UNIVERSIDAD DE CÓRDOBA

ETSIAM
Escuela Técnica Superior de Ingeniería Agronómica y de Montes

Strategies for the optimization of the efficiency in the plant protection product applications in olive canopies

TESIS DOCTORAL

Antonio Miranda Fuentes

Directores:

Dr. D. Juan Agüera Vega
Dr. D. Gregorio L. Blanco Roldán
Dr. D. Emilio Gil Moya

Córdoba, Febrero de 2017

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PROGRAMA DE DOCTORADO

Biociencias y Ciencias Agroalimentarias

Doctorando: **Antonio Miranda Fuentes**

Directores: **Dr. D. Juan Agüera Vega**

Dr. D. Gregorio L. Blanco Roldán

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Córdoba, Febrero de 2017

TÍTULO DE LA TESIS:

Strategies for the optimization of the efficiency in the plant protection product applications in olive canopies

DOCTORANDO/A:

ANTONIO MIRANDA FUENTES

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

Los directores de la tesis, Prof. Dr. Juan Agüera Vega, Prof. Dr. Gregorio L. Blanco Roldán y Prof. Dr. Emilio Gil Moya, informan que el doctorando ha desarrollado los objetivos previstos compartiendo su formación con la investigación. El doctorando ha realizado estancias en el Institute for Advanced Studies and Research (IIFA) de la Universidad de Évora, Portugal, en el periodo comprendido entre el 29 de junio de 2016 y el 30 de septiembre de 2017.

La tesis se presenta en capítulos, que se corresponden con cuatro publicaciones aceptadas en revistas indexadas (Science of the Total Environment, Sensors y Crop Protection).

El doctorando ha puesto en marcha una línea nueva de investigación dentro del grupo de investigación, para estudiar las variables que afectan a la pulverización en el olivar de carácter tradicional, publicando los primeros trabajos que se han llevado a cabo en este cultivo a nivel internacional. En este contexto, se han obtenido importantes resultados de inmediata aplicabilidad que pueden redundar en la sostenibilidad de los tratamientos fitosanitarios llevados a cabo en este cultivo, en el que el conocimiento y la tecnología resultan muy escasos debido a la falta de investigación.

El proyecto en el que se enmarca la tesis (Convenio de Compra Pública Precomercial Mecaolivar), y en el que el doctorando ha participado en la línea de nuevos desarrollos de atomizadores adaptados al olivar tradicional e intensivo, ha sido galardonado con el I Premio Nacional de Innovación, concedido a la Universidad de Córdoba. Asimismo, el doctorando fue galardonado con el Premio Armand Blanc del CIGR en el Congreso EurAgEng 2016, celebrado en Aarhus, Dinamarca, como reconocimiento a la mejor comunicación presentada por un autor menor de 30 años de edad.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, a 19 de diciembre de 2016.

Firma de los director/es:

Fdo.: Juan Agüera Vega

Fdo.: Gregorio L. Blanco Roldán

Fdo.: Emilio Gil Moya

RESUMEN

La aplicación de productos fitosanitarios resulta necesaria para el correcto desarrollo de los cultivos y, por tanto, para asegurar su rentabilidad. No obstante, su mala gestión en los últimos años ha llevado a la aparición de problemas medioambientales de gran calado, lo que ha propiciado que haya una animadversion generalizada contra esta práctica. La Administración europea se ha hecho eco de esta preocupación social y ha impulsado un restrictivo marco legal para garantizar la sostenibilidad de los tratamientos mediante su racionalización. El caso del olivar, un cultivo de gran importancia en España, es especialmente crítico por tres motivos: por una parte, el cultivo se halla muy concentrado en la Cuenca del río Guadalquivir, con lo que la importancia de los impactos es muy alta. En segundo lugar, la escasez de investigación y transferencia hace que los agricultores y técnicos difícilmente estén en condiciones de llevar a cabo sus tratamientos de forma segura, optando generalmente por la sobre-dosificación para garantizar su eficacia biológica. Por ultimo, su carácter tradicional y sus características estructurales (copas de gran dimensión y de forma muy irregular, amplios anchos de calle, alta pendiente…) lo hacen especialmente complejo de cara a la pulverización sobre la copa de los árboles.

El objetivo de esta tesis es desarrollar nuevas estrategias para aumentar la eficiencia de las aplicaciones de fitosanitarios a la copa de los olivos, mediante la actuación simultánea sobre tres líneas clave: determinar la influencia de las variaciones en los principales parámetros de trabajo sobre la calidad de las aplicaciones, obtener un modelo simple para ajustar el volumen de caldo empleado a las características de la vegetación y ensayar nuevas soluciones para adaptar los equipos de pulverización a la forma de la copa de los árboles. Se establecen cuatro capítulos principales que desarrollan estos objetivos.

En el capítulo II, se estudia la influencia del volumen de caldo y del caudal de aire en la eficiencia, cobertura, penetración y homogeneidad de la pulverización. Los resultados muestran que es deseable reducir estos parámetros respecto a los comúnmente empleados en el campo, reduciendo así los volúmenes aplicados y las necesidades de potencia en los tractores.

En el capítulo III se comparan diversos métodos de caracterización del volumen de copa manuales con la tecnología más precisa disponible en la actualidad: el escáner LiDAR. Se muestra que los métodos manuales son precisos y, por tanto, pueden ser útiles a agricultores y técnicos para realizar ajustes sobre el volumen de caldo a aplicar. Se establece el método del 'Mean Vector' como el más polivalente para los diferentes tipos de olivar.

En el capítulo IV se llevan a cabo dos ensayos para determinar el óptimo volumen de aplicación específico (L de caldo por m^3 de volumen de copa) en árboles aislados. Se determina que el volumen de 0.12 $L \cdot m^{-3}$ resulta en un grado de cobertura óptimo, además de mejorar la homogeneidad en la copa y la penetración. Esto supone una importante reducción en los volúmenes a aplicar por parte de los agricultores.

En el capítulo V se detalla el desarrollo de tres nuevos equipos de pulverización adaptados a las condiciones particulares del olivar tradicional e intensivo. Cada equipo presenta unas particularidades que hace que trabaje major en un sistema o en otro, pero mejoran en todo caso al equipo comercial en términos de eficiencia. Incrementos de cobertura de hasta el 61% pueden ser conseguidos con estos nuevos atomizadores.

Palabras clave: olivar, parámetros de trabajo, productos fitosanitarios, volumen de pulverización, caudal de aire, LiDAR, caracterización de la vegetación, ajuste de la dosis, volumen de pulverización específico, desarrollo de prototipos.

ABSTRACT

Pesticide applications are necessary to guarantee the proper development of crops and, therefore, to ensure the profitability for the farmer. However, their mismanagement in last years has led to important environmental problems, triggering the emergence of a generalized animosity towards these practices. The European Administration, by taking into account this social concern, has developed a restrictive legal framework to guarantee the sustainability of treatments through their rationalization. In the case of olive, a very important crop in Spain, this problem is especially critical because of three main reasons. First, it is very concentrated in the Guadalquivir river basin, what makes the negative impacts to be very intense in the area, Next, the lack of knowledge and training makes farmers and technicians to not to be able to properly plan the treatments, generally over-dosing to ensure biological efficiency. Last, the traditional nature of this crop and their structural characteristics (big-sized trees with very irregular tree crown shapes, wide tree and row spacing, high slope conditions…) make it especially complex with respect to spray applications to the tree canopy.

The objective of this thesis is to develop new strategies to increase the efficiency of pesticide applications to olive tree crowns, through the simultaneous action on three key lines: to determine the influence of the variations in the main working parameters on the application quality, to obtain a simple model to adjust the sprayed volume to the canopy characteristics and to test new solutions to adapt the spraying equipment to the canopy shape, These objectives are developed along four main chapters.

In chapter II, the influence of the spray volume and the airflow rate on the efficiency, coverage, penetration and spray homogeneity is studied. The results show that it is appropriate to reduce these parameters with respect to those usually applied in the field, reducing in this way the applied volumes and the power needs in tractors.

