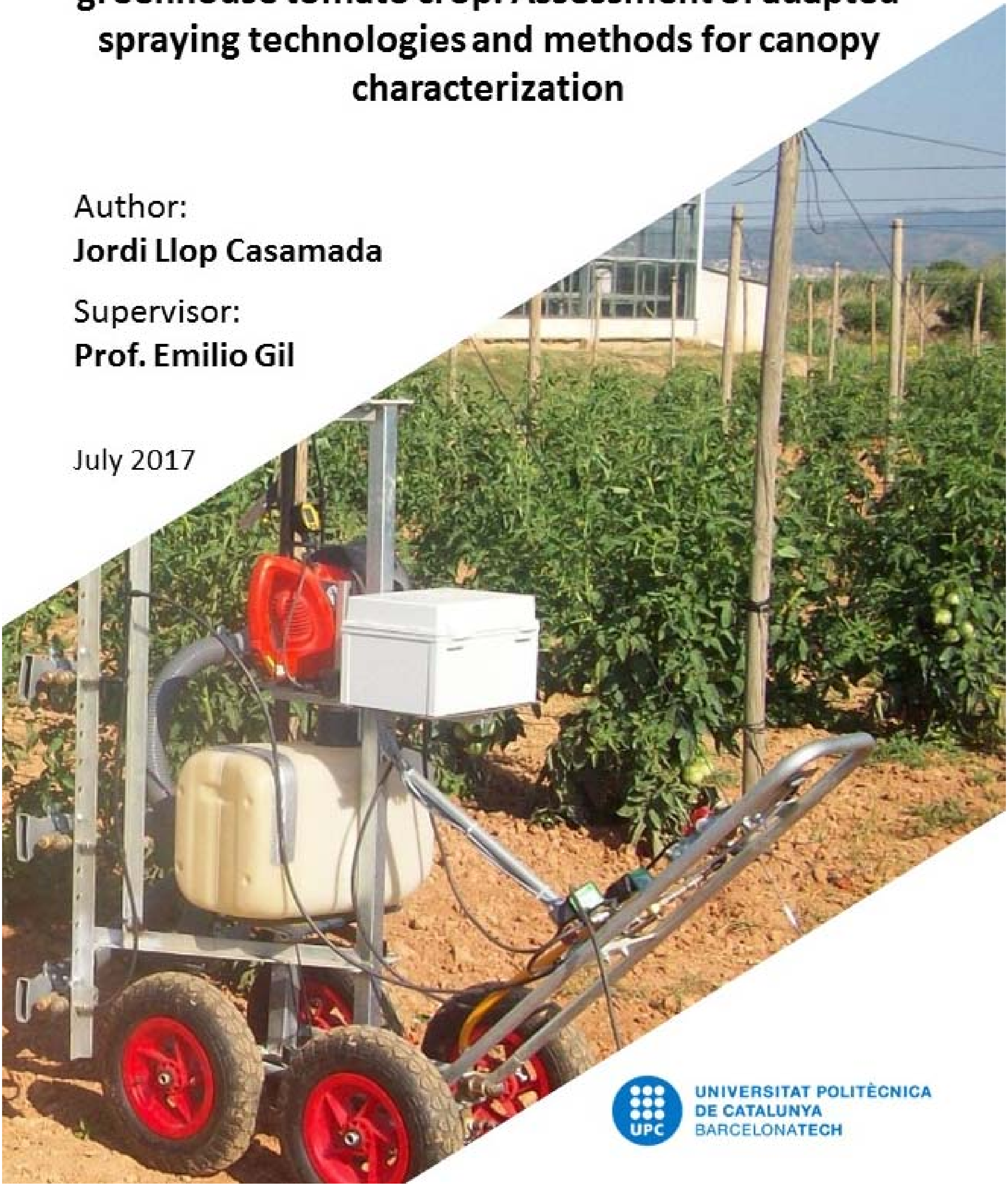
July 2017



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UNIVERSITAT POLITECNICA DE CATALUNYA

Programa de doctorat Tecnologia Agroalimentària i Biotecnologia

Thesis by compendium of publications

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July 2017

A la meva estimada Elena i als meus estimats Raimon i Ignasi

Resum

La producció de vegetals en hivernacle representa una activitat econòmica i productiva important en l'agricultura del Sud d'Europa. Un dels factors de més risc que afecta aquesta activitat està directament relacionat amb l'ús de productes fitosanitaris. La tecnologia més utilitzada per a l'aplicació d'aquests productes són les pistoles i llances de polvorització. Tot i això, diversos estudis han demostrat que, en comparació amb les pistoles, l'ús de carretons de polvorització amb barres verticals millora la distribució de la polvorització i redueix els costos de treball i el risc d'exposició de l'operari. D'altra banda, la caracterització del cultiu és un factor clau per a millorar el procés de polvorització optimitzant l'ajust de la dosificació de producte, permetent una reducció considerable de la quantitat total de pesticida, incrementant l'eficiència del procés general.

El principal objectiu d'aquesta tesis és millorar l'eficiència del procés d'aplicació de pesticides en hivernacles adaptant la polvorització a la vegetació a través de dues accions: a) afegint assistència d'aire a un carretó amb barres verticals arrossegat manualment, i b) desenvolupant un mètode per a la caracterització de la vegetació. En aquesta investigació s'han avaluat l'adequació i beneficis d'un nou prototipus de carretó amb assistència d'aire en comparació amb la tecnologia utilitzada habitualment. En relació a les característiques de la vegetació, s'ha desenvolupat una nova metodologia per a ser aplicada en tomàquet produït en hivernacle.

La incorporació d'aire es va provar en un carretó de polvorització modificat. Aquesta va ser avaluada en dues vegetacions diferents (alta i baixa densitat) i amb varies configuracions diferents (tipus de broquet, assistència d'aire i volum d'aplicació). Per a aquest estudi es va avaluar la deposició de producte en el cultiu, el recobriment i la uniformitat de la distribució. La deposició en les fulles i la penetració en el cultiu utilitzant broquets de ventall i assistència d'aire és significativament més alta en els volums d'aplicació alt y baix. La deposició obtinguda amb el sistema de referència a volum d'aplicació alt en comparació al carretó amb aire i volum d'aplicació baix no presenta diferències significatives. En general

l'assistència d'aire i els broquets de ventall permeten reduir el volum d'aplicació mantenint la qualitat de la distribució de la polvorització.

D'altra banda, també en el cultiu de tomàquet en hivernacle, es va avaluar la influència de la assistència d'aire en la polvorització amb tres màquines diferents: 1) un carretó de polvorització modificat amb assistència d'aire alt i baix; 2) un polvoritzador autopropulsat; 3) un polvoritzador controlat per radio control. Tots els polvoritzadors van ser avaluats considerant la deposició de producte en la vegetació i la seva uniformitat, i les pèrdues al sòl. A més a més es va avaluar la distribució vertical del líquid i de la velocitat de l'aire i es va comparar amb els perfils de vegetació i de distribució de la deposició. Els resultats indiquen que un increment de la velocitat de l'aire no implica una millora de la eficiència de la polvorització. En general, el carretó modificat mostra millors resultats en termes de deposició i uniformitat de la distribució, especialment amb assistència d'aire baix. Aquests resultats han estat confirmats a través de la avaluació de la uniformitat de la distribució de l'aire i el líquid.

Les característiques del cultiu s'han determinat amb un sensor terrestre LiDAR 2D. Els experiments es van realitzar en tres cultius diferents de tomàquet en hivernacle plantats en sistema de parelles. La caracterització electrònica es va realitzar amb un sensor LiDAR (LMS 200, SICK) de 180º d'angle de mesura, escanejant cada parella de plantes per les dues cares de la vegetació. Els paràmetres principals mesurats van ser: alçada, amplada i volum del cultiu i àrea foliar. A partir d'aquestes dades es van poder calcular altres paràmetres importants com el Tree Row Volume (TRV), el Leaf Wall Area (LWA), l'index d'area foliar (LAI) i l'índex de densitat foliar (LAD). En general els resultats mostren una sobre estimació dels paràmetres obtinguts amb els mètodes manuals a causa de l'elevada resolució del perfil a través del sensor. L'alçada de la vegetació, el volum i la densitat es poden estimar de forma fiable a través del volum de vegetació obtingut amb el sensor. Aquest sensor permet la avaluació de la variabilitat de la vegetació al llarg de la fila, sent això important per a la generació de mapes de vegetació.

La determinació de la quantitat de pesticida a aplicar per a un adequat control de plagues i malalties s'ha d'ajustar segons la quantitat de vegetació. El desenvolupament de tècniques que permetin determinar els principals paràmetres del cultiu de manera ràpida i fàcil, així com el desenvolupament de tecnologies que permetin una distribució més eficient del producte, són fonamentals per a una millor aplicació d'aquests productes.

Resumen

La producción de vegetales en invernadero representa una actividad económica y productiva importante en la agricultura del Sur de Europa. Uno de los factores de más riesgo afectando los parámetros económicos, medioambientales y productivos está directamente relacionado con el uso de productos fitosanitarios. La tecnología más usada para la aplicación de estos productos son las pistolas y lanzas de pulverización. Aun así, diversos estudios han demostrado que, en comparación con las pistolas, el uso de carretillas de pulverización con barras verticales mejora la distribución de la pulverización y reduce los costes de trabajo y el riesgo de exposición del operario. Por otro lado, para mejorar el proceso de pulverización, la caracterización del cultivo es un factor clave en un mejor ajuste de la dosificación del producto, permitiendo una reducción considerable de la cantidad total de pesticida, incrementando la eficiencia del proceso.

El principal objetivo de esta tesis es mejorar la eficiencia del proceso de aplicación de pesticidas en invernaderos adaptando la pulverización a la vegetación mediante dos acciones: a) añadiendo asistencia de aire a una carretilla con barras verticales arrastrada manualmente, y b) desarrollando un método para la caracterización de la vegetación. En esta investigación se ha evaluado la adecuación y beneficios de un nuevo prototipo de carretilla con asistencia de aire comparada con la tecnología utilizada habitualmente. En relación a las características de la vegetación, se ha desarrollado una nueva metodología para ser aplicada en tomate de invernadero.

La incorporación de aire se probó en una carretilla de pulverización modificada. Ésta fue evaluada en dos vegetaciones diferentes (alta y baja densidad) y con varias configuraciones distintas (tipo de boquilla, asistencia de aire y volumen de aplicación). Para este estudio se evaluó la deposición de producto en el cultivo, el recubrimiento y la uniformidad de la distribución. La deposición en las hojas y la penetración en el cultivo utilizando las boquillas de abanico y asistencia de aire es significativamente más alta en los volúmenes de aplicación alto y bajo. La deposición obtenida con el sistema de referencia a volumen de aplicación alto en comparación a la carretilla con aire y volumen de aplicación bajo

no presenta diferencias significativas. En general la asistencia de aire y las boquillas de abanico permiten reducir el volumen de aplicación manteniendo la calidad de la distribución de la pulverización.

Por otro lado, también en cultivo de tomate en invernadero, se evaluó la influencia de la asistencia de aire en la pulverización con tres máquinas diferentes: 1) una carretilla arrastrada manualmente con asistencia de aire alta y asistencia de aire baja; 2) un pulverizador autopropulsado; 3) un pulverizador controlado por radio control. Todos los pulverizadores se evaluaron considerando la deposición de producto en la vegetación y su uniformidad, y las pérdidas en el suelo. Además se evaluó la distribución vertical del líquido y de la velocidad del aire y se comparó con los perfiles de vegetación y de distribución de deposición. Los resultados indican que un incremento de la velocidad del aire no implica una mejora de la eficiencia de la pulverización. En general, la carretilla modificada muestra los mejores resultados en términos de deposición y uniformidad de la distribución, especialmente con asistencia de aire baja. Estos resultados han sido confirmados mediante la evaluación de la uniformidad de la distribución del aire y del líquido.

Las características del cultivo se han determinado con un sensor terrestre LiDAR 2D. Los experimentos se realizaron en tres cultivos distintos de tomate en invernadero plantados en sistema pareado. La caracterización electrónica se realizó con un sensor LiDAR (LMS-200, SICK) de 180º de ángulo de medida, escaneando cada pareja de plantas por las dos caras. Los parámetros principales medidos fueron: altura, anchura y volumen del cultivo y el área foliar. A partir de estos datos se pudieron calcular otros parámetros importantes como el Tree Row Volume (TRV), el Leaf Wall Area (LWA), el Indice de Area Foliar (LAI) y el índice de densidad foliar (LAD). En general los resultados muestran una sobreestimación de los parámetros obtenidos con los métodos manuales debido a la alta resolución del perfil medido por el sensor. La altura de la vegetación, el volumen y la densidad se pueden estimar de forma fiable a través del volumen de la vegetación obtenido con el sensor. Además este sensor permite la evaluación de la variabilidad del dosel a lo largo de la fila, siendo importante para la generación de mapas de vegetación.

La determinación de la cantidad de PPP a aplicar para un adecuado control de las plagas y enfermedades se debe ajustar según la cantidad de vegetación. El desarrollo de técnicas que permitan determinar los principales parámetros del cultivo de forma rápida y fácil, así como el desarrollo de tecnologías que permitan una distribución eficiente del producto, son fundamentales para una mejor aplicación de estos productos.

Abstract

Vegetable production in greenhouses is an important and productive economic activity for agricultural businesses in Southern Europe. One of the most risky factors affecting economic, environmental, and production issues in covered horticulture is the use of plant protection products (PPP). Historically, spray guns and lances have been the most common technologies used for this purpose. However, several studies have demonstrated that the use of vertical boom sprayers in greenhouses has several advantages over that of traditional spray guns, such as improved spray distribution, reduced labour costs, and reduced operator exposure. On the other hand, canopy characterization is important for a better adjustment of the amount of pesticide/mixture sprayed, and is a key factor in spray process improvement. When this adjustment is adapted to canopy characteristics, it enables a significant reduction in the quantity of PPP used, which increases the efficiency of the process.

The main objective of this doctoral thesis is to improve the efficiency of the pesticide application process for greenhouse crops by modifying the crop spraying method. To achieve this objective, two actions were planned. The first involved adding an air assistance device to a manually pulled trolley with vertical booms, and the second involved developing a method for canopy characterization. Therefore, this research evaluated the suitability and benefits of the developed prototype with air assistance, and compared those characteristics with common spray techniques already in use. With regard to the canopy characterization process, a new methodology based on LiDAR technology has been developed to be applied to tomato crops in greenhouses.

The effect of the addition of the air assistance device was tested on a modified prototype hand-held pulled trolley sprayer. This prototype was evaluated using two different crop fields (tomato with high and low canopy density) and several sprayer types (nozzle type, air assistance, and spray volume). In this study, deposition on the canopy, deposition coverage, and deposition distribution uniformity have been assessed. The deposition values on a leaf and the penetration of the spray inside the canopy were significantly higher when flat fan nozzles and air assistance

were combined, regardless of the amount of liquid applied. On the other hand, similar values of deposition and penetration were obtained when applying low volumes of liquid with air assistance and when applying high volumes of liquid without air assistance. These results allow us to conclude that air assistance and flat fan nozzles reduce volume rates while maintaining or improving spray quality distribution.

Furthermore, the influence of air-assistance characteristics on spray application was evaluated. For this reason, field tests were arranged for three different sprayers. The first sprayer is a modified commercial hand-held trolley sprayer with two air assistance options (high velocity and low velocity), the second is a self-propelled sprayer specifically designed for greenhouse pesticide applications, and the third is an autonomous self-propelled sprayer commanded by remote control. These three sprayers were evaluated by examining normalised canopy deposition and uniformity, as well as liquid losses to the ground. In addition, the vertical liquid distribution and the vertical air velocity profile of the sprayers were assessed and compared with the obtained canopy profiles and spray depositions. The results indicated that increasing the air velocity does not increase the efficiency of the spray application. In general, the modified hand-held trolley sprayer showed the best results in terms of deposition and uniformity of distribution, especially at the lowest air assistance rate. These results were confirmed through an evaluation of air uniformity and liquid distribution.

For the development of the methodology for canopy characterization, a terrestrial 2D Light Detection and Ranging (LiDAR) sensor was used to compare its results to the results obtained by traditional manual vegetation measuring procedures. The experiments were carried out in three different commercial tomato greenhouses, all of which contained crops planted in a twin-row system. Electronic characterization was performed using a LiDAR sensor (LMS-200, SICK) with an 180° angle measurement by scanning a pair of plants from both sides. The main parameters obtained were canopy height, width, and volume, and leaf area. From these parameters, other important parameters were calculated. These parameters include tree row volume (TRV), leaf wall area (LWA), leaf area index (LAI), and leaf area density (LAD). A general overview of the results showed an overestimation of the parameters measured manually because of the high definition of the profile obtained with this sensor. An estimation of the canopy volume with the electronic device was shown to be a reliable method for estimating the canopy height, volume, and density. This method also was able to assess the high variability of the canopy density along a row, proving to be an important tool for canopy map generation.

The determination of the amount of PPP necessary for adequate control of pests and diseases should be adjusted according to the characteristics of the subject canopy. Advancements in spraying techniques that enable fast and robust characterization of major canopy parameters, and advancements in efficient spray distribution technology are essential for improved pesticide spray applications.

Acknowledgements

Amb aquest document es tanca un període molt important de la meva vida, que comprèn una amplitud de mires molt més enllà del que és l'estudi presentat en aquesta Tesi. Perquè la persona és un tot, tesi, família, universitat, amics, coneguts, activitats, voluntariats.

Durant el 6 anys que ha durat la matrícula del doctorat he tingut la sort de participar en molts projectes. Això m'ha dut a viatjar per tot Espanya i part d'Europa. De preparar i realitzar assajos de camp, de formar tècnics i agricultors......Tot això a estat possible gràcies a treballar a on ho faig, a la UPC, al DEAB, a la Unitat de Mecanització Agrària, amb l'Emilio Gil. És per això que el primer agraïment més profund és per l'Emilio: Director exigent, compassiu, amic.

Mi ámbito profesional te lo debo en gran medida a ti. Tú me has abierto las puertas a un mundo en el que gozo de trabajar. Creo que las palabras quedan cortas para agradecer todo este tiempo. Si algo debo destacar es que me has conocido lo suficiente para darme la libertad que necesitaba para trabajar a mi manera y que de siempre has conocido mi punto débil, ¡conocer el mundo a través de la gastronomía!

Durant aquest temps he tingut la sort de treballar al costat de dos grans companys, dos grans amics: en Jordi Llorens i la Montse Gallart. Gràcies per estar sempre al meu costat i estar disponibles en tot moment.

Una menció molt especial a en Miquel Masip. Amb ell hem construït els prototipus. Per totes les hores invertides gratuïtament en això, i les estones viscudes a l'Agropolis. Gràcies per cuidar-me i recolzar-me sempre.

També vull agrair a tota una colla de companys de camí en la vida universitària i pre-tesica. Dani Fenero, Joan Simó, Ana Rivera, Aurora Rull, Marga Lopez, Ari Giné, Míriam Pocurull, Joan Casals, Graciela Marando, Maria Julià, Sheila Alcalà. Amb tots i cadascun de vosaltres he viscut diferents moments i etapes d'aquest procés. Em crescut plegats en aquest món de la recerca i la docència, i us vull agrair les converses, recolzaments, desesperacions, emocions, estones compartides. Podria escriure amb cadascú de vosaltres unes quantes experiències viscudes.

A la Mireia Ercilla, Jordi Zagarriga, Marcel Valera, Ricard Velez, Javi Campos, Ramon Salcedo, Paula Ortega. Lo que he arribat a gaudir de la vostra companyia no té límit. Gràcies per tantes hores de camí sempre preparats per riure, discutir (i molt Mireia), aprendre, créixer i donar-ho tot en qualsevol moment i en les condicions que sigui.

Al Professore Paolo Balsari per la gran ayuta in tutto momento di tanti anni di lavoro assieme e in particolare per permetirmi fare una stada di riccerca con il suo team e imparare tanto. Anque grazzie al equipo di lavoro delle DISAFA (Dipartimento di Scienze Agrarie, Forestali e Alimentari) Mario, Paolo, Gianluca e specialimente a Marco Grella. Per la vostra recivuta duranti la meva stanza con voi e il lavoro fatto.

Als companys que ens hem creuat en diferents etapes de la vida i que d'una manera o altre han deixat la seva petjada en mi: Clara Almansa, Marçal Plans, Cristina Gonzalez, Xavi Portell, Tania Bayer, Claudia Carvalho, Monica Rinaldi, Mariana Rodriguez.

En el decurs dels assajos que conformen aquesta tesis, també hi han participat moltes persones. Gràcies Raúl Garcia, Pol Puigoriol, Antonio Miranda (gracias por desencallar en último artículo).

A la empresa Syngenta SAU por patrocinar el desarrollo de esta tesis y los trabajos realizados en ella bajo la Catedra Sygenta-UPC (www.catedrasyngenga.upc.edu). Concretamente quiero agradecer a German Canomanuel y a Paco García su respaldo personal durante todo este tiempo. Por tantos quilómetros realizados juntos y buenos ratos vividos. También hago extensible este agradecimiento al equipo de personas de la empresa que me han acompañado durante este tiempo.

A la Laura, el Pablo, el Miguel i al Mario, a l'Ana i el Xurde, a la Fani, el David i la Laia, a la Carlo, el Pru i en Jan, a la Monica i l'Oriol, a la Lucia i la Sora. Gràcies per acompanyar-me i recolzar-me durant tot aquest temps.

Al Julio, al Borja, al Ferran, al Jose, al Xavi R., al Xavi G., al Jesús i la Míriam, a l’Anna, al Dani. Gràcies per simplement ser al meu costat durant aquest llarg periple.

Al Joan, a la Laura, a la Clara, en Pau i en Quim, a la Carla, la Vivi, el Marc i la Lila. Pas a pas, fill a fill, ens heu anat recolzant en tot lo viscut. Gràcies.

A la Blanca, el Yeyu, a la Inés, el Jaume i el Tomàs, a la Cris, a l’Andrés i el Pablo. Gràcies per haver-me acompanyat pacientment en aquest camí que va començar al mateix temps que vaig conèixer l’Elena. Gràcies per ajudar-nos a viure el dia a dia quan la feina de la tesis em retenia.

Al Papa, la Mama, la Núria, el Joan, la Maria i l’Arnau, la Montserrat, el Jordi, el Jaume i la Mercè, la tieta Mercè i la tieta Montserrat, al tiet Ramon i la tieta Dolors. Sembla que sí, que ha arribat el dia. Escrigui el que escrigui sempre es quedarà curt al costat del que sento. Gràcies per la vostra incondicionalitat.

A la meva estimada Elena, i els meus estimats Raimon i Ignasi. Vosaltres mes que ningú heu patit les conseqüències d’aquesta etapa de la meva vida. Gràcies per la comprensió, pel gaudiment en les alegries d’aquest camí i per contenir la desesperació de veure com això s’ha anat allargant.

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ABBREVIATION	DESCRIPTION
AEPLA	Asociación Empresarial para la Protección de las Plantas
BMP	Best Management Practices
CAS	Crop Adapted Spraying
ECPA	European Crop Protection Association
EFS	Exposed Foliar Surface
IPM	Integrated Pest Management
LAI	Leaf Area Index (adim)
LAD	Leaf Area Density ($m^2 \cdot m^{-3}$)
LWA	Leaf Wall Area (m^2 vegetation$\cdot ha^{-1}$)
PPE	Personal Protective Equipment
PPP	Plant Protection Product
PRV	Plant Row Volume (m^3 vegetation$\cdot ha^{-1}$)
SUD	Safe Use Directive
SUI	Safe Use Initiative
TOPPS	Train Operators to Promote best management Practices & Sustainability
TRV	Tree Row Volume (m^3 vegetation$\cdot ha^{-1}$)

1. Introduction

Fresh vegetable production in Southern Europe is an important and productive economic activity. In particular, production in greenhouses represents one of the most important agricultural businesses in Spain, Italy, and France (EFSA, 2010).

Information on the most suitable conditions for pesticide distribution, optimal application amount, and most appropriate spray technique are key contributing factors for the success of any pesticide application process.

The level of awareness among politicians and citizens in the European Union regarding environmental conservation and the protection of the human health is the basis for the definition of best management practices (BMP) in crop protection. For this reason, Sustainable Use Directive (SUD) 2009/128/CE (European Parliament, 2009a) "*establishes a framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides*". The achievement of this purpose is focused on different subjects, such as Integrated Pest Management (IPM) of the crops, operator training, and inspection of sprayers in use, among others.

The use of plant protection products (PPPs) is one of the factors affecting the economic, environmental, and productive parameters in covered horticulture production. Operator safety, residue on produced food, and economic investment are problems linked to this specific and necessary labour, and most of them are directly linked to the technology used (Nilsson and Balsari, 2012; Pergher et al., 1997).

Operator exposure during the application of PPPs is especially critical in greenhouses. In general, the high-volume application rates used to distribute pesticides, combined with low air recirculation and high temperatures inside greenhouses, generate a hazardous environment for the operator. Therefore, an accurate selection of the most suitable spray technology and an adequate selection of the most suitable personal protective equipment (PPE) are key factors that can reduce the exposure risk.

The most common spraying equipment used in Spanish greenhouses is the hand-held spray gun and spray lance (Valera et al., 2014). This simple equipment exemplifies a worst case scenario in crop protection: low spray deposit uniformity on the canopy and significant losses to the ground. This combination creates a high exposure risk for the operator (Sánchez-Hermosilla et al., 2012). Improvements in greenhouse spraying techniques are focused on hand-pulled trolleys with vertical booms. This equipment improves the uniformity of the spray distribution compared to spray guns (Sánchez-Hermosilla et al., 2012). In addition, these trolleys are always behind the operator, which reduces exposure risk.

In order to improve pesticide application efficiency, it is important to adapt the spray to the characteristics of the canopy. The selection of the main parameters involved in the calibration process (volume application rate, nozzles, pressure, etc.) should be based on the target structure. Most pesticide applications are made to control pests and diseases located on top of or below the leaves in the crop. One of the most interesting parameters used to define the canopy is the leaf area surface. A good indicator of this parameter is the Leaf Area Index (LAI). However, determining its value is difficult and requires the destruction of the plant leaves. For successful application, it is necessary to adjust spraying parameters to the shape of the canopy, which is very difficult to define and can vary across a field and along a single row. In this context, it is necessary to develop techniques that allow for quick and simple determinations of the main parameters that define foliar structure and its distribution.

1.1. Legislative framework

The use of PPPs in agriculture is under continuous review to avoid human and environmental risks derived from its use. To that end, the European Commission promotes the safe use of pesticides across several European directives. The major relevant European directives are as follows: 2009/128/CE for the sustainable use of pesticides (European Parliament, 2009a), Directive 2009/127/EC amending Directive 2006/42/EC concerning machinery for pesticide application (European Parliament, 2009b), Regulation No. 1107/2009 concerning the placing of PPPs on the market, and repealing Council Directives 79/117/EEC and 91/414/EEC (European Parliament, 2009c). These directives and regulations address different aspects involved in pest and disease control, such as the management of pesticide containers, the control of the application process or operator risk assessment, and the control of the sprayer manufacturing process.

Regulation 1107/2009 (European Parliament, 2009c) harmonizes the conditions and procedures for the authorization, evaluation, and commercialization of newly developed PPPs. In addition, this regulation establishes a forbidden active ingredients list to control threats to the environment and human health. This regulation also defines operator exposure level, active ingredient toxicity, residuals, and efficacy. This risk has relevant importance in greenhouse applications where spraying conditions are critical for temperature, humidity, and inhalation exposure.

SUD 2009/128/CE (European Parliament, 2009a) guarantees the best use of PPP while also ensuring the best interests of the environment and human health are considered. The actions defined in this EU directive are made for a sustainable use of pesticides involving all stakeholders of the PPP use. Training is one of the most important aspects considered in this EU directive that involves all the subjects concerning from the operator needs to the commercialization of products. Spraying machinery has to pass mandatory inspections to ensure that the parts are functioning properly so that the quality of the spray is not affected, as well as to ensure that the environment is protected while it functions. One of the main goals of this EU directive is the reduction of the amount of PPP used in farming. In this sense, integrated management of the pests and diseases accompanies training, sprayer inspections, and best management of the products.

Spray drift and point source contamination derived from erroneous management of spray technology, is a basic concept involved with contamination risk to the watercourse. One of the most effective ways to avoid this contamination risk is to train operators in BMPs for pesticides (Gil et al., 2008). The selection of the most suitable spraying technology and the use of a precise calibration process are important for the reduction of waste products. This is the most commonly recommended approach for adjusting the volume application rate to the characteristics of a particular canopy.

The proper calibration and inspection of sprayers serves as a foundation for the efficient use of these technologies. Those procedures allow for a reduction in product losses, which can affect neighbouring fields, urban areas, and watercourses.

Mandatory inspections are focused on all factors of a spraying system that influence the quality of the application. Proper functioning of the impulsion devices, regulation system, nozzles, and the pressure losses on the sprayer will affect the spray. In addition, the state of the mixture tank, pipes, and hoses can directly affect the environment due possible leakages in case of wrong functioning of these parts.

In this sense, Directive 2009/127/EC (European Parliament, 2009b) regulates the manufacturing process for newly manufactured sprayers. This directive revises Directive 2006/42/EC (European Parliament, 2006) by introducing elements for the protection of the environment and operator safety aspects. The requirements of this EU directive specify which machinery must comply before being placed on the market and/or put into service for a pesticide application.

After the official publication of the two above mentioned European directives, the SUD, and the Machinery Directive amendment, the European Commission addressed a formal request to CEN (European

Committee for Standardization) for the development of harmonized standards to fulfil the mandatory request of the inspection of sprayers in use. The fulfilment of Annex II of the SUD Directive, related to inspection of sprayers in use, is made according the ISO 16122-1 (ISO 2015a) series, extending the field crop (ISO 16122-2 (ISO, 2015b)), bush tree crop (ISO 16122-3 (ISO, 2015c)) and semi-mobile and fixed installations (ISO 16122-4 (ISO, 2015d)).

The application of EU directives is mandatory for European Union member states, and must be adopted into local legislation within two years. The transposition of Directive 2009/128/CE for the sustainable use of pesticides into Spanish legislation was accomplished through two national royal decrees. RD 1702/2011 (Ministerio de Medio Ambiente, 2011) focused on the inspections of sprayers in use, and RD 1311/2012 (Presidencia, 2012), where all the mandatory requirements of the SUD other than the inspection of sprayers in use are recovered. These two royal decrees have been the foundation for the development of the mandatory National Action Plan (MAGRAMA, 2012). This plan defines general and particular objectives, determines the actuations for each objective and the defined indicators to measure each actuation, and the adoption of a calendar for the accomplishment of the objectives.

1.2. Technical considerations for greenhouse production

Greenhouse production represents an important source of income in countries with favourable climatic conditions for its use. According to EUROSTAT statistics (http://epp.eurostat.ec.europa.eu), the area devoted to protected crop cultivation in European Community member states is roughly 150,000 ha. The countries with the highest areas under protected cultivation are Spain (66,000 ha), Italy (34,600 ha), France (11,400 ha), the Netherlands (10,200 ha), Poland (6,300 ha), and Greece (4,900 ha).

The 65,000 hectares of greenhouse surface in Spain are distributed between horticulture, flowers, ornamentals, and plant nurseries. The main crops are tomato (6,617 ha), pepper (4,361 ha), strawberry (4,267 ha), banana (2,967 ha), cucumber (1,729 ha), watermelon (1,588 ha), nursery (1,460 ha), raspberry (1,347 ha), and flowers and ornamentals (1,184 ha) (ESYRCE 2013). Three areas (Andalucía, Comunitat Valenciana, and Región de Murcia) concentrate 67% of the vegetable production, as well as the 60% of greenhouse crop production. Only one province—Almeria, Spain—locates 47% of its total production in greenhouses (MAGRAMA, 2014).

PPP use in Spain is concentrated in specific areas. For example, 30% of the cultivated surface consumes 66% of commercialized PPP (MAGRAMA, 2013), overlapping with the vegetable production areas mentioned in the previous paragraph. Figure 1 shows that areas with high PPP consumption are located close to the Mediterranean Sea, where fruit crops and vegetables are mainly produced. The high rotation rate of horticultural crops due to short growing periods (i.e. lettuce) plus the high production quantity per unit surface (i.e. tomatoes produced in greenhouses) leads to this high consume of PPP on this areas.

Figure 1. Map of the main vegetable production areas with PPP consumption. Source: MAGRAMA (2014).

PPP use in tomato production has a significant impact on production costs (Figure 2). After the labour cost (31% of the total costs), crop protection is the highest expense, representing 14% of the total cost. Seeds and fertilizers also have a large impact on cost.

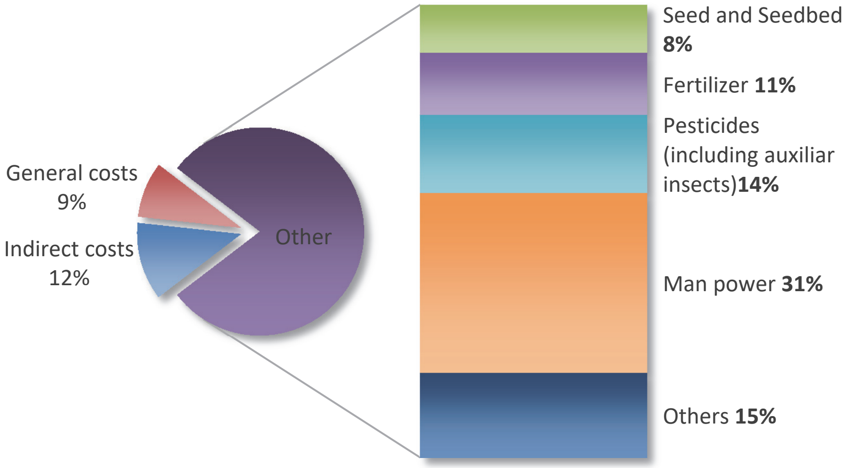

Figure 2. Distribution of production costs for a long tomato cycle. Source: Mercados (2014*).*

Valera et al. (2014) published a study characterizing the production methods used in the most productive greenhouse areas in Almeria. This study was based on a survey. The interest in evaluating this region lies in the fact that it has the highest concentration of greenhouses in Spain, and serves as a reference for crop production across the country. In this study, it is possible to observe the evolution of the spraying techniques used in greenhouses. In 1997, 94.1% of the farmers in Almeria used spray guns or lances for crop protection. After 20 years, the use of this technology has been reduced by approximately 28.7%, going to 65.4% of the farmers (Figure 3). As an alternative to spray guns, 16.3% of farmers are using the cannon mist blower. This equipment can reduce the exposure risk of the farmer, but also presents a low uniformity distribution across each single crop row. Only 8% of farmers use mobile trolleys with vertical booms, which is the most suitable equipment for vertical crops produced in greenhouses. Meanwhile, although the number of hectares using different spraying techniques has increased, there still a large percentage of farmers using a simple spray gun.