In chapter III, different manual canopy characterization methods are compared to the most accurate technology: a LiDAR scanner. It is demonstrated that manual methods are reliable and, therefore, they can be useful to farmers and technicians to make adjustments to the spray volumes to be applied. The Mean Vector method showed to be the most polyvalent for different olive plantation systems.

In chapter IV, two trials were undertaken to determine the optimum specific spray volume (sprayed L per m^3 canopy volume) in isolated trees. It was determined that the specific volume of 0.12 $L \cdot m^{-3}$ resulted in an optimum coverage, in addition to improve the homogeneity of deposition throughout the crown and the spray penetration. This finding can lead to an important reduction in the volumes to be applied by farmers.

In chapter V, the development of three new air-assisted sprayers adapted to the particular conditions of traditional and intensive olive orchards is explained. Each one presents some particularities that make it to be more appropriate for one system or the other, but they all showed to have the potential to improve the efficiency of the conventional airblast sprayer. Coverage increases up to 61% were achieved with these new sprayers.

Keywords: olive, working parameters, pesticides, spray volume, airflow rate, LiDAR, canopy characterization, dose adjustment, specific spray volume, prototype development.

A mis padres, mi hermano y mis tíos.

A Ángela.

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Cuando se habla de la travesía por el desierto que supone la realización de una tesis doctoral, poco se espera uno hasta qué punto la expresión resulta precisa para definir el proceso en su conjunto. Son tantas las dificultades, problemas y sinsabores, que dificilmente en el momento de su lectura se pueden compensar con la alegría que ofrece la finalización del trabajo.

Quiero agradecer, en primer lugar, a mis directores, Juan, Gregorio y Emilio, la ayuda que me han brindado en el proceso, así como su guía en mi desarrollo como investigador y docente, para el que han sido fundamentales. También quiero agradecer a Jesús Gil su incondicional apoyo desde mi entrada al departamento.

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Symbols

AFR: airflow rate

A_{PA}: vertical projected area

ATA: P1 prototype

C_p: coefficient of penetration

CV: coefficient of variation

C_v: specific spray volume

d: spray deposition

d_e: deposit in the external sampling positions in the tree

d_i: deposit in the internal sampling positions in the tree

d_n: normalized deposition

E_a, E_b and E_c: tree crown's ellipsoid axes

F: deposition normalization factor

FS: forward speed

H_c: canopy/crown height

HF: high flow

H_{fl}: height of the first leaf

h_i: sampling height

HN_i: homogeneity in the impact number per area unit

HSC: homogeneity in the percentage coverage

H_T: tree total height

HV: high volume

L_a: treated sample area

LF: low flow

LFR: liquid flow rate

LiDAR: Light Detection and Ranging

LV: low volume

LWA: leaf wall area

MF: medium flow

$\overline{MV}$ or MV: Mean Vector crown characterization method (Chapters III to V)

MV: medium volumen (just in Chapter II)

MyL: P3 prototype

N_i lo: impact number per area unit in the lower side of leaves

N_i up: impact number per area unit in the upper side of leaves

N_i: impact number per area unit

O-S: P2 prototype

P1, P2 and P3: developed air-assisted sprayer prototypes

PTO: power take-off

R: relationship between the applied LFR and the AFR

rs: row spacing

RS: row spacing

SC lo: percentage coverage in the lower side of leaves

SC up: percentage coverage in the upper side of leaves

SC: percentage coverage

S_i: sampling sector

SV: sprayed volume

T_{cl}: Tartrazine concentration in the washing solution

T_d: trunk diameter

TRV: tree row volume

ts: tree spacing

VCPA: Vertical Crown Projected Area method

V_E: ellipsoid tree crown volume

V_L: LiDAR volume

VMD: volumetric median diameter

VR: spray volume rate

V_{TS}: Tree Silhouette Volume method

W: tree width

w: volume of washing extractanct

CHAPTER I – Introduction, objectives and structure of the work.

Chapter I - INTRODUCTION

I–1. Olive history

Olive (*Olea europaea* L.) is an evergreen tree belonging to the family of Oleaceae. Its origin seems to be set in Asia Minor, in the area that extends from the southern Caucasus to the Iranian plateau and the Mediterranean coasts of Syria and Palestine. From this area, it spread because of the Mediterranean civilizations conquers, what made it to be present in different countries from ancient times. The existence of the olive is reported in the twelfth millennium BC.

In the 16th century BC the Phoenicians started disseminating the olive throughout the Greek islands (Fig. I-1), later introducing it to the Greek mainland between the 14th and 12th centuries BC where its cultivation increased and gained great importance in the 4th century BC.

Figure I-1. Olive picture in Knossos palace, in Creete, Greece (www.minoancrete.com).

From the 6th century BC onwards, the olive spread throughout the Mediterranean countries reaching Tripoli, Tunisia and the island of Sicily. From there, it moved to southern Italy. The Romans took olive to North Africa, where it was already grown as its wild cultivars.

The Romans continued the expansion of the olive tree to the countries bordering the Mediterranean. Olive growing was introduced into Spain during the maritime domination of the Phoenicians (1050 BC) but did not develop to a noteworthy extent until the arrival of Scipio (212 BC) and Roman rule (45 BC) (IOC, 2016). After the third Punic War, olives occupied a large stretch of the Baetica valley and spread towards the central and Mediterranean coastal areas of the Iberian Penisula including Portugal. The Arabs brought their varieties with them to the south of Spain and influenced the spread of its cultivation.

With the discovery of America (1492) olive farming was carried from Seville to the West Indies and later to the American Continent. By 1560 olive groves were being cultivated in Mexico, then later in Peru, California, Chile and Argentina. In more modern times the olive tree has continued to spread outside the Mediterranean and today is farmed in places like southern Africa, Australia, Japan and China.

I-2. Olive cultivation

I-2.1. Olive cultivation in the World and Europe.

Nowadays, olive is cultivated in latitudes between 30º and 45º, in both hemispheres, in regions with Mediterranean climate, where summer is hot and dry. Olive is an important crop around the World, in which the total harvested area in the year 2014 was over 10.3 Mha (FAO, 2014). As the importance of the crop in the countries comprised in the Mediterranean basin is major, it is the most important tree crop in Europe in terms of harvested area (EUROSTAT, 2016).

As it can be seen in Figure I-2, many of the main olive growing countries in the World belong to the European Union, where the harvested area rises to 5.06 Mha (49% of the World's total olive harvested area) (FAO, 2014). The olive area in Europe importantly rose in the last 20 years along with the World's area (Fig. I-3). Thus, while the World's area increased in 36.37%, the European area increased at a lower rate, in 16.06%. This fact can be explained by the appearance of new growing countries like Tunisia, Turkey or Morocco, which increased their harvested area significantly in last years, reaching traditional olive growers like Italy, Greece or Portugal (Fig. I-2a).