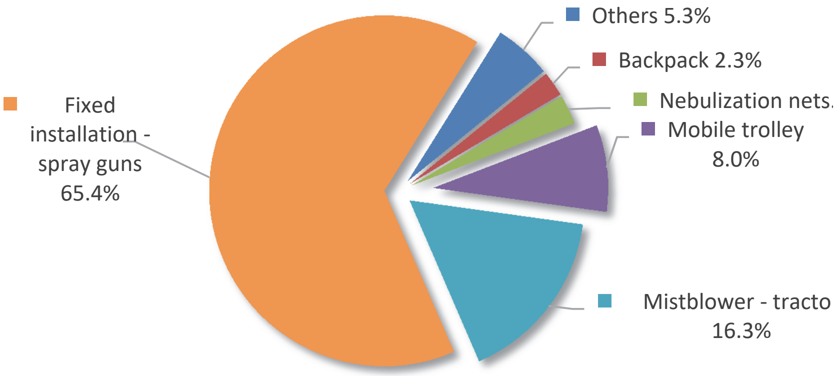

Figure 3. Percentage distribution of sprayer types used in the Almeria region. Source: Valera *et al.* (2014*).*

The type of soil used in greenhouses strongly influences the acceptance of a developed application technique, considering the spray gun or lance and simple and basic tool. The most common type of soil in greenhouses in Almería is “enarenado” (multilayer soil with a top layer of sand), which comprises 80% of the surface (Valera et al., 2014). In some regions of Spain, the presence of natural soils is also close to 80%. However, for manual pulled trolleys, this fact can be a problem because the wheels of the sprayers can stick to the sand, and farmers complain about how difficult it is to pull the heavy trolley and pipe.

1.3. Safe use of pesticides

The safe use of pesticides concern a wide range from environmental care (water conservation) to human health (bystanders and operators safety). Contamination prevention and safe work conditions became the top goals for BMPs in agriculture.

1.3.1. Best management practices for PPPs

The inappropriate use of PPPs can result in environmental degradation through watercourse contamination. In Spain, several hydrographic basin are controlled to detect the presence of PPPs. Each hydrographic basin river publishes this information in public sources, and current data shows that the presence of some active ingredients from pesticides in watercourses is substantial (http://www.datossuperficiales.chebro.es). Several factors can contribute to this contamination, such an improper sprayer rinsing procedure, a mismanagement of buffer zones areas, poor sprayer calibration, or various meteorological conditions. Each of these examples can cause PPP drift or run-off.

A European initiative promoted by the ECPA (European Crop Protection Association) is the TOPPS project (Train Operators to Promote best management Practices & Sustainability) (www.topps-life.org). This project promotes BMPs for the reduction in watercourse contamination risk, as well as risk to human health and the environment. The contamination of water sources with PPP can be caused by point sources (Gil et al., 2008) or run-off and drift (Balsari et al., 2014). The effect of source contamination risk depends on the characteristics of the target crops, which can include arable crops, bush crops, or greenhouse crops.

A greenhouse is a closed room with atmospherically controlled conditions. Because the wind inside the room is depreciable in terms of pesticide application, and because the evaporation of PPP is confined to the walls and roof of the greenhouse, the main sources of risk contamination are point sources. In addition, the combination of high numbers of PPP sprays per season and low efficiency techniques (high losses to the ground) contribute to the increased risk of contamination. In the PPP manipulation process (Gil et al., 2008), the riskiest actions related to environmental contamination are the preparation of the mixture, the application of the pesticide, and the management of the remnants.

Two of the most frequently recommended BMPs are sprayer calibration and volume application rate adjustment based on canopy characteristics (Gil et al., 2008). In this sense, a successful calibration process (which involves appropriate nozzle selection, pressure, and forward speed) and the selection of an adequate spraying technique will lead to the optimal use of the pesticide.

The management of pesticide remnants on the main tank, pipes, and hoses after the spray process is completed is an important element to consider in greenhouse production. In contrast to mounted or self-propelled sprayers that can travel to a rinsing point, greenhouse sprayers are either fixed or semi-mobile installations. This means that the main tank is stationary on one side of the greenhouse, and pesticides are delivered through a network of pipes (which can be longer than 200 m) and distributed over the crop using different technology. In an attempt to fulfil the SUD Directive, the TOPPS project promotes measures to achieve safe management of pesticide remnants.

1.3.2. Operator risk exposure

The operator has a steady role every time the PPP has to be used. The operator is involved the process from beginning to end, from the point of sale to the application to destruction of the packing. In many situations, the operator is exposed to the PPP, which poses an injury risk. In the spray application process, many factors must be considered from the point of view of the operator, such as environmental conditions, sprayer calibration, or sprayer technique. Identification of the contamination source and identification of the appropriate PPE needed in each situation is crucial for reducing exposure risk.

Operator exposure to contamination from PPP can occur through the skin (which is the most common method), by inhalation, or by accidental oral ingestion. Confined spaces or sprays with a large amount of inhalable particles are serious inhalation contamination routes. Small particles 5–30 microns in size tend to get trapped in the nose (nasopharyngeal region), but smaller particles 1–5 microns in size can be deposited in the tracheal and bronchiolar regions, posing a more serious health risk to the operator and any bystanders in the area (Mathews and Hislop, 1993).

Operator exposure in greenhouses during spraying activities largely depends on the spraying technology used (Nuyttens et al., 2004a). In this study, five greenhouse technologies were tested by four different experienced operators. The equipment included a standard spray gun, a spray lance (forward and backward), a self-propelled sprayer, and a manual trolley. The potential dermal exposure was determined at 15 different locations on a coverall with patches of known area. The coverall covers the operator from head to toe.

The results of the study show that even when using the same technique, the skill of the operator has a large effect on the results. Taking the spray gun as the standard spray technique (set to 100% as the default potential), the forward spray lance presents a 216% chance of exposure, while spraying backward reduces the chance to 32%. The manual trolley (4%) and the self-propelled sprayer (1%) present a drastic reduction in potential dermal exposure.

When using the spray gun and spray lance, the highest exposure areas were on the feet and legs, and the lowest (but still considerable) exposure areas were on the hands, forearms, and head. Depending on which side of the row was sprayed first, the exposure on the left or right side of the body will be considerably higher than on the side that was not sprayed first. When using the hand-held trolley and the self-propelled sprayer, the highest potential exposure was observed on the hands.

Using a knapsack sprayer on tomatoes produced in greenhouses, Ramos et al. (2010) also found the highest values of potential exposure on the forearms and lower legs during the application process. The same study compared the three main operations (mix/load, application, and re-entry).

The authors identified the mix and loading operation as the highest exposure actions and the most unsafe operating scenario. This result is important, considering workers rarely use protective gloves during this operation.

Because of the high exposure risk in greenhouses during pesticide applications, the ECPA started the Safe Use Initiative (SUI) project to promote safer management practices (http://www.ecpa.eu/stewardship/stewardship-activity/safe-sustainable-use-initiative). The main objective of SUI project was to encourage safer use of pesticides in Southern European countries. The pillars to reach this objective where the introduction of innovative spray equipment and the training of the operators through training courses and documentation.

A pilot version of the SUI project was incorporated in a Spanish area (2002–2006) with a high greenhouse concentration. The objectives of the project are listed below:

- Reduce operator potential exposure by introducing novel spraying technologies into farms.
- Reduce dermal and inhalation exposure by means of adequate personal protection elements.
- Reduce the environmental impact of the management of pesticide product waste cans.

Under project UMI (Unit Motorized for greenhouses) (www.proyectoumi.es/), the AEPLA association (Asociación Empresarial para la Protección de las Plantas) promoted the pilot version of the SUI project. The fundamental goal of the project was the same as SUI project, but it focused on the implementation of novel technology to reduce operator exposure. The main idea was to promote the use of the manual trolley with vertical booms as the most effective spraying technology for reducing operator exposure and improving spray distribution.

As described in the UMI project, the main advantages of this technology over a traditional spray gun included high spray efficacy, which is achieved through the uniformity of the deposition on the canopy, an increase in product penetration, and a reduction in ground losses. In addition, the spray cloud is always positioned behind the operator, which reduces the exposure risk. The same hose used for the spray gun feeds this trolley, which means that no special adaptations were needed to incorporate the manual trolley.

1.4. Spraying technology in greenhouses: A review

1.4.1. State of the art

The spray application technologies used in greenhouses include a wide range of devices (hand operated, tractor mounted, self-propelled, fixed or semi-mobile sprayers) whose designs range from simple and cheap to complex and expensive. Normally, simple technology involves manual application of some sort, wherein the operator has a strong influence on the efficiency of the spray. Complex technology, on the other hand, incorporates the use of autonomous systems or self-propelled devices.

One of the most difficult elements of spray application in greenhouses is the adjustment of the main parameters to control the volume application rate. In manual operated devices (knapsacks, spray guns, etc.), is very difficult to maintain a constant forward speed of the operator that influences the control of the volume rate. In addition, the lack of knowledge about the flow rate of the nozzles also comprises the adjustment of the calibration parameters.

In this context, training farmers and operators in BMPs related to these technologies is important for optimal and efficient use of PPPs, and to ensure safe environmental conditions for humans.

A wide range of spray technology used in greenhouse pesticide applications are presented below. This technology includes spray guns and lances, knapsack sprayers, cannon sprayers, fogger sprayers and vertical boom sprayers.

1.4.1.1. Spray guns and lances

Hand-held spray guns and lances are the most widely used pesticide application tools in greenhouses, despite their heavy weight and high exposure risk potential (Foqué et al., 2012b).

The droplets are generated by a hydraulic nozzle without transport assistance, mounted on a semi-mobile or fixed installation. This installation is composed of a stationary unit (fixed or tractor mounted) with a moving part (usually a pipe laid along the greenhouse and open field) (ISO, 2015a).

A semi-mobile sprayer is composed of several parts: a main tank, a pump (activated by an electric or combustion engine), a regulator system (manometer, main valve, pressure regulator and pressure compensator), a pipe that distributes the liquid along the greenhouse (can be fixed or mobile), and an individual connection for the feeding of the hose where the gun or lance is connected (Sánchez-Hermosilla et al., 2012).

There are a wide range of options for spray gun and spray lance output patterns. These options include a flat fan and a double flat fan pattern, a hollow cone pattern with a variable flow rate, several mounted nozzles (Figure 4), and a centrifugal nozzle.

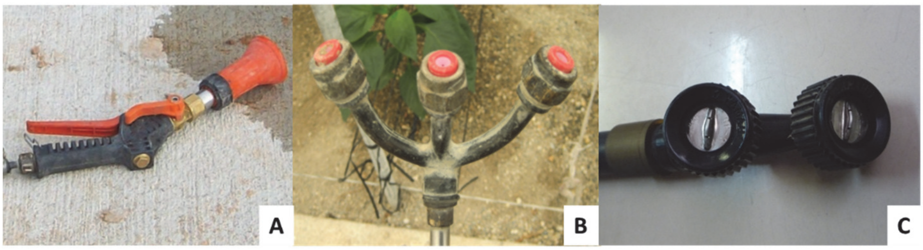

Figure 4 Types of spray output mounted in spray guns or lances: a) hollow cone variable flow nozzle; b) three fixed nozzles; c) double flat fan nozzle.

Using a spray lance for horizontal crops (such as Ivy crops (*Hedera helix*) which are grown in 13 cm diameter pots, Foqué et al. (2012b) resulted in a high uniform distribution with a horizontal boom, despite using high pressures and volume application rates.

Other authors reported the low uniformity spray distribution generated by spray guns in several crops. These crops included poinsettia (Derksen et al., 2010), lettuce (Langenakens et al., 2002), tomato (Nuyttens et al., 2009, 2004b, Sánchez-Hermosilla et al., 2013b, 2012), Ivy (Braekman et al., 2009), and strawberries (Braekman et al., 2010).

Spray guns and lances used in tomato crops present low spray uniformity on canopy distribution. Sánchez-Hermosilla et al. (2013b) tested the effect of pressure spraying by using a lance configuration with a twin flat fan nozzle at three pressures (10, 15, and 20 bar) on a tomato crop with two developmental growth stages (1.47 m and 2.67 m height). In general, the deposition on the canopy was 22.5–34.6% lower at 20 bar than at 10 or 15 bar. The uniformity of the spray was influenced by the type of lance used and the spraying technique of the operator. The penetration inside the crop was lower when using a 20 bar pressure because the small droplet size has small inertial momentum. In a fully developed canopy, the penetration was 50% of the total sprayed product to the inner part of the canopy, with an average volume application rate of 1,608 $L \cdot ha^{-1}$. In addition, the losses to the ground presented high values of deposition. These deposition values ranged up to 2.5 times greater than the low growth stage and 2.2 times greater than a fully developed growth stage.

Spray guns and lances are the most common equipment used in greenhouse-produced crops. As shown before, the use of this equipment presents a low uniformity spray distribution. The pressure affects this distribution, and high pressures (20 bar) are less effective. The pressure reduction supposes a benefit for equipment maintenance. In addition, the proportion of small droplets generated by the spray guns and lances will be reduced, thereby improving the protection of the operator (reduction in oral ingestion exposure risk). Losses to the ground are very large when spray guns and lances are used. These losses are a source of potential water contamination, and represent a loss of product.

1.4.1.2. Knapsack sprayers

A common piece of equipment used for pesticide application in many diverse crops is the knapsack sprayer. These sprayers usually consist of a 15-liter human-mounted tank, a piston pump or diaphragm pump, an air chamber, a hose connected to a hand-held lance with a valve, and one or more hydraulic nozzles. Most knapsack sprayers are manually operated with a lever, but there are some configurations where the pump is activated by a fuel engine. In addition, knapsack sprayers contain mist blowers with a pneumatic droplet generation.

One of the most complex elements of these sprayers is the calibration. Because the sprayer follows the operator, it is very difficult to maintain a constant forward speed or a constant pressure (especially in lever-operated sprayers). This affects the selection of the flow rate, depending on the nozzle type and volume rate.

All of these variations (forward speed, pressure, flow rate, spray pattern) highlight the importance of finding a harmonization system to characterize nozzle behaviour. Balsari et al. (2012) tested eight nozzles with different spray patterns by measuring droplet size and flow rate variation. A significant result is that the nozzles did not have any indication about their nominal flow rate defined by the manufacturer. In addition, the nozzles with adjustable flow rates generated substantial problems on reproduce the flow rate each different time. Increasing the flow rate increased the size of the droplets, which was not expected based on the information provided by the manufacturer.

Llop et al. (2014) reproduced similar tests with another set of nozzles. Their results showed that the flow rate increased from 45–72% in the worst case scenario. As the angle of the cone was reduced, the droplet size (VMD) was almost constant at approximately 150 µm, except in the last step of the adjustment nozzle where in some cases the droplet size was 700 µm.

Concerned with the difficulty associated with knapsack sprayer calibration, Bjugstad and Skuterud (2009) proposed the need to control the application to ensure good spraying quality. They proposed that this could be accomplished through proper calibration of the sprayer, movement of the nozzle, spray coverage, and correct pesticide dosage. The most important factor is that the operator should be skilled in how to perform a precise and safe application.

Due to this problems of calibration, and because knapsack sprayers are the most widely used sprayer used in developing countries (Mathews and Hislop, 1993), a significant effort has been made to incorporate this sprayer and train operators in its use. Part of this effort involved the creation of the web site, https://www.pesticidewise.com/, which is promoted by Syngenta SAU. This website functions as an easy training tool for operators, and contains a systematic procedure that teaches them how to calibrate the sprayer and how much PPP should be mixed in the tank.

1.4.1.3. Cannon mist blower

The cannon mist blower used in greenhouse pesticide spraying is characterized by liquid and air canalization through one single output (sometimes two or three, but always smaller than the main output). The sprayer is composed of a main tank with a regulator system fitted on the same frame as the spraying output, and it is activated by a tractor. The air generated by the cannon is made by a centrifugal fan connected to a single conduction that directs all the air to one single output. This output produces air at a velocity of approximately 19,000 $m^3 \cdot h^{-1}$ at a working distance of up to 50 m (Pulverizadores Fede S.L., Hardi-international, A/S).

This type of sprayer is mainly used in nursery growers, tall tree plantations, public parks, and gardens, where all of the plants are placed in pots close together. Cannon sprayers applied in greenhouses can be used primarily in two ways. One way involves spraying from the main corridor to the adjacent aisles, and the other way involves spraying from the outside of the greenhouse through a window (Figure 5).

Figure 5 Cannon mist blower applications: A) spraying from outside of the greenhouse; B) spraying tall trees.

Douzals et al. (2010) evaluated the effect of product (water or oil) sprayed with a cannon mist blower on an open field. No essential differences were noted between either product with regard to spray target distribution. However, significant variability was noticed on deposits along the target in a triangular distribution. The highest values were discovered 8 m away from the spray output (Figure 6). This distribution illustrates the complexity required to obtain a uniform distribution. The results showed a spray recovery (collected fraction) of approximately 45–60% of the total volume sprayed, indicating that a substantial amount of product is lost.