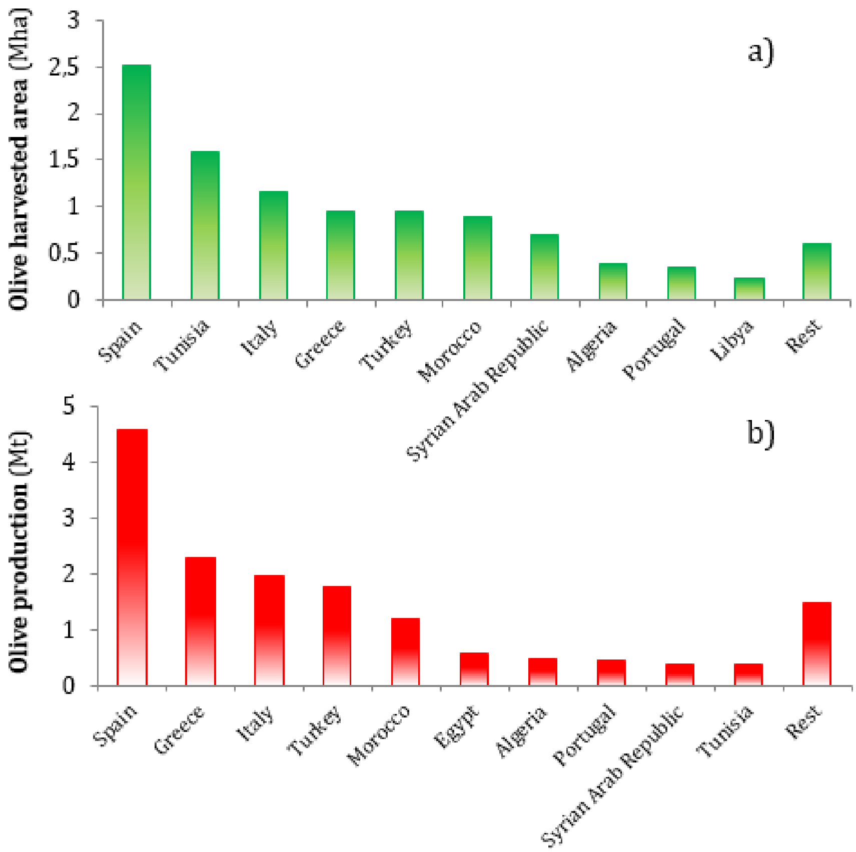

Figure I-2. Olive harvested area (a) and olive production (b) in the main growing countries (FAO, 2014).

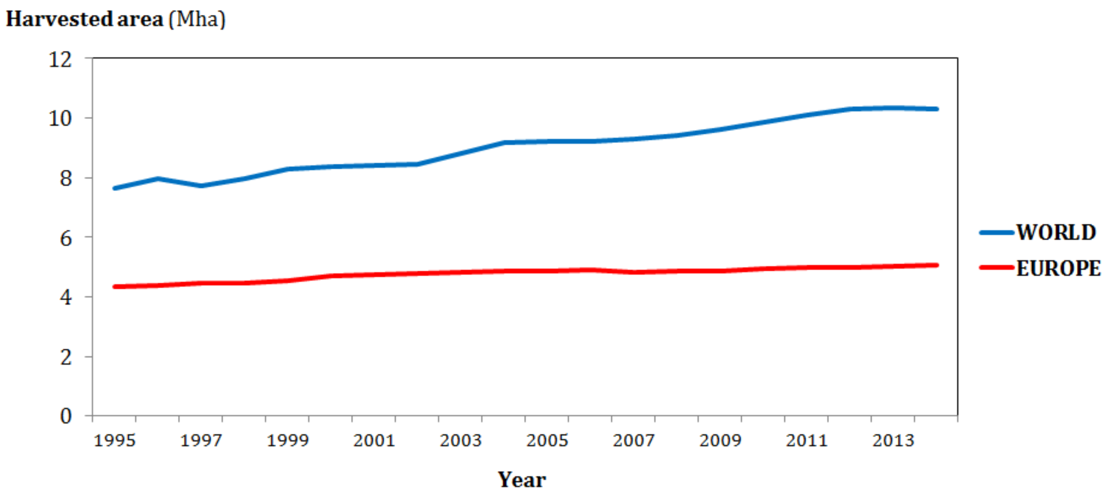

Figure I-3. Olive harvested area in the World and Europe from 1994 to 2014 (FAO, 2014).

Speaking about olive production, the World's rises to 15.5 Mt in 2014 (FAO, 2014). The top ten main producers in the World are shown in Figure I-2b. Spain remains to be the main producer in the World, followed by Greece and Italy. It is remarkable the fact that the rest of the countries comprised in the top ten producers are placed in the Mediterranean basin as well. The production in Europe rises to 9.43 Mt, what accounts for 60.8% of the total World's production, and Spain, with 4.58 Mt, yields 48.6% of the European production and 29.5% of the World's, and has a major importance in the olive oil and table olive markets.

Figure I-4 shows the evolution of olive oil, the main olive outcome, production and consumption in the World and Europe.

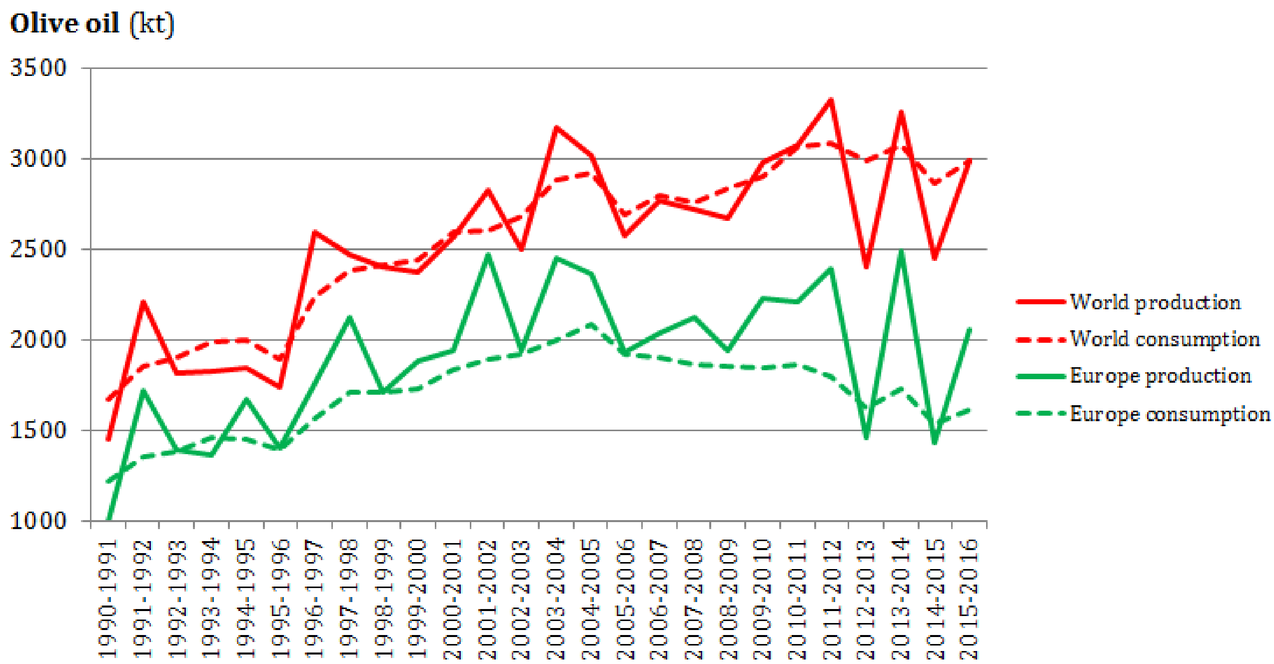

Figure I-4. Olive oil production and consumption in the World and Europe from 1990 to 2016 (IOC, 2016).

The olive oil counts with a great commercial appreciation because of its highly beneficial properties for human health in comparison with animal fats (Alarcón de la Lastra et al., 2001). Thus, Fig. I-4 shows that, even though the World production has followed a marked growing trend since year 1990 to date, the consumption has increased at the same rate. The total increase registered in the production for the considered period was 1535 kt, which means 105.7% of the initial production. The increase in the consumption was 1322 kt, 79.4% higher than 1990's (IOC, 2016).

The trend in the relation between production and consumption is not so clear in Europe, where the production grows along the whole period while the consumption do so until 2004 and presents a continuous decrease onwards. Thus, the total increase of production of 1056 kt (106.3%) does not match with the increase in consumption in the period, 400 kt (33.0%).

I-2.2. Olive cultivation in Spain.

Spain is the most important olive grower in the World with 2.52 Mha, what means almost 50% (49.76%) of the total Europe's olive harvested area (FAO, 2014) (Fig. 2a). The distribution of the olive harvested area in Spain is very uneven among its different regions (Fig. I-5), with Andalusia being the region with the highest importance (59%) in the total Spanish olive harvested area, followed by Castilla-La Mancha, in the second place with 16%. In the Andalusian Community, its highest intensity can be found in the Guadalquivir river basin (Fig. I-6).

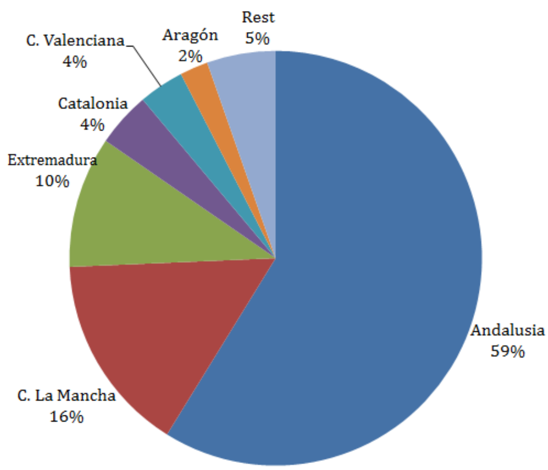

Figure I-5. Olive harvested area per autonomous region in Spain (MAPAMA, 2015).

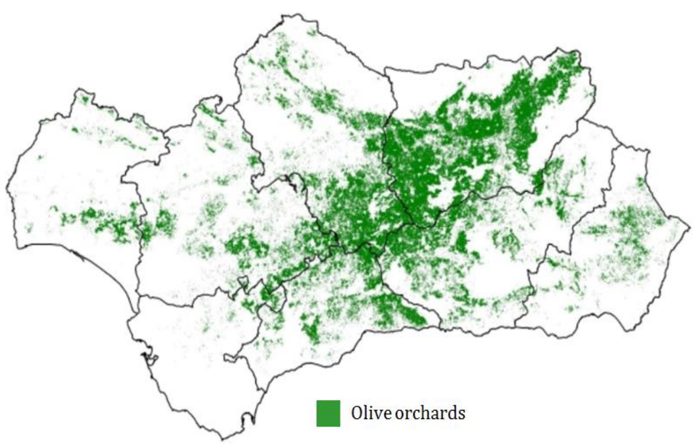

Figure I-6. Olive harvested area in Andalusia (Junta de Andalucía, 2002).

According to Civantos (2008), there are four different olive growing areas in Andalusia, regarding the prevalence of one olive variety or other. Thus, in the Area 1, of about 700,000 ha, and comprising the whole province of Jaén, the North of Granada and the West of Córdoba, the 'Picual' variety is the most important. This variety is grown for oil obtention, resulting in oils with a high content in polyphenols, what makes them very resistant to oxidation (Humanes and Civantos, 1993). Area 2, comprising about 430,000 ha in the province of Córdoba, is mainly grown with 'Hojiblanca' variety, which has a double use for oil obtention or fresh consumption as table olives. Area 3 is placed in the western Andalusia, with about 230,000 ha in the provinces of Seville, Cádiz and Huelva, mainly. In this area, there are many olive varieties but with a special importance of those intended to be consumed as table olives: 'Manzanillo' and 'Gordal'. Lastly, Area 4, of about 120,000 ha, is set in the eastern Andalusia, in the provinces of Almería, Málaga and Granada. This area contains many varieties with oil purpose, like 'Aloreña', 'Verdial de Vélez-Málaga' and 'Picual de Almería'.

Olive orchards in Spain are grown, according to AEMO (2012), in three different growing systems (Table I-1, Fig. I-7).

Table I-1. Main characteristics of the most common plantation systems in Spain (AEMO, 2012).

Plantation system	Number of trunks	Tree/Row spacing (m)	Plantation density (trees · ha^{-1})	Irrigation	Yield (kg · ha^{-1})	Plantation age (years)
Traditional	2 - 4	10-12/10-12	80 - 120	Not usual	2000 - 4000	> 25
Intensive	1	3-8/6-8	200 - 600	Usual	8000	< 40
Superintensive	1	1-3/4-6	1000 - 2000	Mandatory	12000	< 15

Figure I-7. Olive cultivation systems across Spain: a. Traditional, b. Intensive, c. Superintensive.

As it can be seen, the superintensive system is the only one similar to fruit orchards in central Europe, with a hedgerow disposition. The other two systems have big-sized isolated trees with several trunks in the case of traditional ones, very irregular crown shapes and wide tree and row spacing, what make the plantation density to be very low (80-120 trees per ha), with important gaps in between the trees. According to AEMO (2012). In 2012, the superintensive system accounted for only 2% of the total Spanish olive area, with 45,000 ha. Intensive orchards were 22% in percentage of the total surface, with 550,000 ha, and traditional orchards 76%, with 1,855,000 ha.

I-3. Pesticide applications.

Pesticide applications have a key role in crop production but this is one of the most controversial and difficult agricultural tasks nowadays. Its difficulty lies on the fact that, on the one hand, the agricultural outcomes must be free of any kind of pathogen or disease and, on the other hand, they must be free of pesticide residues at the same time. In addition, incorrect pesticide applications may cause severe environmental problems, producing water contamination events that affect flora, fauna and human health. Their use in Europe is very important, with a consumption of 396,000 t in 2014 (EUROSTAT, 2014). This remarkable use of these products, known by the European population to be harmful for the environment and themselves, aroused a general concern about their misuse that even made people to have a negative concept of agriculture in general.

The European Administration echoed this concern and began to work in strategies to properly regulate these operations. Thus, in 1979, Directive 79/117/EEC established the first base for the commercialization of some plant protection products. This Directive would be modified by Regulation EC 1107/2009, which also modified Directive 91/414/EEC about pesticide commercialization, and by which the registration of active ingredients was harmonized. This registration aimed to guarantee that all these substances were subjected to the same requirements in terms of toxicology and ecotoxicology.

The context of the plant protection product applications is present in the VI Environmental Action Plan’s development (2002), being one of its main objectives the reduction of the pesticide use.

Directive 2009/127/EC came into force on year 2009, affecting the machinery regulation by focusing on the environmental risks of the spraying equipment. Behind this Directive is present the fact that pesticide use represents a very important risk for human health and the environment. For this reason, the design, construction and maintenance of sprayers are seen as key phases to reduce any negative impact. Therefore, the aforementioned Directive introduces the requirements of environmental protection in the design and construction of these machines.

At the same time, Directive 2009/128/EC establishes the Community Action Plan to achieve a sustainable use of pesticides by applying these products in a secure and adequate way. This sustainable use is based on the promotion of the integrated pest control strategies along with alternative systems of pest control.

This Directive establishes the need to develop National Action Plans by the European countries. The National Action Plans are the basic instruments that the Member States have to ensure that the requirements established in the Directive are satisfied appropriately, and they can include aspects like the operator protection, the environmental security, the residue management or the use of specific techniques or crops.

The Spanish regulation that directly transposes Directive 2009/128/EC is the Royal Decree 1311/2012 that completely defines the Spanish National Action Plan to achieve a sustainable use of the pesticides. Previously, in 2011, the RD 1702/2011 arose to be in charge to establish a regime of periodical inspections of the spraying machinery in use to guarantee its good maintenance and operation quality. Figure I-8 summarizes the main European and Spanish laws regarding pesticide applications.

I-4. Pesticide applications in olive orchards

Pesticide applications have a remarkable importance in olive orchards. Spain, where olive is the second crop in importance after cereals (FAOSTAT, 2014), is the first consumer of pesticides in the European Union, with an annual consumption of nearly 79,000 t, a 20% of the total European's (EUROSTAT, 2014). It is estimated that they count for a 13.6 % of the total growing costs in olive cultivation (Fig. I-9).