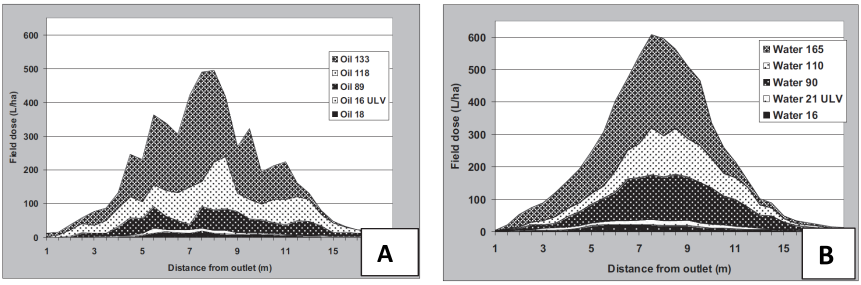

Figure 6 Deposit pattern of cannon mist blower for oil (A) and water (B). Source: Douzals et al. (2010).

Garzón et al. (2000) tested a cannon mist blower in greenhouses. The trials were performed in a greenhouse without any crops; therefore, a canopy was simulated with a pole with three positions in height. The sprayer was a cannon mist blower fitted with six nozzles working at 20 Bar and emitting product at a 70 L·min^{-1} flow rate. The air generated was 12,500 m^{3}·h^{-1}, and the output was positioned at a height of 1.8 m. The results present a higher deposition on the middle and top sampling positions than at the bottom. In addition, the distribution along one row presented high variation where the highest values were obtained, which was close to the output and at the furthest positions. On the other hand, no differences appeared in upper and lower leaf deposition. This is explained by the presence of air assistance. In addition, significant losses to the ground were observed. As a general conclusion, the cannon mist blower presents a low uniformity distribution on the canopy and great losses to the ground.

In spite of these results, this spraying technique allowed the farmers to complete the spraying procedure faster than they could using hand-operated alternatives. In some cases, the cannon is used from the outside the greenhouse because the architecture of the greenhouses and the layout of the crop. In these cases, the exposure risk decreases because of the significant distance between the operator and the sprayer output.

1.4.1.4. Fogging sprayers

There are many techniques available to generate fog for pesticide applications. Some require a special pesticide formulation because of the principle of function of the fogging sprayers (aerosols “bombs”, smoke generators and micronized dusts). Most of these techniques are forbidden due to the toxicity of the pesticide product (Mathews and Hislop, 1993).

Thermal foggers and cold foggers are the main pieces of equipment used for fog spray. The thermal fogger is characterized by its ability to inject PPP into very hot gas (500 °C), causing it to vaporize into droplets under 15 µm in size. Because this technique produces droplets at this size, it is recommended for greenhouses or warehouses. One of the main problems is that some active ingredients are degraded at these high temperatures. The mobility of the sprayer frame has a determinant effect on the distribution of the product. Systems that are semi-mobile present low uniformity distribution. The fixed systems are superior unless the spray is distributed by an air assistance system.

Several techniques can generate the same effects as thermal foggers without the need for heat. The current systems used are high pressure systems, low pressure systems, and air-water systems (Sánchez-Hermosilla et al., 2013b). The air-water systems uses twin fluid nozzles that combine the PPP mixture and compressed air flow rates to generate the droplets. Two pipes are distributed across the greenhouse. One pipe contains the PPP mixture at a pressure of 2–3 bar, and the other pipe contains compressed air at 6–7 bar (Sánchez-Hermosilla et al., 2012). The functioning principle is similar to a pneumatic system, wherein contact between compressed air and the liquid generates small droplets less than 15 µm in size (Mathews and Hislop, 1993). Most of this air-compressed droplet generation is limited to the roof of the greenhouse spraying over the canopy. In some cases, this fogger system is attached to an axial fan to optimize the distribution over the field.

Sánchez-Hermosilla et al. (2013a) evaluated the distribution of sprays using a fog cooling system. He compared the distribution of that system in a greenhouse to a spray gun at the same volume application rate. The results showed very low values of deposition with the fog cooling system. The values were approximately eight times lower than the deposition produced when using the spray gun. Losses were also very high in spite of the saturated atmosphere. No data was provided in terms of uniformity distribution along the greenhouse surface.

Olivet et al. (2011) evaluated the spray distribution of a stationary cold fogger in pepper plants in a greenhouse. The results are shown in Figure 7, where low distribution uniformity across the greenhouse is presented in both spray deposition and air distribution. This performance combined with the heterogeneous distribution of the pests and diseases results on a difficult plant protection control.

Both studies demonstrated that this technique presents poor results in terms of deposition and spray spatial distribution. The authors highlighted that the selection of the sprayer should be determined by the size of the greenhouse and the types pests and diseases seeking to be controlled.

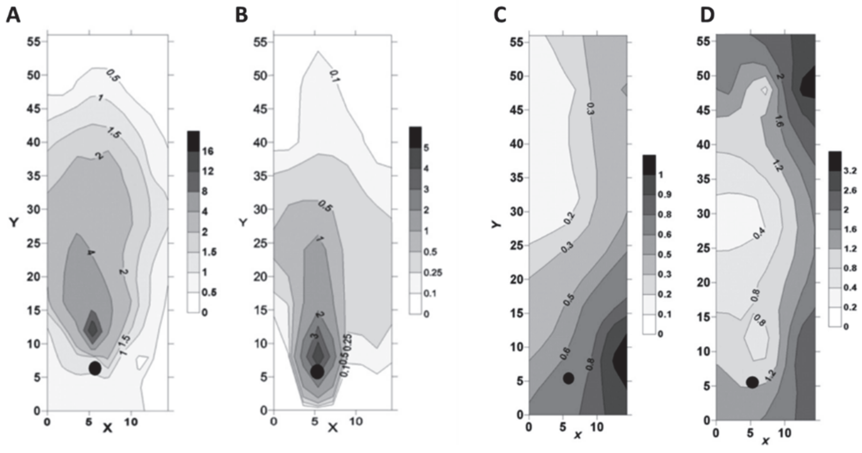

Figure 7 Distribution of a stationary cold fogger in a greenhouse: A) tracer deposition (µg · cm^{-2}); B) airspeed (m · s^{-1}); C) Mean distribution of thrips per flower; D) number of colonies of powdery mildew per leaf. Black point shows the sprayer position. Source: Olivet et al. (2011).

1.4.1.5. Vertical boom sprayers for greenhouse

Vertical boom sprayers are presented (SUI project) as an alternative to spray guns and lances to improve pesticide distribution on the canopy. They reduce the volume application rate at a low cost investment when compared to other alternatives (fogger systems, tractor mounted cannon mist blower). In addition, vertical boom sprayers have demonstrated the ability to reduce the risk of operator exposure (Nuyttens et al., 2004a).

The main feature of this sprayer is a vertical boom with several mounted nozzles that operate in parallel to the canopy. The sprayers can be divided into two categories: self-propelled and manually pulled. For the self-propelled sprayer, the pump, tank, and regulator system are installed together on the sprayer. For the manually pulled sprayer, the vertical booms are mounted on a hand-held trolley that has to be pulled. The feeding system consists of a hose that connects a fixed tank to the sprayer—the same arrangement used for spray guns and lances.

Several studies have already demonstrated that the use of vertical boom sprayers in greenhouses improves spray distribution (Nuyttens et al., 2004b; Sánchez-Hermosilla et al., 2012), reduces labour costs, and reduces operator exposure (Nuyttens et al., 2009, 2004a) compared to spray guns. Sánchez-Hermosilla et al. (2003) tested a manually pulled vertical boom against a spray gun in a greenhouse tomato crop. The volume application rates used with the vertical boom sprayer resulted in a reduction of 50%, 37.5%, and 25% at a pressure of 15 bar in comparison to the spray gun whose rate was 2000 $L \cdot ha^{-1}$ at a pressure of 38 bar. The leaf area covered by the tracer was similar when using 750 $L \cdot ha^{-1}$ and the spray gun. This represents a high savings in volume application rate and maintenance of the equipment due to the wear reduction in the spray components. In general, the penetration was higher with the vertical boom than the spray gun because of its more uniform nozzle distribution along the canopy height.

Other researchers have investigated automatic spraying of PPPs using new technologies. Mandow et al. (1996) proposed an autonomous mobile robot (AURORA) that can also be manually operated. This platform runs on four wheels powered by a petrol engine. As was developed for all types of agronomic operations in greenhouses, tests were primarily carried out with a commercial knapsack, which was conveniently adapted to the AURORA platform. Sammons et al. (2005) developed an autonomous pesticide-spraying robot for greenhouses. The defining feature of this platform was that it ran over a steel pipes from the cooling system. This is possible in greenhouses fitted with a water heating system mounted on pipes along the ground. González et al. (2009) developed an automatic platform (Fitorobot) that utilized an electric engine for motion and moves on two rubber tracks. These tracks provide a larger contact surface with the soft ground in greenhouses. The control of the platform was completely autonomous, and utilized ultrasonic sensors and a webcam for the guidance. Balsari et al. (2012) developed an electric platform radio controlled with four wheels. This platform and the Fitorobot were mounted on a 300 L tank fitted with vertical booms for a pesticide application. Sánchez-Hermosilla et al. (2011) tested a self-propelled sprayer (Tizona) fitted with a vertical boom sprayer that demonstrated good results for canopy deposition. However, the large cost of these vehicles limits their practicality.

1.4.2. Technological improvements to vertical booms

Several improvements and new developments have appeared over the last few years with the goal of improving spray application technology in greenhouse applications. One new alternative has a low implementation cost (compared to air blast or fogging systems) and is composed of a vertical boom sprayer mounted over a manual trolley. Most of the studies published using this sprayer were tested on a tomato crop grown in a greenhouse.

The efficiency of the spray application using vertical booms can be conditioned by several parameters, including nozzle pattern distribution and flow rate, nozzle orientation, nozzle distribution along the boom, distance to the target, working pressure, forward speed, air assistance, and air outlet type. Studies on the comparison of these parameters are presented in this section, with the intention of determining an optimal set-up for the vertical boom sprayer as a starting point.

1.4.2.1. Air assistance in vertical crops

Air-assisted sprayers are the most common equipment used in 3D crops such orchards, olives, citrus, and vineyards, and only a simple calibration is required to reduce losses and spray efficiently. However, although the optimal volume application rate has been studied and determinations have been made, very few studies on the determination of air volume are available.

Regarding vineyard crop studies, Balsari et al. (2008) tested several air velocities that characterize the air assistance system. On fully developed vegetation, the deposits were higher at a 4 $Km \cdot h^{-1}$ forward speed with an air velocity measured at 0.5 m from the air spout of 4.7 $m \cdot s^{-1}$. Clearly, the canopy deposition generated at a forward speed of 6 and 8 $km \cdot h^{-1}$ was lower. This study also demonstrates that higher air assistance velocities yield lower ground losses. However, higher air assistance velocities increase the volume of airborne losses. On the same crop, Gil et al. (2015) used a multi-row sprayer to test different air volumes. Their results showed that a 25% reduction in the maximum air flow rate (4,750 $m^3 \cdot h^{-1}$) did not significantly affect deposition or distribution uniformity. With orchard crops, Cross et al. (2003) concluded that a 11.3–7.5 $m^3 \cdot s^{-1}$ reduction in the air volumetric flow rate can reduce the spray drift without affecting the spray distribution on the canopy. However, this reduction causes the spray plume to become more vulnerable to cross-winds that may affect the penetration. On olives trees, Miranda-Fuentes et al. (2015a) tested different volume application rates (183, 619, and, 1603 $L \cdot ha^{-1}$) and three air volume rates (11.93, 8.90, and 6.15 $m \cdot s^{-1}$). Their results showed that the effect on the deposition of the volume application rate is higher than the effect of the air volume rate; however, a decrease in the uniformity of the deposition was observed with a high air volume rate. In citrus, it has been shown that the influence of the canopy characteristics on airflow behaviour generates turbulence structures above and behind the tree (Salcedo et al., 2015).

Air assistance has been considered one of the key elements for improving the efficiency of the spray application process in greenhouses, especially for dense crops (Llop et al., 2015). Derksen et al. (2007) achieved higher spray coverage on the lower surfaces of bell pepper leaves using air-assisted delivery with single-fan nozzles than when using conventional delivery with either twin-fan or air induction nozzles. Similar results were obtained by Braekman et al. (2010) and Abdelbagi and Adams (1987). However, although air assistance has proven to be important for improving deposition on the canopy, it is still necessary to investigate the air distribution based on the canopy structure and the optimal relationship between the vertical distributions of the three factors affecting deposition: canopy surface, air velocity profile, and liquid distribution.

On a bay laurel crop, Foqué et al. (2012a) tested nozzle type, angled nozzles, and air support in laboratory conditions. No clear effect on deposition results was obtained from the use of air assistance. The best configuration obtained in this study is similar to the previous section (flat fan nozzles spaced 0.3 m apart), but here spraying is applied directly to the crop without air assistance.

On a tomato crop, Lee et al. (2000) tested the effect of nozzle type, nozzle configuration, application volume rate, and air assistance. Deposition on the underside of the leaves can be increased by using flat fan nozzles directed upwards at 45° or with air-assisted application systems. This study also showed that improved uniformity on the upper and lower leaf surfaces can be obtained by application systems using flat fan nozzles directed upwards at 45°, or with air-assisted systems at volume application rates of 400 to 500 $L \cdot h^{-1}$.

In summary, interest in using air assistance on tridimensional crops has been demonstrated, but there is still a need to determine the most suitable airspeed or air volume rate according to the canopy characteristics for bush crops (vineyards, orchards, etc.) or greenhouse vertical crops (tomato, pepper, cucumber, etc.).

1.4.2.2. Sprayer configuration

The configuration of the sprayer has a very significant effect on the uniformity of the distribution and the penetration of the spray over a crop. The research presented in this section is focused on evaluating the distance between nozzles and the spraying pattern.

Nuyttens et al. (2004b) tested a vertical boom fitted with nozzle distances of 0.35 m and 0.5 m, and the spray distance to the crop was also 0.35 and 0.5, using an 80° flat fan nozzle with a 7° offset angle to prevent the spray jets from crossing. The configuration that generates the highest deposition on the canopy was the flat fan nozzle arrangement spaced 0.35 m within nozzles. The coefficient of variation produced using the 0.5 m distance was four times higher than that produced using the 0.35 m spacing.

Sánchez-Hermosilla et al. (2011) compared the canopy deposition of a spray gun to the canopy deposition using a trolley with vertical booms and a 0.5 m nozzle spacing. They obtained similar results by reducing the application volume by 45% with the boom sprayer.

Llop et al. (2013) tested the effect of the spray on vertical distribution using a flat fan and hollow cone. They separated the nozzles 0.5 m and 0.3 m apart, and varied the distance to the canopy by the same values (0.5 m and 0.3 m). Their results showed higher uniformity with 110° flat fan nozzles spaced 0.3 m apart, 0.3 m from the canopy (CV 13%) with a 7° nozzle offset, than the hollow cone nozzles in the same conditions (CV 27%). This confirmed the results obtained by Nuyttens et al. (2004b) on nozzle spacing.

On the assessment of the nozzle spray pattern, Sánchez-Hermosilla et al. (2003) tested hollow cone and flat fan nozzles on tomatoes produced in a greenhouse. Their results showed that standard flat fan nozzles present high deposition, high coverage area on the canopy, and higher values of penetration into the canopy than hollow cone nozzles. In addition, Sánchez-Hermosilla et al. (2012) tested standard flat fan nozzles and air induction flat fan nozzles. No significant differences with regard to deposition or uniformity were observed.

Braekman et al. (2010) tested several nozzle patterns in a tomato greenhouse using a semi-automated trolley sprayer. The authors tested 110° flat fan nozzles (conventional and drift reducing spray), a hollow cone nozzle, an air induction double flat fan, and 80° flat fan nozzles with air assistance spouts. Tests with air assistance were fitted with 80° flat fan nozzles with air spouts offset to 45° upwards and 30° backwards. The techniques tested with no air assistance were mounted on a vertical boom with an offset angle of 7° to avoid crossing the sprays. High deposition was obtained on the contour of the plant and inside the canopy using the pressure recommended by the manufacturer. The air induction double flat fan performed best, followed by 110° flat fan. The hollow cone nozzle and flat fan yielded low penetration capacity, most likely due to the small droplet size (82.2 µm and 191.8 µm, respectively) generated by the high pressure used (based on the manufacturer recommendation).

A variety of nozzles were tested on a vertical boom for a conical bay laurel crop (*Laurus nobilis*). Foqué et al. (2012a) tested hollow cone, flat fan, deflector flat fan, air inclusion twin flat fan, and air inclusion flat fan nozzles on a vertical boom with the nozzles directed horizontally towards the canopy (the bottom nozzle had an angle offset of 10° upwards). Their results showed that the best values of deposition of product on the leaves were obtained using hollow cone nozzles, followed by flat fan nozzles and air inclusion flat fan nozzles, at an application rate of 4900 L·ha^{-1}. The main differences between spray deposits are related to droplet characteristics and spray direction.

On Ivy potted plants, Foqué and Nuyttens (2011) tested the effects of nozzle type and spray angle on flat fan nozzles, using a volume application rate of approximately 970 L·ha^{-1}. The highest depositions were obtained using hollow cone nozzles (because of the swirling effect) and the air induction flat fan nozzle (because their high droplet momentum). Flat fan nozzles with different angle offset were studied with no significant effect on the deposition. The authors pointed out that the high application rate can disguise the effect of the nozzle technology.

These studies show that flat fan nozzles with a 7° offset, spaced 0.35 m apart, are the most successful configuration. That arrangement generated better results than hollow cone nozzles or flat fan nozzles with reducing drift technology.

1.5. Canopy characteristics and their relation with the spray application

The framework established by SUD 2009/128/CE encourages operators and technicians to improve the quality of the applications using technical knowledge and suitable technology.

Among the parameters influencing the optimal pesticide deposition rates, such as growth stage, pest/disease characteristics, substance mode of action, spraying technologies or weather conditions, the shape of the canopy and its dimensions have a very important influence on the efficiency of pesticide distribution during the spraying operation.

It is possible to detect two main groups of crops related to the target characteristics: open field crops and bush crops. The variation of the height, width, and density of leaves when considering bush crops (orchard, vineyards, citrus, olives or horticultural crops with tall development) play a very important role. This group of crops is defined as 3D crops. 2D crops represent arable crops (wheat, oat, barley, corn, sugar beet, sunflower, soybean, etc.).

Because of the complexity of 3D crops and the enormous variability of crop architecture within the Mediterranean region, a discussion is currently being held on how to determine the optimum pesticide and water rate for each particular scenario. This discussion has not yet reached a clear consensus.

The dosage expression for the PPP that farmers and operators use is shown in different ways: g of PPP per L of spray water or solvent, or g of PPP per hL of spray water. The dosage expression can also vary by European Union member state (Wohlhauser, 2009). In some cases, the dose is defined by the ground surface. However, this dosage system seems to be incomplete when considering 3D crops, because the amount of active ingredient used is related to the amount of water sprayed, which depends on the experience of the farmer and the spraying technology used. In addition, it must be considered that the canopy changes within fields, along the season and with the pass of the seasons.

In this context, the characterization of the canopy for pesticide dosage is a key factor for improving the efficiency of pesticide application. By means of the adjustment of the pesticide to the canopy, it allows the reduction of the losses as origin of environment contamination as well as human health hazard. Canopy characterization is a complex task that has been solved in very different ways over the last few years. The growth of three-dimensional crops (defined as bush crops) and horticultural crops (tomato, pepper, cucumber, etc) are produced on a row and the growth of the canopy is developed in height and width. 3D crops shape varies during different phases of the season. The pruning system and canopy manipulation have a significant influence on the spraying characteristics (Balsari and Tamagnone, 1997).

Canopy characterization methods can be classified into two methods: manual and electronic. The manual methods are those that are based on manual measurements performed with measuring tape, topographic milestone, etc. These methods vary depending on canopy structure, and are much simpler to use in hedgerow orchards than in isolated trees or plants (Miranda-Fuentes et al., 2015b). One of the best indicators for defining canopy characteristics is LAI, but it is difficult to determine. Canopy density results are extremely difficult to evaluate using manual methods. To avoid this difficulty, the point square method is proposed for vineyards (Smart et al., 1990). This method provides information about the density,the porosity of the canopy or the exposed foliar surface.

Therefore, the electronic methods seem to be the more appropriate option to satisfy the requirements for dose adjustment. Among the electronic characterization methods, the most frequently used equipment includes ultrasonic sensors (Gamarra-Diezma et al., 2015; Llorens et al., 2011; Walklate et al., 2003), stereo vision (Andersen et al., 2005), light sensors (Sinoquet et al., 2005) and the LiDAR scanners (Gil et al., 2013; Méndez et al., 2013; Sanz-Cortiella et al., 2011). According to Rosell and Sanz (2012), the LiDAR is the most accurate technology available to characterize the canopy. In fact, it has been shown to be very reliable at predicting canopy parameters in different studies (Gil et al., 2014; Llorens et al., 2011; Sanz-Cortiella et al., 2011).

Knowledge of the canopy structure allows the operator to adapt spraying to its specific characteristics, and therefore the dosage rate of the product can be adjusted. Obtaining a consistent amount of product per unit surface or canopy volume is very important for maintaining biological efficacy of the products. Felber (1997) introduced crop adapted spraying (CAS) to adjust the spraying of pesticides to the canopy characteristics. This method allows for a reduction in product loses and no negative effect on biological results.

The CAS method applied to orchard crops is called tree row volume (TRV), and was proposed by Byers et al. (1984 and 1971). The method treats the canopy as a rectangular prism by calculating the cubic meters of canopy per hectare of ground surface. Another method known as the leaf wall area (LWA) method was proposed by Koch (1993). On the LWA method the area to be sprayed is considered as a wall composed of leaves. This method is well adapted to crops produced in a trellis system. Once the orchard is isolated, those methodologies seem to be less appropriate. In these cases, it is more useful to use the projected area of the crown or the ellipsoid method (Miranda-Fuentes et al., 2015b). In addition, Walklate et al. (2003) presents the tree area density (TAD) method, which provides information about what is happening behind the canopy. A LiDAR sensor is required for this method, as it is more complicated to use than the TRV and LWA methods

The adaption of the dose to the canopy characteristics involves two basic aspects: the determination the mount of PPP in relation of leaf surface and the determination of the amount of mixture to distribute the PPP on the canopy. The first item is related to pests/diseases and the way in which the active ingredient works. The amount of water is determined by the ability of the sprayer to distribute droplets over the canopy. In both cases, this information should appear on the label of the plant protection product.

The determination of the active ingredient in pesticide use has been widely discussed (Furness, 2003; Gil et al., 2005; Siegfried et al., 2007; Walklate et al., 2003). All of these studies have a common objective to adapt the amount of pesticide to the canopy characteristics, presenting particular difficulties in defining the most suitable canopy parameter for crop size determination.

Walklate et al. (2003) proposed an equation to calculate the adjustment of the volume application rate based on the TRV method: $D = A + TRV \times i$, where D ($L \cdot ha^{-1}$) is the volume application rate per ground surface, TRV ($m^3 \cdot ha^{-1}$) is the canopy volume, and A ($L \cdot ha\text{-}^1$) and i ($L \cdot m^{-3}$) are constants. Several variations of this equation are presented depending on the region studied, resulting in different models (Table 1).

Table 1 Parameters for TRV adjustment equation.

Parameter A ($L \cdot ha^{-1}$)	 i ($L \cdot m^{-3}$)	Crop	Country	Reference
0	0.130	Orchards	USA	(Byers et al., 1971)
330	0.033	Orchards	Poland	(Doruchowski et al., 1996)
125	0.0125	Orchards	Netherlands	(Heijne et al., 1997)
200	0.020	Stone fruit	France	(Ruegg et al., 1999)
0	0.095	Vineyard	Spain	(Gil et al., 2007)
0	0.05-0.13	Vineyard	Switzerland	(Siegfried et al., 2007)
0	0.140	Olives	Spain	(Miranda-Fuentes et al., 2015)
0	0.13	Tomato	Spain	(Sánchez-Hermosilla et al., 2013)

Once the amount of liquid to be sprayed is determined, it is also important to define the efficiency of the spray as influenced by the sprayer, meteorological conditions, the trellis system, product action, etc. Gil (2003) presented DOSAVIÑA, a support decision tool that calculates the efficiency of the spray according to several parameters. Gil et al. (2011) validated this software with field experiments, demonstrating the control of several pests in different years. This achievement shows that the reduction in PPP used for pest and disease control does not affect the efficacy of the product.

Similar tests have been performed in greenhouses. Sánchez-Hermosilla et al. (2013) studied the effect of the crop growth stage, the volume application rate, and the efficiency of the spraying technology. The results of this experience are shown in the Green Rate program. This application is based on an Excel sheet and proposes a model for the pesticide dosage in tomato crops based on the canopy size and the spraying equipment used.

2. Objectives and thesis outline

The most common technology used in greenhouses it still have a lack of development as discussed in the introduction section. There is an abundant amount of technologically advanced equipment available, but few farmers use it.

For this reason, the main objective of this doctoral thesis is:

Improve the efficiency of the plant protection product application process on tomato crops produced in greenhouses through spray application techniques and the characterization of the target canopy.

Three particular goals are defined within this objective:

- Evaluate and quantify the effect of nozzle type, volume application rate, and canopy density on spraying quality.
- Improve spray distribution by evaluating the effect of air assistance on liquid distribution on the canopy.
- Characterize the canopy with a method based on LiDAR technology.

These particular objectives are related with the following scientific publications:

Chapter 3: *Spray distribution evaluation of different settings of hand-held trolley sprayer used in greenhouse tomato crops*, published in the Pest Management journal. A developed prototype was tested on a tomato crop in field conditions. The main innovation of the sprayer was the addition of an air assistance device for spraying. The sprayer adjustments tested were compared to a reference sprayer in two different greenhouse canopy densities, and with high and low volume application rates.

Chapter 4: *Influence of air-assistance on spray application for tomato plants in greenhouses*, published in the Crop Protection journal, presents a study to determine the amount of air needed to assist the spraying and evaluate the suitability of the prototype in front of another device for greenhouse with air supply.

Chapter 5: *Testing the suitability of a terrestrial 2D LiDAR scanner for canopy characterization of greenhouse tomato crops*, published in the Sensors journal. This study presents the suitability of a Lidar sensor for tomato canopy characterization. Measurements with the LIDAR sensor were performed and data analysis was conducted in order to evaluate different parameters to characterize the crop. These measurements were validated with the height and width of the crop measured manually and with the LAI.

3. Spray distribution evaluation of different settings of hand-held-trolley sprayer used in greenhouse tomato crops

Abstract

Protected horticulture production represents one of the most important agricultural businesses in Southern Europe. However, several problems related to the lack of mechanisation, the intensive use of pesticides, and in some cases, undesirable residues on food, have not been solved yet. In this context, application technology is a key factor for the improvement of the efficacy and efficiency of plant protection products. Spray guns and knapsack sprayers are the most common technologies that have been used for this purpose. However, several studies have demonstrated that, as compared to spray guns, the use of vertical boom sprayers in greenhouses improves spray distribution and reduces labour costs and operator exposure. The main objective of this study was to evaluate the influence of air-assistance on spray application in conventional tomato greenhouses. For this purpose, three different spray concepts were evaluated. The first was a modified commercial hand-held trolley sprayer with two air assistance concepts, the second was a self-propelled sprayer, and the third was an autonomous self-propelled sprayer with a remote control. All the sprayers were evaluated in terms of absolute and normalised canopy deposition, uniformity of distribution, and losses to the ground. In addition, the vertical liquid and air velocity distributions of the sprayers were assessed and compared with the canopy profiles and spray depositions. Yellow tartrazine (E-102 yellow) was used as a tracer for deposition evaluation. The results indicated that increasing the air velocity does not increase the efficiency of a spray application. In general, the modified hand-held trolley sprayer showed the best results in terms of deposition and uniformity of distribution, especially at the lowest air assistance rate. These results were confirmed with evaluation of the uniformity of the air and liquid distribution.

Keywords: Hand-held trolley sprayer, air assistance, vertical pattern, air velocity, spray deposition

Information on the publication:

PEST MANAG SCI 2015
ISSN: 1526-498X
DOI: 10.1002/ps.4014
Impact Factor 2015 (JCR): 2.811
Impact Factor Av 5 years (JCR): 3.16
Quartile: Q1

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The page 37 and following, which contain this article, are available on the publisher's website http://onlinelibrary.wiley.com/doi/10.1002/ps.4014/full

4. Influence of air-assistance on spray application for tomato plants in greenhouses

Abstract

Hand-held trolley sprayers have been recently promoted to improve spray application techniques in greenhouses in South-eastern Spain. However, there are still some aspects to improve. A modified hand-held trolley sprayer was evaluated in two different canopy scenarios (high and low canopy density) and with several sprayer configurations (nozzle type, air assistance, and spray volume). In this study, deposition on the canopy, coverage, and distribution uniformity has been assessed. Deposition on the leaves was significantly higher when flat fan nozzles and air assistance were used at both high and low spray volumes. No differences were detected between the reference system at a high spray volume and with the modified trolley at a low spray volume. Flat fan nozzles with air assistance increased penetration capability into the canopy. The use of air assistance and flat fan nozzles reduced the volume rates while maintaining or improving spray quality distribution. The working parameters of the hand-held sprayer must be considered to reduce environmental risk and increase the efficacy of the spray process.

Keywords: greenhouse, tomato, hand-held trolley, air assistance, deposition, coverage, nozzle type

Information on the publication:

CROP PROT 2015,
ISSN: 0261-2194
DOI: 10.1016/j.cropro.2015.09.026
Impact Factor 2015 (JCR): 1.652
Impact Factor Av 5 years (JCR): 1.79
Quartile: Q1

ATTENTION ¡
The page 39 and following, which contain this article, are available on the publisher's website
http://www.sciencedirect.com/science/article/pii/S0261219415301253

5. Testing the suitability of a terrestrial 2D LiDAR scanner for canopy characterization of greenhouses tomato crops

Abstract:

Canopy characterization is a key factor to consider when adjusting pesticide dosage for an amount of vegetation. This fact becomes especially important when the target is a fresh exportable vegetable like greenhouse-produced tomatoes. The particularities of this crop, whose plants are thin, tall, and planted in pairs, make their characterization difficult with electronic methods. This study attempts to assess the accuracy of the terrestrial 2D LiDAR sensor for determining major canopy parameters related to its volume and density, and it establishes useful correlations between manual and electronic parameters for leaf area estimation. The experiments were carried out at three different commercial tomato greenhouses on crops planted in a twin row system. The electronic characterization was conducted with a LiDAR sensor (LMS-200, SICK) with a 180° angle measurement by scanning the pair of plants on both sides. The main parameters obtained were canopy height, canopy width, canopy volume, and leaf area. Other important parameters were calculated from these parameters, such as the tree row volume (TRV), the leaf wall area (LWA), the leaf area index (LAI), and leaf area density (LAD). A general overview of the results show an overestimation of the parameters with manual measurements because of the high definition of the profile obtained with this sensor. The estimation of the canopy volume using the electronic device proved to be a reliable parameter for estimating the canopy height, volume, and density. In addition, the LiDAR scanner was able to assess the high variability of the canopy density along the row, proving itself to be an important tool for canopy map generation.

Keywords: greenhouse; tomato crop; LiDAR sensor; canopy characterization; LAI

Information on the publication:

SENSOR-BASEL 2015,
ISSN: 1424-8220
DOI: 10.3390/s16091435
Impact Factor 2015 (JCR): 2.033
Impact Factor Av 5 years (JCR): 2.437
Quartile: Q3

sensors MDPI

Article

Testing the Suitability of a Terrestrial 2D LiDAR Scanner for Canopy Characterization of Greenhouse Tomato Crops

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Academic Editor: Simon X. Yang
Received: 9 July 2016; Accepted: 1 September 2016; Published: 6 September 2016

Abstract: Canopy characterization is essential for pesticide dosage adjustment according to vegetation volume and density. It is especially important for fresh exportable vegetables like greenhouse tomatoes. These plants are thin and tall and are planted in pairs, which makes their characterization with electronic methods difficult. Therefore, the accuracy of the terrestrial 2D LiDAR sensor is evaluated for determining canopy parameters related to volume and density and established useful correlations between manual and electronic parameters for leaf area estimation. Experiments were performed in three commercial tomato greenhouses with a paired plantation system. In the electronic characterization, a LiDAR sensor scanned the plant pairs from both sides. The canopy height, canopy width, canopy volume, and leaf area were obtained. From these, other important parameters were calculated, like the tree row volume, leaf wall area, leaf area index, and leaf area density. Manual measurements were found to overestimate the parameters compared with the LiDAR sensor. The canopy volume estimated with the scanner was found to be reliable for estimating the canopy height, volume, and density. Moreover, the LiDAR scanner could assess the high variability in canopy density along rows and hence is an important tool for generating canopy maps.

Keywords: greenhouse; tomato crop; LiDAR sensor; canopy characterization; Leaf Area Index (LAI)

1. Introduction

Public concerns due to environmental problems associated with an inaccurate pesticide application process led the European Directive 2009/128/EC of the European Parliament to establish a regulatory framework [1]. In this document, the need to improve the efficiency in the use of Plant Protection Products (PPPs) is remarked. For this purpose, pesticides dose must be adjusted according to the canopy characteristics, thus avoiding overdosing and unnecessary losses to the environment.

The greenhouse tomato crop, grown to be consumed as a fresh product, is very important in Spain, with a cultivated area of 6189 ha [2]. The accurate application of pesticides is essential for all type of crops or circumstances. In particular, fresh products to be directly commercialized in the market require accurate and safe pesticide application in order to prevent health risks. Pesticide residues on vegetables constitute a possible risk to consumers and have been a human health concern [3]. However, although some researchers have evaluated the optimal volumes of pesticides to be applied [4,5], few studies have related all parameters influencing the relationship between the canopy characteristics and the amount of plant protection product according to the real needs.

Greenhouse tomato rises from the ground and develops a long stem, which is fixed by the farmer to a fixed structure to make it stay in a vertical disposition. Therefore, this crop belongs to the group called 3D crops; that is, crops that present a complex geometry for the sprayer in contrast to arable crops, which are treated as if they were a flat 2D target. The constant dose per unit ground area results less suitable for 3D crops [6], because the varying geometry of the vegetation make it difficult to set a general application volume that results in a satisfactory application quality. Therefore, researchers have established other systems that focus on different parameters related to the canopy structure. The first two methodologies proposed were the Tree Row Volume (TRV) and Leaf Wall Area (LWA). The TRV method involves calculating the canopy volume by assuming its prismatic shape; hence, the canopy height and width, along with the row spacing, are the base parameters to determine the TRV, which is expressed in cubic meter canopy per hectare of ground [7,8]. The application volume will be proportional to this TRV parameter according to a specific coefficient that will have different values according to the crop [9–11]. On the other hand, the LWA is calculated based on the assumption that the canopy sides are completely flat, and hence, they form a "wall". Canopy height is the main parameter to calculate the LWA [12], and therefore, the canopy width is ignored. The LWA is expressed in square meters of LWA per hectare of ground. The sprayed dose is calculated for every 10,000 m^2 of LWA. These two systems are well-established, and at present, there is a general discussion among the countries of the European Union regarding which of these systems should be used as the standard label dosing system for all crops [13,14]. Nevertheless, in recent years, researchers have proposed alternative systems because the TRV and LWA methods do not consider the leaf density, which is an important canopy parameter [14]; therefore, these methods are incomplete. Various dosing systems have been proposed for different crops, including vineyards and citrus and fruit trees such as apple trees [6,15–18]. Although these systems differ in their basis, assumptions, and calculations, they all rely on an accurate canopy characterization system.