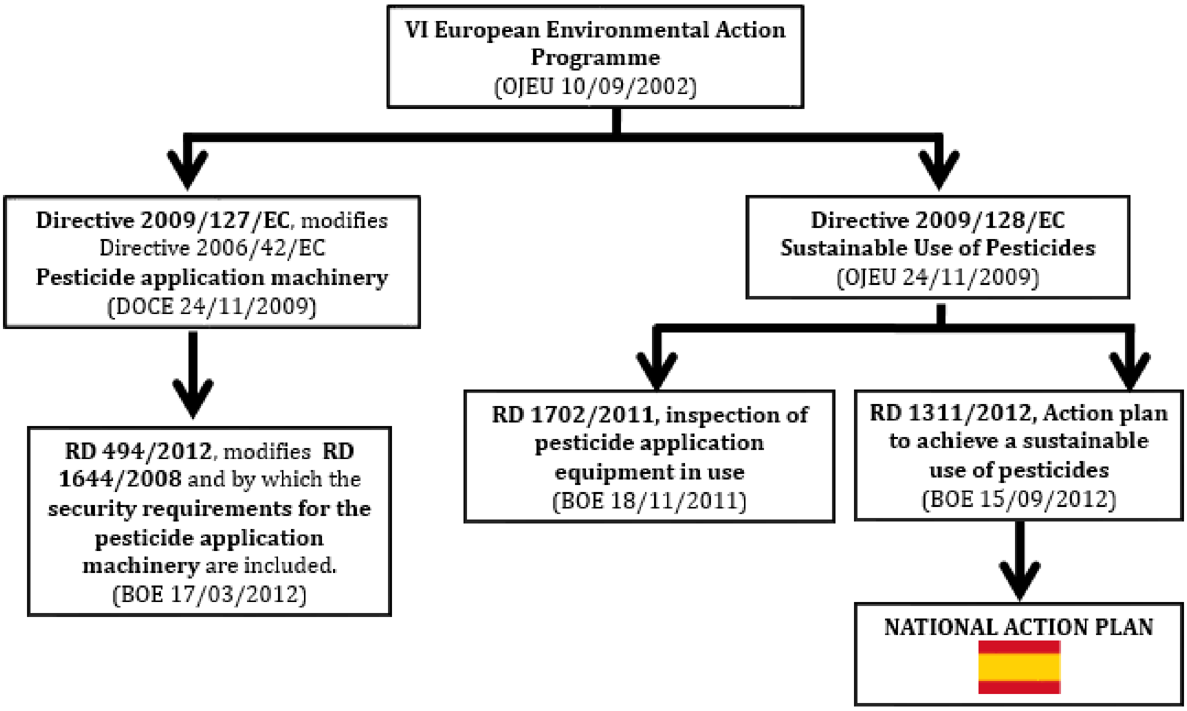

Figure I-8. European and Spanish laws regarding the pesticide applications.

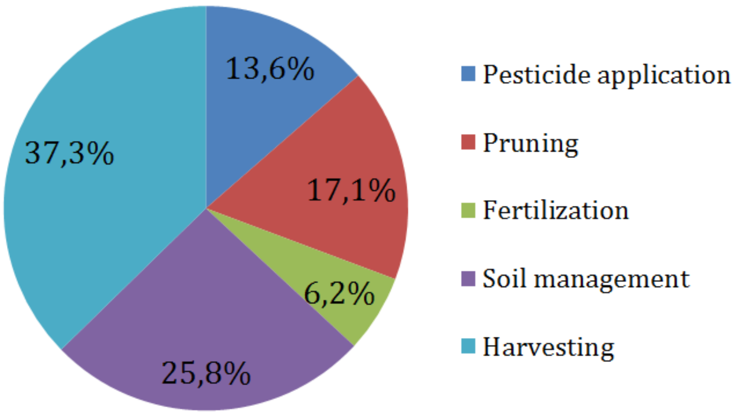

Figure I-9. Cost distribution of different operations in non-irrigated olive orchards in Spain (AEMO, 2012).

There are two main groups in which olive treatments can be classified: ground applications and applications to the tree canopy (Table I-2). In the case of ground spraying, it is typical to have two applications: a first one in late autumn or early winter to eliminate weeds under the tree crowns, in which those growing between rows are not sprayed to keep a spontaneous vegetal cover, and a second application in early spring to remove the vegetal cover in order to avoid its competition with olive trees for water, the most limitant factor in non-irrigated orchards.

In the case of the canopy applications, these are focused on pests and diseases affecting the crop (Table I-2). The main concern of farmers is the olive leafspot (*Spilocaea oleagina*), which has a remarkable importance in Spanish olive orchards and can produce significant losses in olive productions. The most commonly applied fungicides are copper salts that act by contact, making the fungus spores to not to be able to germinate (Campillo, 1998). The rest of the main pathological agents can also be controlled with these copper salts, which have the capability to act as a bactericide in the case of olive knot (*Pseudomonas savastanoi* pv. *savastanoi*). The treatments against pathogens are usually done in spring (typically one to three) and autumn (usually one). In the case of insect pests, the most important are the olive fly (*Bactrocera oleae*) and the olive moth (*Prays oleae*), with varying important of different kinds of cochineals, being the most important *Saissetia oleae*. The first agent has traditionally been controlled by the Public Administration with aerial applications, but the rest are usually handled by farmers with insecticides, being very common the organophosphorate dimethoate. It is very usual that farmers group treatments and apply, at the same time, a copper salt mixed with the insecticide and, most times, a foliar fertilizer as well.

Table I-2. Main treatments in olive orchards

Treatment type	Main agents*	Application equipment	Most usual products	Treatments per year
Ground treatment	Spontaneous weeds	Boom sprayer	Non-selective herbicide	Typically 2
Canopy treatment	*Bactrocera oleae*** *Prays oleae* *Saissetia oleae* *Parlatoria oleae* *Lepidosaphes ulmi* *Phloeotribus scarabaeoides*	Airblast sprayer	Organophosphorate insecticide	Typically 2
Canopy treatment	*Spilocaea oleagina* *Colletotrichum gloeosporioides* *Pseudomonas savastanoi* pv. *savastanoi* *Pseudocercospora cladosporioides*	Airblast sprayer	Copper salts (contact fungicide and bactericide)	2 to 4

* Alvarado et al., 2008; Trapero and Blanco, 2008.

** Agent traditionally controlled by the Public Administration through aerial treatments on reproduction focuses.

These treatments involve a very important pesticide consumption every year. There are four main problems by which they are not well executed in olive orchards:

A. Lack of knowledge about the influence of the operational parameters on the application homogeneity and efficacy. The traditional lack of investment by the main growing countries (Villalobos et al., 1995) have led to a situation in which there is an absolute uncertainty about the optimal application parameters in different olive systems.
B. Special characteristics of the olive orchards that importantly reduce spray application efficiency due to drift and runoff losses. The main difficulties are the wide tree and row spacing (usually 10 – 12 m) (Fig. I-10a), the high slope (usually higher than 10%) (Fig. I-10b) and the crown shape irregularity (Fig. I-10a).
C. The lack of specificity of the canopy spraying equipment. The airblast sprayer with axial fan and hollow cone nozzles is the most usual spraying equipment in olive orchards. These sprayers are not well adapted to the particular conditions metioned above.
D. Lack of effective dosing criteria. Most treatments are done with fixed working parameters with no regard for any aspect as the canopy shape, volume or density, the environmental conditions, the agent to be fought or the product to be applied.

These factors make farmers to perform very deficient treatments in which overdosing is very common (Fig. I-11). Their only objective is to completely cover the whole leaf surface to enhance the copper salts' contact action, with no corcern about the amount of active ingredient applied or the associated environmental and personal risks.

Because of the crop distribution, mainly focused on the provinces of Jaen, Cordoba and Granada (Figs. I-6 and I-10b), these territories are enormously influenced economically, socially and culturally by olive growing. Nevertheless, this fact also represents an important risk, as these areas, with important water reservoirs exposed to human consumption, receive a very important amount of pesticides as a consequence of the water runoff, favored by the high slope conditions (Gómez-Calero, 2009). These problems are the main reason why different authors found pesticide traces in the Guadalquivir river in the last years (Espigares et al., 1997; Barba-Brioso et al., 2010; Hermosin et al., 2013; Robles-Molina et al., 2014) which, even being in most cases under the security thresholds, are beginning to constitute a serious problem in this area. In addition, pesticide traces have been found in olive oil for human consumption (Amvrazi and Albanis, 2009).

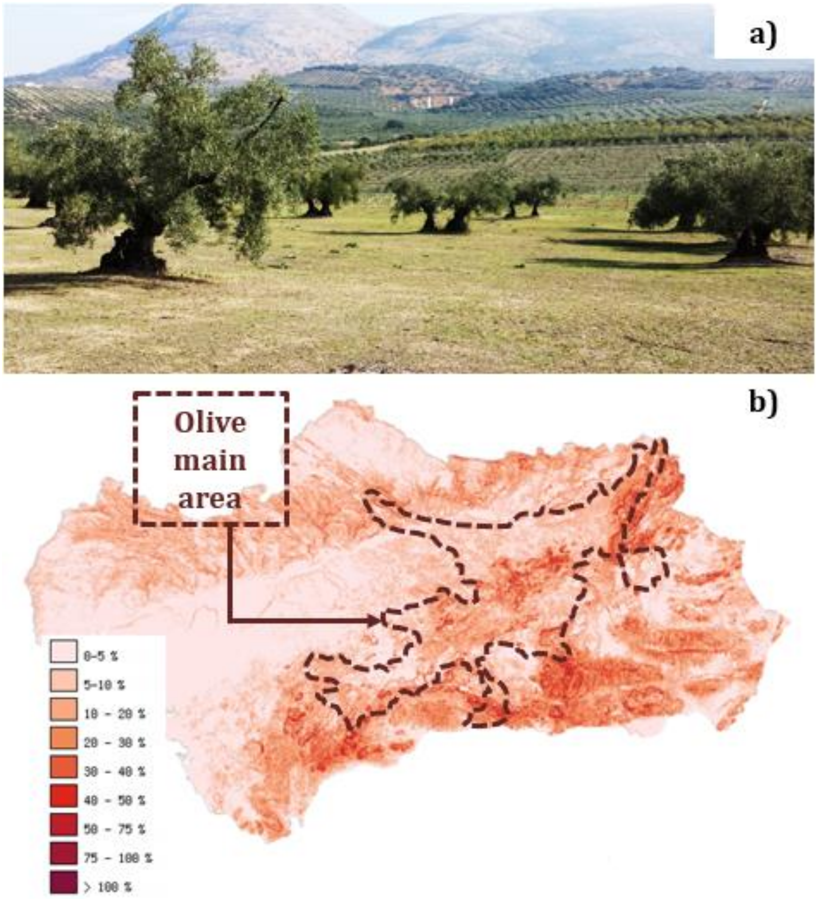

Figure I-10. a. Wide tree and row spacing in traditional olive orchard. **b.** Mean slope in Andalusia and olive main area (Junta de Andalucía, 2016).

Figure I-11. Overdosing with a copper salt to prevent from olive leafspot and olive knot.

I-5. Working parameters adjustment

The working parameters and the application equipment play an essential role in the quality and efficiency of the treatment. According to Cross et al. (2001), there are five main operational parameters that can be independently adjusted on any airblast sprayer: the spray liquid flow rate, the spray quality, the positioning of nozzles, the volumetric airflow rate and the forward speed. Among them, the liquid flow rate and the airflow rate are the most critical, as the farmer usually tends to maximize them to look for the highest penetration of the spray inside the canopy.

The liquid flow rate along with the forward speed, with a certain row spacing, result in a liquid volume rate (VR), usually expressed in $L \cdot ha^{-1}$. When working at a constant active ingredient concentration in the sprayer's tank (it is the case when the tank's stirrer works correctly), the VR determines the pesticide dose in kg or L per ha ground, so enhancing the accuracy of the VR can represent a very important measure to increase spray application efficiency in orchards. The optimum VR is that in which a proper coverage degree is granted while maximizing the spraying efficiency. Nevertheless, in most cases the farmer tends to apply higher volumes than the recommended ones, with the consequent problems and overcost (Landers, 2012).

The airflow rate (AFR) is usually expressed as the air volume that the sprayer fan's propeller blows per time unit (usually in $m^3 \cdot s^{-1}$ or $m^3 \cdot h^{-1}$). This parameter is linked to the air speed in the outlet, unless the sprayer carries some system to modify the outlet area, what is not very usual. The farmer tends to maximize AFR intuitively thinking that the higher the air velocity, the higher the penetration inside the canopy. Nevertheless, different studies have demonstrated that this belief is not true. For example, Marucco et al. (2008) found that intermediate air speed and AFR values led to a higher deposit on peach leaves than very high values. The reduction in the AFR can make the farmers to save money, because of the lower rotary speed in the tractor power take-off and also to reduce drift problems, clearly associated to this parameter (Cross et al., 2003).

It is mandatory, therefore, to assess the influence of the VR and the LFR in the spray deposit and homogeneity in olive canopies, as there is no knowledge on which a proper configuration system for the sprayers can be advised.

I-6. Pesticide dose adjustment

As a consequence of the risks concerning pesticide applications, immediate attention should be paid to the adjustment of the sprayed doses in order to guarantee that the optimal amount of active ingredient is applied.

The dose adjustment consists of adapting the amount of product (active ingredient) sprayed to the real needs to avoid excessive dosages while ensuring crop protection (Pergher and Petris, 2008a). The doses to be applied for each product can be easily found in its label. Nevertheless, there are different dosing recommendations across Europe (Table I-3), what makes pesticides to be applied in very different ways depending on the country.

Table I-3. Label dosing systems across Europe (Llorens, 2011). Data from Frieβleben et al. (2007). H_c means Canopy Height, TRV means Tree Row Volume and LWA means Leaf Wall Area.

	Fruit trees	Vineyards	Crops	Citrics/Olives
Austria and Germany	kg/ha/m H_c, max. kg/ha	max. %, kg/ha	kg/ha/m H_c, max. kg/ha	-
Belgium	kg or L/10000 m^2 LWA, max. kg or L/ha	-	kg/ha	-
France	kg/ha	kg/ha	kg/ha	-
Netherlands	max. %, L/ha	-	max. %, L/ha	-
Switzerland	kg/ 10000 m^3 TRV	max. %, L/ha	max. %, L/ha	-
Norway	kg/100 m row lenght	-	-	-
Greece	max. %, L/ha	max. %, L/ha	max. %, L/ha	max. %, L/ha
Italy	min-max. %, L/ha	max. %, L/ha	max. %, L/ha	max. %, L/ha
Portugal	max. %, L/ha	max. %, L/ha	max. %, L/ha	max. %, L/ha
Spain	max. %, L/ha	max. %, L/ha	max. %, L/ha	max. %, L/ha

Regarding to the spray dosing, there are important differences between the arable crops, considered as nearly planar targets when spraying, and those called 3D crops or high-growing crops (i.e. orchards and vineyards) (Walklate et al., 2006), in which the spray deposit per leaf area unit depends on different structural parameters of the trees or bushes. In these systems, different authors refuse the practice of spraying at fixed water volumes per ground area unit in favor of that known as crop-adapted dosing, which consists of adapting the sprayed doses to different characteristics of the target canopy (Walklate et al., 2003; Gil et al., 2005; Godyn et al., 2005; Viret et al., 2010). Nevertheless, and even though these authors propose different ways to adapt the spray application to the canopy characteristics, no agreement has been reached up to date about the best parameters to use. As a result, many proposals of models to adjust the pesticide doses have arisen (Doruchowski et al., 2009; Gil and Escolà, 2009; Jaeken et al., 1999; Walklate et al., 2011, 2006, 2003; Weisser and Koch, 2002). However, the two main dosing systems that are mainly used are the Tree Row Volume (TRV) and the Leaf Wall Area (LWA) (Fig. I-12).