Various methods for canopy characterization, which is a complex task, have been proposed in the last years. The canopy characterization methods can be classified in two general categories: manual and electronic methods. The manual methods are based on manual measurements with a measuring tape or topographic milestone. These methods vary according to the canopy structure and are much simpler for hedgerow orchards than for isolated trees or plants. Although they are reliable, fast, and simple to use for the farmer, they become less useful for more advanced tasks such as generating prescription maps for proportional spray application, like the one proposed by the aforementioned dosing systems. In addition, it is difficult to evaluate the canopy density with manual methods because they require complete defoliation of a representative plant sample to obtain reliable values. Therefore, the electronic methods seem to be an appropriate option to accomplish the requirements of dose adjustment. Electronic characterization methods using ultrasonic sensors [18–21], stereo vision [22], light sensors [23], and LiDAR scanners [24–29] are more frequently used. According to Rosell and Sanz [30], LiDAR is the most accurate technology for canopy characterization, and in fact, it has been demonstrated to be very reliable at predicting canopy parameters in different studies [20,24,31]. The LiDAR scanner uses the time-of-flight principle to calculate distances—the sensor measures the elapsed time between laser beam emission and reception and automatically calculates the distance to the target point [32]. This process is repeated along a plane in 2D scanners or in three dimensions by rotating the scanning plane in 3D LiDAR. The 2D sensor is cheaper and can have a third coordinate by moving it along the axis perpendicular to the scanning plane [24,28]; hence, it is more frequently used for canopy characterization.

The characteristics of tomato plants—thin, tall, and planted in pairs—make their characterization with the electronic methods difficult because it is difficult to identify the parameters related to each individual plant. Furthermore, the narrow row spacing limits the field-of-view of the sensors used. Therefore, this study aims to: (1) assess the accuracy of the LiDAR sensor for determining major canopy parameters related to canopy volume and density; (2) establish useful correlations between manual and electronic parameters for leaf area estimation; and (3) exploit the LiDAR technology to assess the variation in canopy density along a row as a basis to generate canopy density maps for pesticide dose adjustment.

2. Materials and Methods

2.1. Experimental Fields

The experiments were performed in three different tomato cultivar greenhouses located in El Ejido (Almería, Spain) (36°45′22.90″ N; 2°48′34.89″ W) and Viladecans (Barcelona, Spain) (14°18′46.46″ N; 2°1′48.44″ W), both important fresh produce growing areas on the Spanish Mediterranean coast. The greenhouses grew tomato crops of the *Velasco* and *Barbastro* varieties with similar plantation patterns (Table 1). The plants were planted in a twin row system (Figure 1a), where the crop was planted in pairs in the same row. The three greenhouses had a main corridor with adjacent and perpendicular rows (Figure 1b). The row spacing, *rs*, plant spacing in the row, *ps*, and twin plant spacing, *tps*, are specified in Table 1 and represented in Figure 1b.

Table 1. Main characteristics of the experimental fields.

Greenhouse ID	Location	Plant Layout (Row Spacing × Plant Spacing) (m × m)	Crop	BBCH Scale
GH 1	El Ejido (Almería)	2.5 × 0.4	*Solanum lycopersicum* L. cv. Velasco	79
GH 2	El Ejido (Almería)	2.8 × 0.4	*Solanum lycopersicum* L. cv. Velasco	79
GH 3	Viladecans (Barcelona)	2.0 × 0.4	*Solanum lycopersicum* L. cv. Barbastro	76

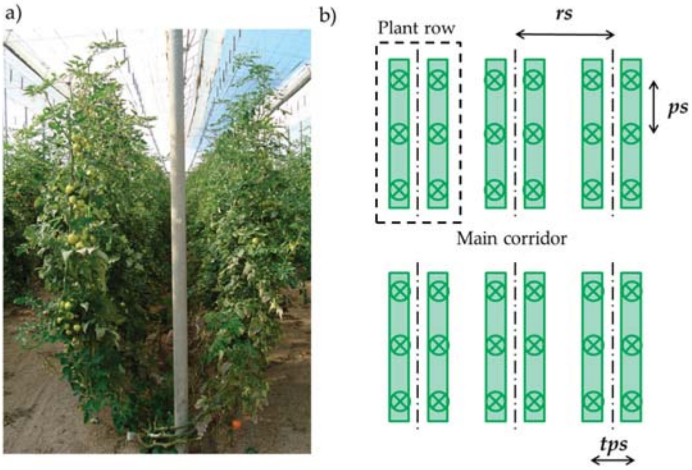

Figure 1. (**a**) Twin plantation system; (**b**) Plantation layout inside the greenhouse, with row spacing, *rs*, plant spacing in a row, *ps*, and twin plant spacing, *tps*.

2.2. Manual Canopy Characterization

For manual canopy characterization, the total canopy height, H_M, and canopy width, W_M, were measured along the row. The measurements were performed with a measuring tape by the same operators in the three fields of study, with 30 replications per field of study for each measurement. The total canopy height, H_M, was measured from the lowest leaves on the plant stem to the top leaf of each plant (Figure 2). The canopy width was measured from the outer to the inner part of the canopy.

The measurement was done at 1.5 m of the plant height as a compromise to the thicker part of the plant and the wider part. Each plant of the twin plantation system was measured separately (Figure 2).

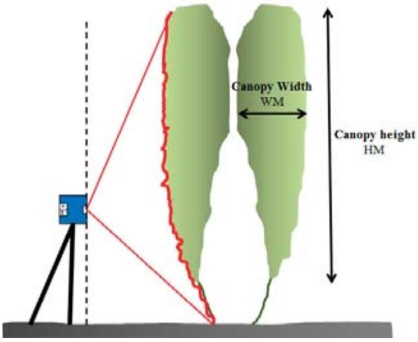

Figure 2. Measured parameters for the manual canopy characterization and LiDAR scanner location.

The total leaf area per single plant was also determined. The plants were collected in pairs: two pairs (four plants) for greenhouses 1 (GH1) and 2 (GH2) and three pairs (six plants) for greenhouse 3 (GH3). They were appropriately stored in sealed plastic bags. Then, under laboratory conditions and before they had dried out, the leaves were removed from the plants and subsamples 80 g in weight were planimetered with a leaf planimeter (LI 3100C, LI-COR, Lincoln, NE, USA) to obtain the total leaf area of the subsample (cm^2) as well as the leaf area–weight ratio [4,33,34], which enables obtaining the leaf surface area by only weighing the leaves, thus saving time.

From these measured parameters, the other parameters could be calculated: TRV that quantify the amount of canopy volume per ground surface from canopy height and width and the distance between rows, data is expressed in cubic meters per hectare of ground [7,33,35]; LWA that quantify the canopy surface per ground surface from canopy height and the distance between rows, data is expressed in square meters of vegetation per hectare of ground [36,37]; Leaf Area Index (LAI) that shows a dimensionless ratio between leaf area and ground area surface; and Leaf Area Density (LAD) obtained from the LAI and TRV values expressed as square meters of vegetation divided by cubic meters of canopy [38,39].

2.3. LiDAR Canopy Characterization

2.3.1. Canopy Scanning

A terrestrial 2D low-cost general-purpose LiDAR scanner (LMS-200, Sick, Düsseldorf, Germany) was used in this study. It is a fully automatic divergent laser scanner that can measure time-of-flight with an accuracy of ±15 mm in a single shot measurement and a 5 mm standard deviation in a range up to 8 m [20]. The sensor has a maximum scanning angle of 180° and selectable angular resolutions of 1°, 0.5°, and 0.25°. A scanning angle of 180° has been shown to be suitable for accurate canopy characterization [40]; therefore, it was chosen for the present study. The device was supplied with 24 V by an autonomous battery and it was connected to a laptop via an RS-232 serial port for data transmission.

The sensor was installed at the centre of the space between the crop rows and it was mounted opposite to the canopy in such way that it can properly scan the entire plant from the base to the top (Figure 2). The sensor was then moved along a constant track, scanning the pair of plants from both sides. Although the same plant could not be scanned from both sides because of their paired disposition, the high resolution of the scanner enabled a high percentage of the laser beams to penetrate the first plant and scan the second. Furthermore, three replications per side and canopy section were performed.

Two types of structures were used in the scanning process. In GH1 and GH2, the LiDAR sensor was mounted on a mobile platform that was manually pulled at a constant average speed (0.06 m·s^{-1} ± 0.009) to make it slide along an aluminium rail 2.4 m in length mounted on trestles (Figure 3b). In GH3, the LiDAR sensor was mounted on an autonomous spraying platform described in Balsari et al. [41] (Figure 3c). This platform was moved by an electric engine and remotely radio controlled. In both cases, the data-acquiring laptop was mounted on the platform to simplify the wiring connections.

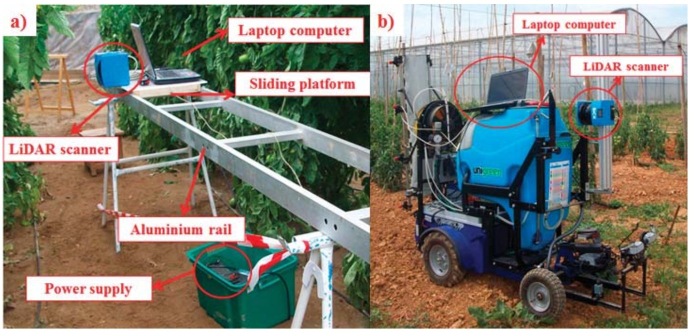

Figure 3. (**a**) Fixed structure of the LiDAR support system for measurements in greenhouses 1 and 2; (**b**) LiDAR scanner mounted on a radio-controlled mobile platform for measurements in greenhouse 3.

The mobility of the autonomous platform in GH3 enabled scanning the entire tomato row (23.4 m in length) from both sides of the canopy with three replications. These measurements enabled obtaining information regarding canopy variation along the row.

2.3.2. Data Processing

Data from the LiDAR sensor was obtained in polar coordinates (each point has an angle direction and distance response). To manage the information, the raw data was converted to *XYZ* coordinates with R-software® (3.0.2) (R Development Core Team, 2013, Vienna, Austria), where *X* axis corresponds to the plant width, *Y* axis is the plant height, and *Z* axis is the row length (Figure 4a).

Because the LiDAR sensor was mounted on two different structures for the measurements, the analysed values could have variations. Furthermore, the forward speed of the sensor varied among replications (coefficient of variation 16.8%) in the case of the fixed structure as it was manually driven. Therefore, number of LiDAR scans were normalized by considering the forward speed of the mobile sensor and the scanning frequency (Hz). This speed could be calculated in the analysis process because the data acquisition system recorded the time elapsed since the beginning of data recording and the LiDAR track's length was known. Assuming these differences, a fixed length of canopy to be evaluated was stablished. Then, the number of slices of LiDAR measurements to be analysed were determined for every single replication in order to evaluate the same length of canopy.

Once the data were appropriately normalized, the results were imported to the CloudCompare® software (TelecomParisTech, Paris, France) in order to obtain the 3D LiDAR points cloud and to ensure that there were no problems or irregularities in the data acquisition process or data normalization. As the LiDAR sensor does not only scan the plants but also scans the greenhouse's top and ground as well as the sensor support system, the points that belong to the canopy must be defined and distinguished from the others. This process was performed for each scanning file (from one side) by observing the points cloud from the *Z* axis with an orthographic projection and determining some border points by setting one of the known coordinates and obtaining the remaining from the first (Figure 4a). Then, both sides of the scanned plants were manually aligned and positioned to define the entire canopy structure (Figure 4b). After this first approach, it was necessary to delimit the points belonging to each one of the two paired plants (Figure 4b). This process was performed manually by determining their centre, which was assigned as the (0,0) coordinate.

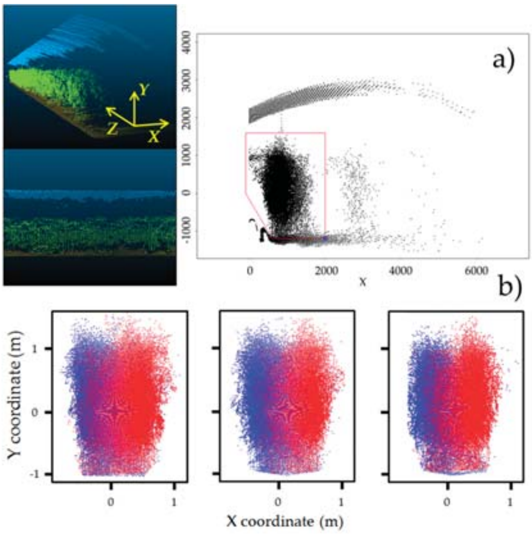

Figure 4. (**a**) LiDAR points cloud from one side in CloudCompare® software with coordinate system and canopy delimitation procedure; (**b**) Plant delimitation process from twin plants (three replications).

At this stage, different parameters, such as canopy height, H_L, and width, W_L, the number of points on the target (IMP), and the canopy volume, V_L, could be obtained or calculated from the LiDAR points cloud.

To calculate H_L, the difference between the highest and lowest points in each LiDAR slice (Figure 4a), i.e., the maximum length on the *Y* axis for each LiDAR profile, was determined. H_L was then calculated as 95% of the maximum value among all previously determined values. This 95% value was chosen to filter possible unusual profiles or data errors that could affect the measurement reliability. W_L was calculated by determining half of the total width, measured on the *X* axis, of each plant pair. Once this distance was known, W_L was obtained as 95% of the value for the aforementioned reasons.

IMP was determined as the number of LiDAR beam impacts on the canopy per row length unit (impacts m^{-1}). This parameter was included in the analysis process owing to its significant correlation with manually measured LAI values in a previous study performed in a vineyard [20].

To obtain the canopy volume per single plant, V_L, the methodology described in Xu et al. [42] and in Miranda-Fuentes et al. [40] was applied. This methodology divides the points cloud corresponding to the entire canopy into horizontal slices of a certain height, Δh. Next, all points belonging to the same slice are projected on the same horizontal plane. Then, their external perimeter is delimited using the convex hull algorithm [43], and its inner area, A_i, is determined. The volume of each slice, V_L, can be calculated as its internal area, A_i, multiplied by its height, Δh. Therefore, the total volume of the plant is calculated as:

$$V_L = \sum_{i=1}^{n} A_i \times \Delta h, \tag{1}$$

where n is the number of horizontal slices, V_L is expressed in cubic meters, A_i in square meters, and Δh in meters.

As it is evident, the lower the Δh, the higher the vertical resolution of the method. In some studies, Δh values of 0.001 m have been used [42]. Nevertheless, values of 1 cm have been shown to be sufficiently accurate in previous studies [40] and to accelerate the calculation process. Therefore, we chose a Δh value of 0.01 m in the present study.

2.4. Statistical Analysis

In the statistical analysis, a linear correlation between all measured and calculated parameters was performed using the statistical R-Software® (3.0.2) (R Development Core Team, 2013) with the *Agricolae* package. The data analysis related all measured and calculated results to identify the most significant and interesting correlations between them, always considering the manually measured parameters as a reference.

The Shapiro-Wilk test ($p > 0.05$) [44,45] and a visual inspection of the data histograms were performed. Moreover, normal Q-Q plots and box plots were drawn to ensure that the data were normally distributed in all cases. The interest of the linear correlations between the parameters obtained from the manual characterization, H_M, W_M, LAI, TRV, LAD, and LWA, and those obtained from the LiDAR scanning of plants, H_L, W_L, V_L, and IMP was evaluated with the correlation p-values and their determination coefficients (R^2).

3. Results

3.1. Canopy Characterization Parameters

The parameters obtained from the canopy characterization are listed in Table 2. It can be observed that the canopies of the three greenhouses had similar height characteristics. The maximum height of the plants is not determined by the plant growth but by the structure of the greenhouse, in which the stems are fixed to the greenhouse structure when they grow to that level, continuing the growth process downwards toward the ground. The canopy width is quite different overall in GH2, which also has a low LAD. Note that the width values were measured from the centre of the two paired plants to the edge of each plant. These two parameters, especially the height, were constant in all studied fields.

Table 2. Average measured and calculated geometrical and density parameters and its Standard Deviation of the MEAN.