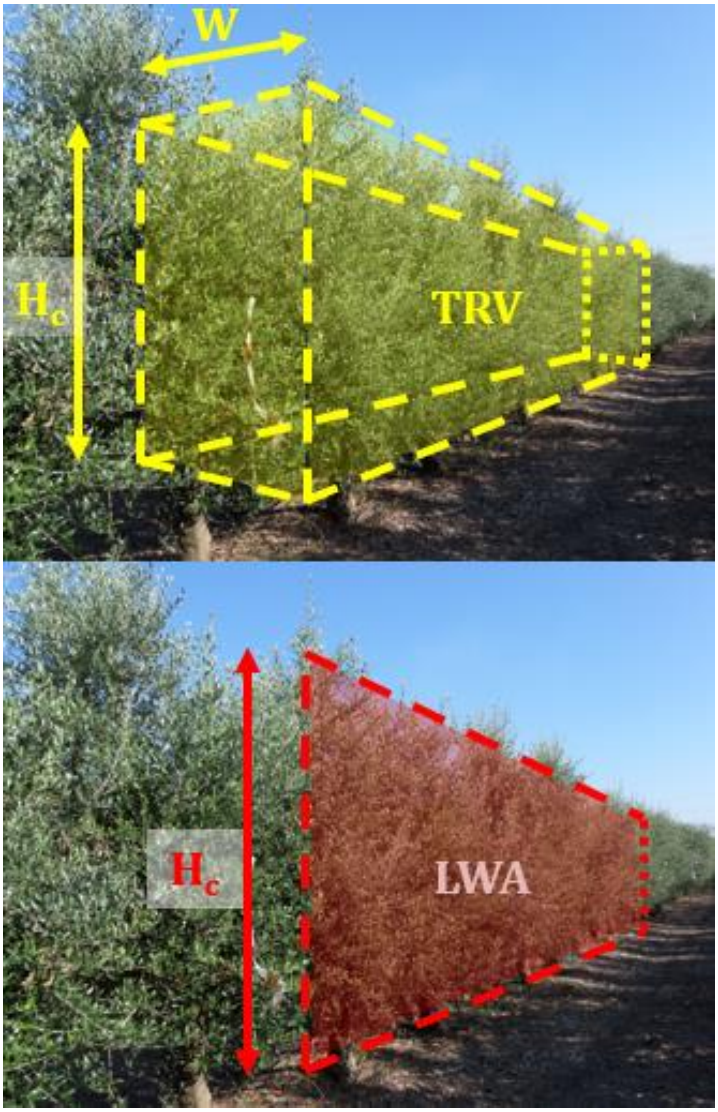

Figure I-12. Tree Row Volume (TRV) and Leaf Wall Area (LWA) representation in a superintensive olive orchard. In the picture, ‘H_c’ means canopy height and ‘W’, canopy width.

The TRV system (Byers et al., 1971; Sutton and Unrath, 1984) consists of determining the canopy volume (m^3 canopy) per hectare ground area as the parameter to adjust the applied dose to. Therefore, the necessary parameters to calculate this TRV are the row spacing and the tree height and width, according to Eq. I-1. The LWA (Morgan, 1981), on the other hand, establishes that the orchards behave as a planar vertical area when sprayed, to make an analogy with the arable crops. This dosing system is based, therefore, in the tree height and the row spacing, and the parameter to adjust the applied doses are the 10000 m^2 LWA (like when spraying a hectare ground area in an arable crop), as expressed in Eq. I-2.

$$TRV = \frac{H_C \times W \times 10000}{rs} \qquad \text{(I-1)}$$

$$LWA = \frac{2 \times H_C \times 10000}{rs} \qquad \text{(I-2)}$$

Where 'H_c' is the canopy height, or treated height in those cases in which the whole canopy profile is not sprayed, 'W' is the canopy width, and 'rs' is the row spacing.

In some countries, like Switzerland or Belgium (Table I-3), these two systems have succeed because of their simplicity and ease to use by farmers and technicians in the field, and in fact, they are included in the label doses. For this reason, they have been considered as possible references for a dose harmonization across Europe (EPPO, 2012). Different authors defended one or the other. Thus, Rüegg et al. (2001) proposed TRV and Frieβleben et al. (2007), the LWA. There are, therefore, two different trends: dosing according to the canopy volume (3 dimensions, TRV) and dosing according to canopy projected area (2 dimensions, LWA).

However, in spite of their advantages, these systems are reported to have some drawbacks, with the lack of consideration of the canopy density as the most important, especially in deciduous crops, which substantially vary their leaf area through the growing season (Walklate et al., 2006; Pergher and Petris, 2008).

In last EPPO Workshop, held in Vienna in October 2016, it was concluded that LWA could be a suitable dose expression method for those crops that are grown in a "wall" structure, i.e., pome fruits, vineyards and high-growing vegetables, while those called globular trees, i.e., citrus, olive and stone fruits, should include a third dimension in their dosing systems (EPPO, 2016). Therefore, olive trees need a three-dimension system to be properly dosed. Nevertheless, TRV is not suitable for these orchards, as the most usual plantation systems are the traditional and intensive systems (98% of the total harvested area, according to

AEMO, 2012), and these do not have hedgerow structure (Table 1), so the crop is not continuous along the row, leaving very important gaps in between the trees. Besides, the globular shape of the trees make the width to not to be constant along the row, but very irregular. Therefore, the first step towards an appropriate dosing system should be an accurate canopy characterization system.

On the other hand, in those tree crops in which the volume is used as the reference for dosing, it is necessary to define the specific spray volume parameter, i.e., the litres of spray mix per m^3 canopy volume. This parameter is mandatory to adjust the applied doses, converting canopy volume into spray volume. Different specific spray volume values have been used by different authors on different crops. For example, Llorens et al. (2010) and Gil et al. (2013) used the specific spray volume of 0.095 $L \cdot m^{-3}$ in vineyards. This specific volume mainly depends on the main characteristics of the canopy and can be modified according to different factors, but the finding of a base value that works properly in any growing stage in perennial trees, like olive, is a very important step forward in the development of a canopy-adapted dosing system.

I-7. Canopy characterization methods

The canopy characterization methods are the basis of the crop-adated dosing, as it was explained in the previous section. The existing methods in the bibliography can be divided in two broad categories: manual and electronic methods.

The manual canopy characterization methods consist of manually taking measurements from the trees by using a measuring tape or topographic milestone. It is usual that two operators work at the same time, the first one holding the measuring instrument and the second one taking the measurements and noting them down (Fig. I-13).

Figure I-13. Operators taking manual measurements from a superintensive olive orchard.

Different manual methods for canopy characterization have been widely applied to isolated trees. Among them, the ellipsoid method is the most widely used (Villalobos et al., 1995; Zaman and Schumann, 2005). This methodology consists of assuming that the tree crown shape is similar to an ellipsoid and, therefore, its volume can be obtained from two crown diameters and the canopy height. Usually, the diameters are measured at an intermediate height in the canopy but, in order to obtain more information about the canopy shape, some authors suggest to measure the diameter at different heights rather than only one (Zaman and Salyani, 2004, Fig. I-14).

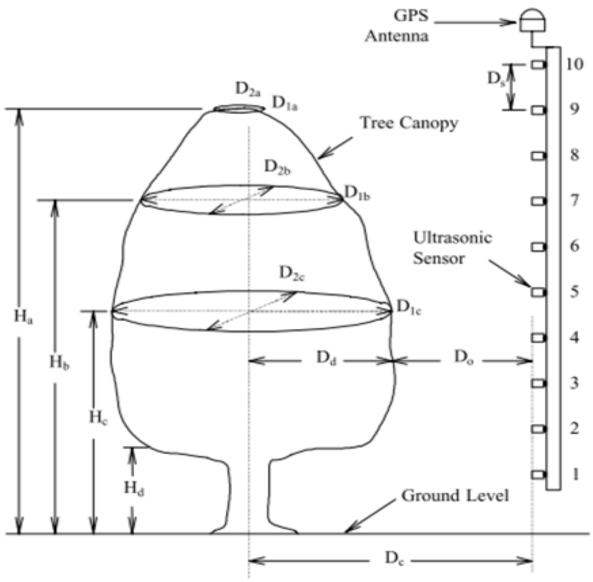

Figure I-14. Field arrangement for the canopy characterization through the ellipsoid manual method with different measurement heights (Zaman and Salyani, 2004).

Alternatively, the method of delimiting and measuring the projected area of the tree crown (Iniesta et al., 2009) has been proposed as a manual measurement process. Vertical crown projection onto the soil can be related to canopy volume (Xu et al., 2013). Several possibilities for crown projection were established by the same authors, who proposed another canopy characterization methodology named tree silhouette.