Parameter			**Greenhouse ID**		
			1	**2**	**3**
Manual characterization	**Manual Height**	$\mathbf{H_M}$ (m)	2.19 ± 0.02	2.50 ± 0.02	1.96 ± 0.04
	Manual Width	$\mathbf{W_M}$ (m)	0.62 ± 0.02	0.43 ± 0.04	0.53 ± 0.01
	Tree Row Volume	**TRV** ($m^3 \cdot ha^{-1}$)	10,882 ± 397	7711 ± 212	10,397 ± 252
	Leaf Wall Area	**LWA** ($m^2 \cdot ha^{-1}$)	35,111 ± 360	35,683 ± 290	39,170 ± 755
	Leaf Area Density	**LAD** ($m^2 \cdot m^{-3}$)	5.81 ± 0.28	3.15 ± 0.15	5.30 ± 0.19
Electronic characterization	**LiDAR Height**	$\mathbf{H_L}$ (m)	1.90 ± 0.07	2.12 ± 0.01	1.93 ± 0.03
	LiDAR Width	$\mathbf{W_L}$ (m)	0.71 ± 0.02	0.64 ± 0.02	0.59 ± 0.03
	LiDAR Volume	$\mathbf{V_L}$ (m^3)	1.13 ± 0.07	1.32 ± 0.03	2.42 ± 0.12

The lowest value of TRV is found in GH2 (7771 $m^3 \cdot ha^{-1}$), which is significantly different from those in GH1 and GH3 (10,882 and 10,397 $m^3 \cdot ha^{-1}$, respectively). These differences can be explained by the difference in the measured canopy width. Therefore, the LWA did not follow the same trend as the TRV; it was the largest in GH3, at 39,170 m^2 ha^{-1}, and had very similar values in GH1 and GH2.

The LAD was the lowest in GH2 (3.15 $m^2 \cdot m^{-3}$) and very similar in the other two fields (5.81 and 5.30 $m^2 \cdot m^{-3}$ in GH1 and GH3, respectively).

Regarding the electronically measured parameters, the LiDAR height, H_L, was found to be generally lower than that manually measured, H_M, with a 12.12% lower mean value. Nevertheless, the H_L parameter followed a trend similar to H_M, with the maximum height being measured in GH2. On the other hand, the canopy width was overestimated by the scanner, but this mainly occurred in the case of GH2, in which the electronically measured canopy width was 48% greater than the manually measured value.

The standard errors of the mean (SEM) in the measurements are generally low, being below 10% in all cases and below 1% in most cases. The standard errors in the geometrical measurements of all parameters of the three GHs are very similar. The standard error in the measurement of the LAD parameter is slightly higher, which is normal considering the variability of this parameter along the canopy.

3.2. Correlations among Parameters Obtained with Manual and Electronic Methodologies

Table 3 shows the determination coefficients (R^2) for all paired linear correlations among all parameters related to the canopy volume and density.

The height (H_L) parameter obtained with the LiDAR has been significantly correlated with the manually measured height, H_M ($R^2 = 0.59$), manual width, W_M, ($R^2 = 0.52$), and manual TRV value ($R^2 = 0.46$). Nevertheless, there is no correlation between H_L and LWA ($R^2 = 0.004$). This could be because this parameter was not proportional to the canopy height in the three GHs and was the maximum in GH3 even when the maximum height was found in GH2 (Table 2).

On the other hand, the LiDAR width, W_L, was only significantly correlated with the LWA; even the LWA calculation is not affected by the canopy width; this correlation shows the importance of the width in these types of crops where the height is limited by the greenhouse structure.

The LiDAR volume, V_L, seems to be the most reliable parameter to estimate the geometrical characteristics of the canopy as it is significantly correlated with the H_M, TRV, and LWA with determination coefficients of 0.69, 0.37, and 0.33, respectively. It can be observed that the determination coefficients of the TRV and LWA are very similar. Because the LiDAR volume, V_L, is statistically reliable, it could be the most complete parameter for estimating the TRV and LWA.

All correlations between the canopy density parameters—LAI and LAD—and the other parameters are presented in Table 3. Interesting correlations can be observed between some manually measured geometrical parameters, such as H_M and W_M, and the canopy density. In fact, both parameters are significantly related to the LAI ($R^2 = 0.60$ and $R^2 = 0.70$ for H_M and W_M, respectively), and to the LAD ($R^2 = 0.53$ and $R^2 = 0.65$ for H_M and W_M, respectively), which is not surprising as both density parameters are closely related. The TRV values are highly correlated to the LAI and LAD values with determination coefficients of $R^2 = 0.89$ and $R^2 = 0.79$, respectively. On the other hand, the LWA values were found to not be appropriate estimators of the leaf density, showing no significant correlations. The IMP parameter, expressed as the number of LiDAR impacts per length unit, has been shown to have strong correlations with the leaf density parameter in previous studies. In this study, IMP was found to be inaccurate for predicting the LAI and LAD values of tomato plants. More tests need to be performed to identify the reason for this.

Figure 5 shows the correlations between the LAI and V_L (Figure 5a) and those between the LAI and TRV (Figure 5b). It can be seen that the TRV values are well aligned with the LAI values. On the other hand, V_L has a lower determination coefficient, $R^2 = 0.36$.

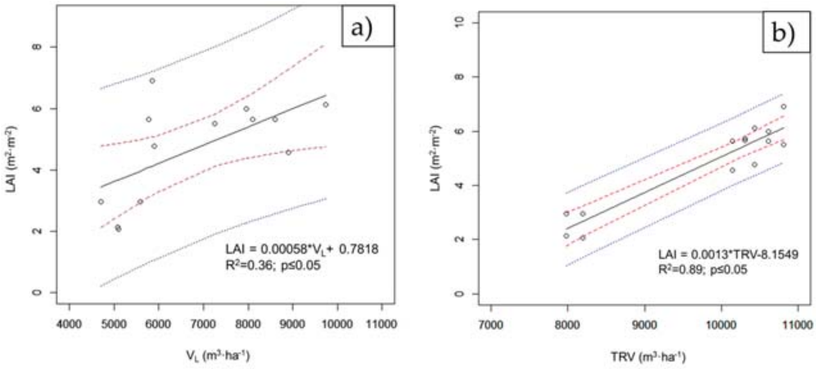

Figure 5. Linear correlations between (**a**) LAI and V_L and (**b**) LAI and TRV.

Table 3. All possible comparisons among all measured and calculated parameters related to the canopy volume and density.

			Manual Measurements						**LiDAR Measurements**			
			H_M	**W_M**	**LAI**	**TRV**	**LWA**	**LAD**	**IMP**	**H_L**	**W_L**	**V_L**
			(m)	**(m)**	**($m^2 \cdot m^{-2}$)**	**($m^3 \cdot ha^{-1}$)**	**($m^2 \cdot ha^{-1}$)**	**($m^2 \cdot m^{-3}$)**	**(m^{-1})**	**(m)**	**(m)**	**(m^3)**
Manual	**H_M**	(m)	1	0.29 **	0.60 **	0.50 **	0.21 *	0.53 **	0.20 *	0.59 **	0.003	0.69 **
	W_M	(m)		1	0.70 **	0.86 **	0.01	0.65 **	0.20 *	0.52 **	0.10	0.16
	LAI	($m^2 \cdot m^{-2}$)			1	0.89 **	0.02	0.97 **	0.01	0.52 **	0.01	0.36 **
	TRV	($m^3 \cdot ha^{-1}$)				1	0.08	0.79 **	0.03	0.46 **	0.01	0.37 **
	LWA	($m^2 \cdot ha^{-1}$)					1	0.01	0.51 **	0.004	0.29 **	0.33 **
	LAD	($m^2\ m^{-3}$)						1	0.01	0.47 **	0.01	0.32 **
LiDAR	**IMP**	(m^{-1})							1	0.0001	0.17	0.27 *
	H_L	(m)								1	0.10	0.31 **
	W_L	(m)									1	0.03
	V_L	(m^3)										1

Selection criteria: * interesting relationship; ** good correlation is expected.

3.3. Canopy Characterization Along a Row Based on LiDAR Scanner Measurements

The mobile platform enabled scanning the entire row from two sides. The LAI was used as an example of the variation in the vegetation along the row. This estimation was based on the V_L as it was found to be the most accurate with the largest determination coefficient among the studied parameters. The calculated variation in the LAI in GH3 is shown in Figure 6. In this graph, the variation in the LAI value is calculated every 10 cm.

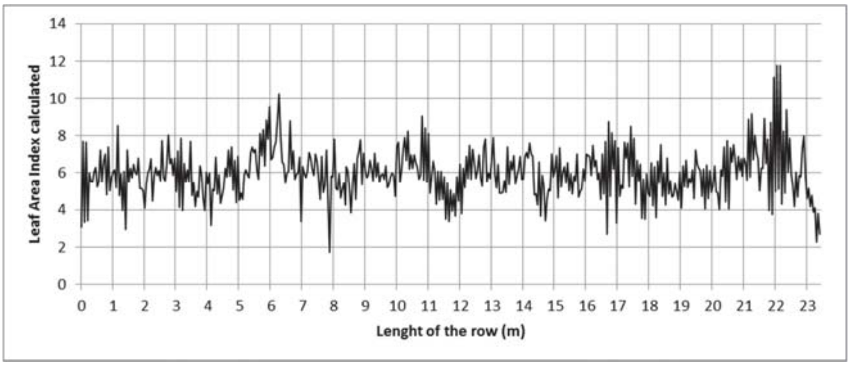

Figure 6. Calculated LAI variation along the scanned row in GH3.

Although the variation range is relatively constant along the row, the continuous changes in the canopy reflect the important variation in the LAI. The LAI values usually range from 3 to 9, with exceptions like those found for the Z positions 6 m, 8 m, and 22 m. The variation rate, calculated as the number of times the LAI value varies by more than 10% per linear meter, has a mean value of 10 m^{-1}. The values observed in Figure 6 are consistent with the LAI mean value (5.9). The standard error was found to be very small (0.17) in the manual measurements.

4. Discussion

A 2D LiDAR scanner was used to electronically obtain canopy parameters related to the canopy volume and density of a 3D crop with a complex structure, which is a difficult task. The general results in Table 2 show that the LiDAR values for geometrical characteristics, such as height and width, differ from the manual measurements, which were overestimated. This has also been observed in previous studies using this sensor [20,40]. The plant height value is influenced by the manual measurement method, in which one operator stands with a topographic milestone and other, at a certain distance, must take the measurements by observing the top part of the plants. As this height is important (>2 m) and the row spacing is narrow (2–2.8 m), the operator must have good skills in reading the height value and must not instead read its conical projection. In the case of the width, the most external points are taken, and therefore, the measured width for each section is not the mean but the maximum.

It is very noticeable the fact that the mean LWA values in the three GHs do not coincide with the H_M values, with the maximum mean value observed in GH3 rather than in GH2, which has the highest mean H_M value. At this point, the row spacing has a greater influence on the LWA calculation than the canopy height. On the other hand, the TRV values show a similar behaviour related to variation in the height and width values. In this particular case, the obtained data show that because the canopy height is constant (because of the greenhouse structure) and the row spacing is also determined by the farmer and conditioned by the greenhouse structure, the only parameter that changes is the canopy width. Therefore, in the case presented in this research, the TRV method seems to be more suitable than the LWA method to determine the canopy volume and density, which are mainly influenced by the row spacing.

In greenhouse tomato crops, the evolution of the LAI is linked to the plant height until the plant reaches the top of the greenhouse structure, where the canopy grows along the width. In this case, the TRV seems more suitable to describe the vegetation because it gives more information across the canopy width rather than the LWA, which in this particular case, is more affected by row spacing than by canopy height.

To estimate the canopy volumes, given by its TRV, it could be said that the LiDAR methodology is an interesting alternative measurement procedure, with acceptable determination coefficients, especially for H_L (Root Mean Square Error (RMSE) 9659.4 $m^3 \cdot ha^{-1}$) and V_L (RMSE 3446.09 $m^3 \cdot ha^{-1}$). This has been observed in other crops such as vineyards [20], hedgerow fruit trees [46], and large isolated trees like citrus [47] or olive [40]. Spray application based on canopy volume has been shown to be sufficiently accurate to be considered a first step in the dose adjustment process even for complex canopy structures [11,48]. Therefore, it is essential to accurately estimate parameters that allow farmers or technicians to have a very simple criterion to adjust the sprayed volumes, which can be easily done by constructing a canopy volume map or using a sensor operating real time and automatically adjusting the spraying parameters [49].

The importance of canopy density has been strongly suggested by different authors for modifying the spray volume calculated with volume-based dosing methods [16,18,50]. This parameter can be automatically estimated with the LiDAR scanner, as shown by the significance of the correlations between the LAI and H_L and those between the LAI and V_L. These results are consistent with those of other studies [51]. They have an important consequence in the automatic adjustment of the spray dose because the estimation of canopy density can be added to the volume estimator for the real-time adjustment of the spray dose, which has been implemented in other crops [50,52]. It was surprising that the number of LiDAR points per row length unit was not correlated with canopy density. This can be explained by the paired plantation system, which only allows the laser to scan one plant side and difficult the penetration of the laser beam into the canopy, and therefore, did not allow the researchers to properly study the correlation between the LiDAR points and the individual plant's LAD. In further studies, this parameter should be studied from the top view in addition to the side view in order to validate this parameter.

Regarding the canopy variation along the row, the LiDAR scanner properly characterized all longitudinal variations in this parameter, and considering that this parameter can vary 10 times per meter, as a mean value, manual methods cannot handle such a high variability. In this sense, the research on mapping methodologies has been very important in recent years [30], and further research is necessary to adapt these methodologies to the particular case of paired plantation systems in greenhouse tomato crops. The optimal spray volumes should also be adjusted according to the canopy volume and density in order to transform these volume or density maps in spray volume maps to optimize the spray application process.

5. Conclusions

Canopy characterization with a terrestrial 2D LiDAR scanner was performed in a paired plantation system in three tomato crop greenhouses and its accuracy was compared with manual characterization methods. The following conclusions can be drawn:

- The LiDAR scanner underestimates certain manual values, but this can be due to the inherent higher resolution (larger number of point measurements) when compared with manual methodology.
- Volume parameters, such as the TRV and LWA, can be estimated with the laser scanner with a high statistical significance and high determination coefficients. This is very important to satisfy the new requirements for dose harmonization according to these parameters in the European Union to ensure the most optimal dose rate adjustments.

- LAI can be estimated by the sensor from the calculated height or volume, but not from the number of impacts per hedgerow length unit, as expected. Further improvements in the laser scanning process could improve this estimation.
- Canopy variations along a single row are very important to determine the exact input needed in each part of the field, and therefore, manual methods are unsuitable because of their low longitudinal resolution. LiDAR scanners can adapt to this variability and hence are an appropriate alternative for generating canopy density maps.

Acknowledgments: This work was funded by the Spanish Ministry of Economy and Competitiveness AgVANCE project AGL2013-48297-C2-1-R) and the European Regional Development Fund (ERDF), and Cátedra Syngenta—UPC agreement for support training and research activities. The author would also like to thank the farmers who allowed us to use their fields.

Author Contributions: Jordi Llop and Emilio Gil conceived and designed the experiments; Jordi Llop, Jordi Llorens, and Montserrat Gallart performed the experiments; Jordi Llop and Jordi Llorens analysed the data; Jordi Llop, Emilio Gil, and Antonio Miranda-Fuentes wrote the paper; Emilio Gil is the project manager.

Conflicts of Interest: The authors declare no conflict of interest.

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6. General discussion

Three studies have been presented with the goal of improving the pesticide application in greenhouses by means of improving a vertical boom for spraying, and by the characterization of the tomato canopy.

In the first study, the objective was to improve the spray application process in greenhouses through the modification /improvement of an existing spray technology. A modified hand-held trolley sprayer was evaluated in two different canopy scenarios: high and low canopy density (5.96 and 2.53 LAI value respectively). In addition, several sprayer configurations were modified. These modifications affected nozzle type (flat fan and hollow cone), air assistance (activated or not activated), and spray volume (1,000 or 600 $L \cdot ha^{-1}$). In this study, deposition on the canopy, coverage of the deposition, and deposition distribution uniformity has been assessed. Overall results show the important effects of canopy density, spray application rate, and working parameters (mainly with regard to nozzle settings and air assistance) on the final quality of the spray distribution on tomato plants. In general, the highest values of leaf deposits have been obtained in low canopy density situations (LAI = 2.96).

After determining and testing the most suitable sprayer configuration, it was necessary to define the amount of air needed. In this sense, a second study was carried out with the aim to evaluate the influence of air-assistance on spray application in conventional tomato greenhouses. Three different spray configurations were evaluated. The first was a modified commercial manual trolley sprayer with two air assistance concepts, the second was a self-propelled sprayer, and the third was an autonomous self-propelled sprayer with a remote control. All of the sprayers were evaluated in terms of absolute and normalized canopy deposition, uniformity of distribution, and losses to the ground. In addition, the vertical liquid and air velocity distributions of the sprayers were assessed and compared to the canopy profiles and spray depositions. The overall results show that an increase in the airspeed does not imply an increase in deposition on the canopy and an increase in penetration. Losses to the ground are high mainly because of the pruning carried out by the farmer.

The characteristics of the canopy are important for the determination of the spray parameters, and consequently, for the efficiency of the spray procedure. For this reason, it is important to determine the main characteristics of the canopy. In the third study, where the main goal was to assess the accuracy of the LiDAR sensor for the characterization of the tomato canopy, a LiDAR sensor was used in three different greenhouses to determine the main parameters related to height, width, and volume, as well as leaf area. In addition, correlations between manual and electronic parameters were investigated in order to estimate the leaf area. With the possibility to mount the LiDAR sensor in a mobile platform, it was possible to scan the entire row in order to evaluate the canopy variations. Good correlations are obtained with manual measurements of LAI and TRV and with parameters measured with LiDAR sensor.

Evaluation of the spray deposition

In Chapter 3, in a greenhouse with a high, dense canopy, air assistance had a greater effect on the spray deposition results than the volume application rate. The volume application rate presents a significant effect when hollow cone nozzles are used, despite the fact that air assistance is used with the reference sprayer (flat fan nozzles without air assistance). Increasing the number of active nozzles by the reduction the distance between them from 0.5 m to 0.30 m, does not improve the results, despite the findings obtained by Nuyttens et al. (2004b) which conclude that reducing the nozzle distance improves spray deposits.

In the low density canopy, the high volume application rate (1,000 L·ha^{-1}) achieved when using six nozzles per side results in an increase in the deposition with and without air assistance. On the other hand, no difference appears between the results obtained with flat fan nozzles and air assistance at a 600 L·ha^{-1} and the reference sprayer at a 1000 L·ha^{-1} volume application rate. The hollow cone nozzles (at both volume application rates) and the reference sprayer at a low volume application rate present similar results. These low spray deposits obtained by hollow cone nozzles were also described by Foqué et al. (2012c) and Sánchez-Hermosilla et al. (2011). These studies also portray the flat fan nozzles as a technology with better spray deposition results.

Canopy density plays an important role in general canopy deposition. At the same time, air assistance is more significant at low density than at high density, even though spray deposits with air assistance were high.

In all cases, the deposition on the external part of the canopy is always higher than the deposition inside the canopy. The penetration inside the crop is mainly influenced by canopy density. In the high canopy density greenhouse, the maximum penetration index value is 59.7%, and in the low canopy density greenhouse, the density is 70.3%. In both cases, these values were obtained with the prototype sprayer with flat fan nozzles using air assistance.

In the most complex canopy (high density), the deposition is affected by several factors. The highest penetration value was obtained with flat fan nozzles with air assistance, followed closely by the reference sprayer (50%). This difference is explained by the density of the canopy. Even the results of the hollow cone nozzles (56.5%) are in accordance with those obtained with flat fan nozzles (57.9 – 50%); the average deposition in this case is the lowest among all treatments.

On the other hand, the effect of air assistance on the spray penetration in low canopy density is clear. The spray deposits inside the crop are higher for both application volume rates, which is explained by the penetration index values that reach up to 70% obtained with flat fan nozzles and air assistance.

Evaluation of air assistance.

Air assistance plays a very important role in the distribution of the spray onto the target because the transport of the droplets and shaking the vegetation. The study of the amount of air needed to obtain a uniform distribution and better penetration in comparison to sprayers without air assistance is presented in this section. In general, the maximum spray deposition was obtained with the configuration most similar to the previous test: airspeed of 14 $m \cdot s^{-1}$, six flat fan nozzles per side, but higher distance within (0.35 m).

The spray penetration index does not suffer significant variation (33.3–44.0 %) at high airspeed values, and are according to the penetration index values observed in Chapter 3. An increase in airspeed does not translate to an increase in penetration. On the external part of the canopy, spray deposits were higher than on the internal side. The penetration index ratio indicates as much external deposition as internal deposition. In addition, spray deposits at the top of the canopy interior present the lowest values of deposition, in spite of the 25 cm increase in nozzle position height (compared to the study presented in Chapter 3).

Losses to the ground were very high, and on the same order of magnitude as the measurements on the canopy. The main source could be the tomato growing system where the lowest 35 cm of the plant was defoliated. In some cases, the lowest nozzle position of the sprayer was close to the ground. These results point out the importance of a good sprayer adjustment according the canopy characteristics. The high amount of deposits on the centre aisle on the ground with 31 $m \cdot s^{-1}$ was explained by the excessive air crossing the canopy.

Liquid distribution tested on a vertical patternator was not affected by the air velocity. The most significant factor that affects liquid distribution is the nozzle spray pattern and distribution . In addition, the air distribution profile is clearly affected by the output distribution and direction, as well as airspeed. On the sprayers with individual spouts, areas within the outlets present lower air velocity.

Evaluation of the characterization of the canopy.

A 2D LiDAR scanner was used to electronically obtain canopy parameters related to the canopy volume and density of a three dimensional crop with a complex structure (this is a difficult task). The general results show that the LiDAR values for geometrical characteristics, such as height and width, differ from the manual measurements, which were overestimated. This has also been observed in previous studies using this sensor (Llorens et al., 2011;Miranda-Fuentes et al., 2015b). The plant height value is influenced by the manual measurement method, in which one operator stands with a topographic milestone and the other, at a certain distance, must take the measurements by observing the top part of the plants.

It is very noticeable that the mean LWA values in the three greenhouses studied do not coincide with the height of the plants values measured with a topographic milestone, with the maximum mean value observed in GH3 rather than in GH2, which has the highest mean HM value. At this point, the row spacing has a greater influence on the LWA calculation than the canopy height. On the other hand, the TRV values show a similar behaviour related to variation in the height and width values. In the case presented in this research, the TRV method seems to be more suitable than the LWA method for determining the canopy volume and density, which are mainly influenced by row spacing.

To estimate the canopy volumes given by its TRV, it could be said that the LiDAR methodology is very accurate, with high determination coefficients, especially for height and canopy volume measured with LiDAR. This has been observed in other crops such as vineyards (Llorens et al., 2011), hedgerow fruit trees (Rosell-Polo et al., 2009), and large isolated trees like citrus (Tumbo et al., 2002) or olive (Miranda-Fuentes et al., 2015b).

The canopy density can be automatically estimated with the LiDAR scanner, as shown by the significance of the correlations between the LAI and height measured with the LiDAR and those between the LAI and canopy volume measured with the LiDAR. It was surprising that the number of LiDAR points per row length unit did not correlate with canopy density. This can be explained by the paired plantation system, which only allows the laser to scan one plant side, and therefore did not allow the researchers to properly study the correlation between the LiDAR points and individual plant LAD. In further studies, this parameter should be studied from the top view in addition to the side view in order to validate this parameter.

Regarding the canopy variation along the row, the LiDAR scanner properly characterized all longitudinal variations in this parameter, and considering that this parameter can vary 10 times per meter as a mean value, manual methods cannot handle such a high variability. The optimal spray volumes should also be adjusted according to the canopy volume and density in order to transform these volume or density maps into spray volume maps, in order to optimize the spray application process.

Terrestrial 2D-LiDAR sensors can be the most appropriate alternative for canopy characterization for high-accuracy estimation of the canopy volume and density. Moreover, their longitudinal resolution makes them a useful tool for support decisions to adjust the liquid flow rate at a very specific level, allowing farmers to optimally protect their plants and prevent unnecessary pesticide waste that affects the environment and increases production costs.

7. Conclusions

In general, the results show that it is possible to improve the efficiency of pesticide application in greenhouse crops. The use of air assistance reduces the volume application rate and allows for good pesticide distribution uniformity. In addition, a strong correlation has been established between manual and electronic measurements that allow canopy characteristics to be defined.

Evaluating the settings of the manually-pulled trolley yielded the following conclusions:

- The density of the canopy has an effect on spray deposition, because the average values of leaf deposition obtained at low canopy density conditions were higher than those obtained for high canopy conditions.
- Clear differences in average deposition between external and internal sections of the canopy have been shown.
- All treatments using air assistance yielded better results in terms of deposition at the internal canopy zones. This resulted in higher penetration index values compared to treatments applied without air assistance.
- High canopy density was shown to not be affected by nozzle type. On the contrary, tests carried out at low canopy density have shown a tendency to increase deposition when flat fan nozzles and air assistance were used.
- Considering the effect of volume application rate on the quality of spray distribution, a more significant influence of the sprayer set up has been observed than that of the volume application rate. There are no clear benefits to increasing water volume rates.
- Air assistance configurations reduce the volume application rate without creating significant differences in both canopy densities.

Evaluating the effect of the air assistance device:

- Even when air assistance was used, there was a significant variability between external and internal deposition, considering the different canopy sections. The deposition at the internal part of the canopy was at least 2.5 times lower than the external side, highlighting the difficulty of penetrating the internal side of the canopy.
- The modified spray manual trolley with an airspeed of 14 m·s-1 showed the highest values in terms of deposition. However, increasing the air velocity did not increase the efficiency of the spray application.
- Air velocity and vertical spray pattern significantly affected the pesticide distribution on the canopy. The determination these parameters was a useful tool to assess the spray distribution on the canopy. In general, the ground losses were relatively high, even higher than the canopy in some cases, revealing a high risk of ground contamination.
- Considering the importance of greenhouse production in the area, there is a need to improve the pesticide application process, which is still hindered by a lack of advanced technologies compared to other agricultural sectors.

On the development of a methodology to characterize the canopy:

- The LiDAR scanner measurements of the shape parameters of the canopy are highly correlated with the manual measurements. The LiDAR scanner underestimates certain manual values, but this can be due to its higher accuracy and manual methodology limitations.
- Volume parameters, such as the TRV and LWA, can be estimated with the laser scanner with a high statistical significance and high determination coefficients. This is very important for satisfying the new requirements for dose harmonization according to the parameters set by the European Union, to ensure the most optimal dose rate adjustments.
- LAI can be estimated by the sensor from the calculated height or volume, but not from the number of impacts per hedgerow length unit, as expected. Further improvements in the laser scanning process could improve this estimation.

- Canopy variations along a single row are very important for determining the exact input needed in each part of the field. Therefore, manual methods are unsuitable because of their low longitudinal resolution. LiDAR scanners can adapt to this variability, and therefore are an appropriate alternative for generating canopy density maps.

8. Future works/research

The evaluation of the manually-pulled trolley with air assistance, and the improvements presented in this doctoral thesis, establish a strong basis for other improvements to this technology. The contents of this study studied deeply the characterization of the canopy by alternative methodologies to manual measurements and the development of a pre-commercial sprayer.

Future works and research concerning pesticide application in greenhouses will focus on:

- Establishing an accurate relationship between canopy stage and volume application rate in order to obtain a particular relationship between litres of product and canopy volume.
- Simplifying the determination and characterization of the canopy in order to clearly explain to farmers and operators.
- Improving the practicality, reliability, and robustness of the manually-pulled trolley.
- Determining the optimal parameters needed to reduce the volume application rate and PPP according to SUD 2009/128/CE.

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10.List of publications

In this section is presented the contribution of the author of this thesis in several types of publications. The following list includes publications accepted in peer review journals, a list of communications accepted in conferences, a list with collaborations on specific section on books, and a final list of the projects that I was involved during the 2010-2016 period synchronized with the period of time of PhD grant.

10.1. Publications in peer-reviewed journals

Llorens, J.; Gil, E.; **Llop, J.**; Escolà, A. Ultrasonic and LIDAR Sensors for Electronic Canopy Characterization in Vineyards: Advances to Improve Pesticide Application Methods. Sensors 2011, 11, 2177-2194.

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Llop, J.; Gil, E.; Llorens, J.; Gallart, M.; Balsari, P. 2015. Influence of air-assistance on spray application for tomato plants in greenhouses. Crop Protection, 78: 293-301

Llop, J., Gil, E., Llorens, J., Miranda-Fuentes, A., Gallart, M., 2016. Testing the Suitability of a Terrestrial 2D LiDAR Scanner for Canopy Characterization of Greenhouse Tomato Crops. Sensors 16, 1435. doi:10.3390/s16091435

10.2. Publications in conference proceedings

Llop, J., Llorens, J., Gil, E. 2010. Aplicació variable de fitosanitaris en vinya utilitzant sensors d'ultrasons. Ajust del volum en funció de les característiques de la vegetació. IX Jornades de Sanitat vegetal 2010, Barcelona.

Llop, J., Parera, J., Llorens, J., Gil, E. 2010. APLIPUR, herramienta para la regulación de los equipos de aplicación de purines. Congreso ECOFARM 2010, Barcelona.

Llorens, J.; Gil, E.; **Llop, J.;** Villalta, E. The error of speed and path deviation during proportional spray application in vineyard. Analysis and consequences. Suprofruit 2011. Book of Abstracts p. 42-43.

Gil, E.; Llorens, J.; **Llop, J**. DOSAVIÑA: five years of successful experiences in field tests. SuProFruit 2011. Book of Abstracts p. 82-83.

Gil, E.; Llorens, J.; **Llop, J**. 2012. New technologies adapted to alternative dose expression concept. *Aspects of Applied Biology 114, 2012 International Advances on Pesticide Application Techniques*

Gil, E., Gallart, M., Llorens, J. **Llop, J**. 2012. Determination of Drift Potential Value (DPV) for different flat fan nozzles using a horizontal drift test bench. AgEng Conference, Valencia.

Llorens, J., Gil, E., Duarte, S., **Llop, J**. 2012. First results using terrestrial LIDAR sensor for drift detection in vineyard spraying. AgEng Conference, Valencia.

Llop, J.; Gil, E.; Gallart, M.; Bayer, T.; Sánchez-Hermosilla, J. 2013. Efecto del número y tipo de boquillas en la calidad de las aplicaciones en invernaderos con barras verticales. Actas del Congreso Ibérico de Agroingenieria, 1-5.

Llop, J.; Gil, E.; Gallart, M.; Bayer, T.; Sánchez-Hermosilla, J. 2013. Spray distribution produced by a hand-held trolley boom sprayer in greenhouses. Proceedings of the 12th Workshop on Spray Application Techniques in Fruit Growing Suprofruit 2013, Valencia.

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Llop, J.; Gil, E. Nozzle characterization of knapsack sprayers. 2014. In: Workshop on Developments in hand-held application techniques. Castelldefels (Spain).

Gil, E.; **Llop, J.**; Gallart, M.; Valera. M.; Llorens, J. Design and evaluation of a manual Device for air flow rate adjustment in spray application in vineyards. 2015. Proceedinggs of the 13th Wokshop on spray application techinques in fruit growing 2015. Lindau (Germany)

Llop, J.; Gil, E.; Gallart, M.; Llorens, J. Improvements of spray Applications in greenhouses using hand-held trolleys with air assistance. 2015. Proceedinggs of the 13th Wokshop on spray application techinques in fruit growing 2015. Lindau (Germany)

10.3. Publications in national journals/books

Gil, E.; Gràcia, F.; Escolà, A.; Llorens, J.; **Llop, J**.; Camp, F.; Val, L.; Gracia, C.; Blanco, G. 2011. Manual de inspección de equipos de aplicación de fitosanitarios en uso. Ed: Ministerio de Medio Ambiente y Medio Rural y Marino. ISBN: 978-84-497-1159-4

Gil E., **Llop J**. Deutz-Fahr Agrotron 7250 TTV: Prueba superada para el nuevo referente en alta potencia. Agrotecnica suplemento especial. Marzo 2013.

Gil, E., Llorens, J. **Llop, J**. 2014. McCORMICK X7 670, tecnología al alcance de todos. Agrotécnica, Junio 2014, pp. 42-49.

Llop, J. Gil, E. Gallart, M. 2013. Efecto del número y tipo de boquillas en la calidad de las aplicaciones en invernaderos con barras verticales. Horticultura Diciembre 2013.

10.4. Participation in training/research projects

Herramientas de base fotónica para la gestión agronómica y el uso de productos fitosanitarios sostenible en cultivos arbóreos en el marco de la agricultura de precisión. AGL2013-48297-C2-1-R. Fundings: Ministerio de Ciencia e Innovación. Coordinate project. Main Researcher: Emilio Gil. Involvement: Collaborator. Duration: 2014-2017.

Proyecto LIFE FITOVID - Implementation of Demonstrative & Innovative Strategies to reduce the use of phytosanitary products in viticulture. LIFE13 ENV/ES/000710. Funding: Life-EU programme. Main Researcher: Yolanda Fernández (Neiker). UPC researcher: Emilio Gil. Involvement: Researcher. Duration: 2014 -2017.

Estrategias integrales para una utilización de fitosanitarios segura y eficaz. Pulverización inteligente en viña. AGL2010-22304-C04-04. Fundings: Ministerio de Ciencia e Innovación. Coordinate project. Main Researcher: Emilio Gil. Involvement: Collaborator. Duration: 2011-2014.

TOPPS Project - Train the operator to promote Best Practices and Sustainability. Fundings: European Crop Protection Association (ECPA). Main Researcher: Emilio Gil. Involvement: Researcher. Duration: 2015 – 2017.

Topps-Prowadis – Train the operator to promote Best Practices + Sustainability/ Protect Water from Diffuse Sources. Fundings: European Crop Protection Association (ECPA). Main Researcher: Emilio Gil. Involvement: Researcher. Duration: 2011 – 2013.

Cátedra Syngenta Agro en innovación y mejora de las buenas prácticas fitosanitarias. Fundings: Syngenta Agro, S.A. Main researcher: Emilio Gil. Involvement: Researcher. Duration: 2013-2015.

Specific projects under Catedra Syngenta-UPC:

Desarrollo y puesta a punto de un equipo para tratamientos fitosanitarios en invernadero. Main researcher: Emilio Gil. Involvement: Researcher. Duration: 2011-2014

Acción formativa buenas prácticas fitosanitarias en la cuencas hidrográficas del Ebro y del Duero. Main researcher: Emilio Gil. Involvement: Researcher. Duration: 2011-2013

Avaluació de l’eficàcia en l’aplicació de productes fitosanitaris en cultius hortícoles a la zona del Baix Llobregat i formació técnica per als aplicadors. Fundings: ADV-Horta Baix Llobregat. Main Researcher: Emilio Gil. Involvement: Researcher. Duration: 2011.

Avaluació de la qualitat de les aplicacions de fitosanitaris a la DO Penedès. Fundings: Consell comarcal de l’Alt Penedès. Main Researcher: Emilio Gil. Involvement: Researcher. Duration: 2014.