Electronic measurement methods are based on sensors by which geometrical parameters of the canopy can be measured or calculated. From these parameters, it is possible to obtain others, like the canopy volume or the leaf density. The main sensors used in these studies are the ultrasonic sensors (Fig. I-15a), the optical sensors (Fig. I-15b) and the laser-based sensors (Fig. I-15c) (Rosell and Sanz, 2012). There are other techniques, like the photographic methods (Leblanc et al., 2005) and the stereovision (Kise et al., 2005) that, even being very accurate, are more difficult to use by farmers and require important training. Therefore, they remain only in the research field for the moment.

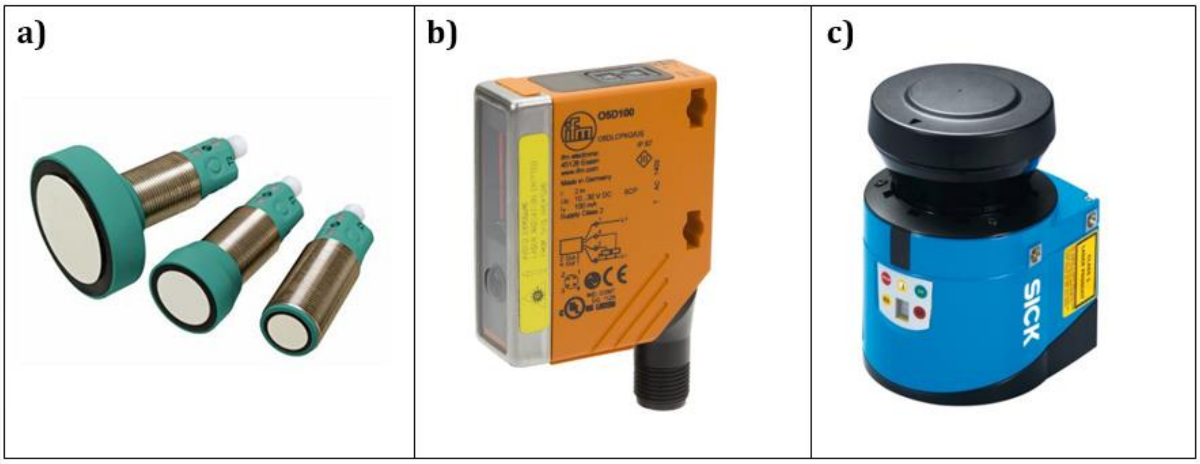

Figure I-15. Sensors commonly used in research for electronic canopy characterization. a. Ultrasonic sensor. b. Optic sensor. c. LiDAR scanner.

Ultrasonic sensors have been used for canopy volume measurements in vineyards (Gil et al., 2007; Llorens et al., 2011), orchard fruits (Jeon et al., 2011; Stajnko et al., 2012; Walklate et al., 2002), citrus plantations (Tumbo et al., 2002; Zaman and Salyani, 2004) and olive plantations (Gamarra-Diezma et al., 2015) due to its easy operation and management and affordable real-time data processing. However, there are doubts as to the accuracy of such measurements (Escolà et al., 2011; Gamarra-Diezma et al., 2015). Further, laser technology has been found to achieve higher precision in comparison with ultrasonic sensors (Llorens et al., 2011a; Tumbo et al., 2002), and has been already validated in olive canopies (Moorthy et al., 2011) (Fig. I-16).

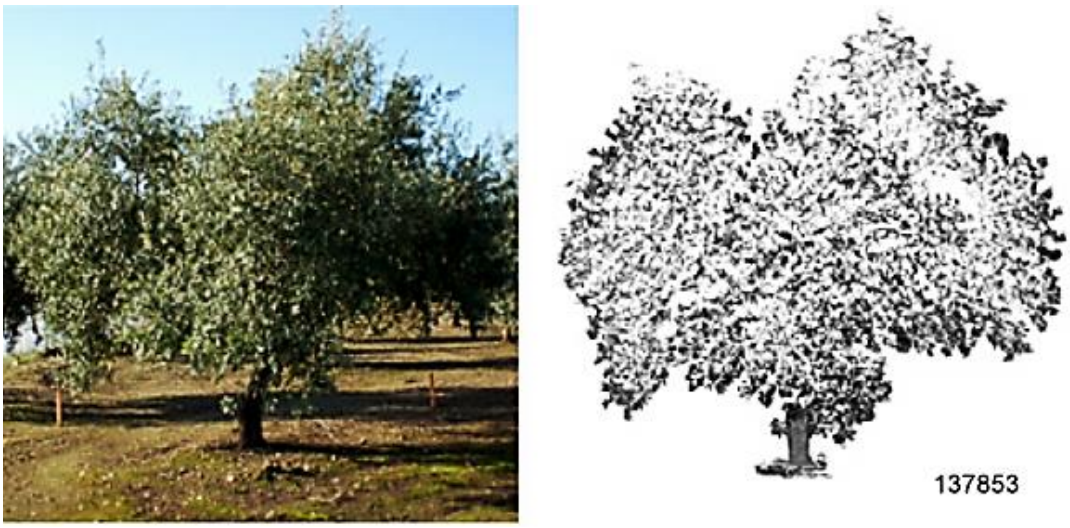

Figure I-16. Comparison between a picture of an olive tree and the corresponding projectection of a point cloud generated with a 3D LiDAR scanner (Moorthy et al., 2011).

Despite its precision, field management of those electronic devices is complex and not very well understood by farmers and technicians. Conversely, accurate protocols for manual canopy characterization seem much more affordable and user-friendly, utilising simple and quick measurements. Whatever the selected method for canopy evaluation, it should guarantee some minimum requirements in terms of accuracy (as close as possible to the real canopy dimensions) in order to apply the most suitable amount of pesticide. Up to the date, there is no knowledge about the accuracy of each one of the existing manual methods in different kinds of olive canopies.

I-8. Spraying equipment

As it was pointed out previously, the spraying equipment presents two main problems with respect to the efficiency of applications in olive canopies. On the one hand, the maintenance of the sprayers in use is very poor. To deal with this circumstance, the RD 1702/2011, through the official Inspection Manual (MAGRAMA, 2014), establishes the requirements that the spraying equipment must accomplish to be considered valid to operate in Spain. There are three kinds of inspection of the sprayer's elements: visual inspection, operation inspection and measurements (Cano and Blanco, 2016). The bad maintenance is a real problem for application efficiency. For example, a previous research of the Group AGR-126 of the University of Córdoba showed that, in 256 inspections of sprayers in use in Andalusia, 79.3% of the sprayer manometers failed in accuracy or resolution, making impossible to correctly set the spraying pressure and, therefore, misadjusting the liquid flow rate and the applied dose.

The second aspect by which these machines cannot achieve high efficiency rates is the lack of specificity of the airblast sprayers to traditional and intensive olive plantations. Even perfectly adjusting the VR and the AFR according to the canopy characteristics, a good efficiency is difficult to achieve if the sprayer is unable to efficiently carry the droplets to the target leaf surface. The sprayer used in olive nowadays is the airblast sprayer commonly used in other tree crops (Fig. I-17).

Figure I-17. Commercial airblast sprayer in a traditional olive orchard in the southern Spain.

This sprayer has suffered few changes since it was first developed, in the early 1950s (Fox et al., 2008), and the only new technology it incorporates is the ON/OFF ultrasonic sensor. This sensor makes the equipment to only spray when canopy is detected inside its measuring range (usually 6 m), remaining the electrovalves closed in the opposite case. This technology showed to generate an important pesticide saving when spraying trees with important gaps along the row (Ganzelmeier and Rautmann, 2000; Brown et al., 2008), as it is the case in traditional and intensive olive plantations. Nevertheless, the high row spacing (usually 12 m) and tree crown volumes (in traditional orchards they reach 100 m^3 easily) make this equipment to be very inefficient in the pesticide use, making necessary to apply high volumes to increase the coverage on leaves. This circumstance was already observed in other crops (Holownicki et al., 2000), where it was concluded that the bigger and older the trees, the lower the efficiency of the common airblast sprayer. Therefore, the development of new airblast sprayers adapted to traditional and intensive olive orchards would enable the complete application optimization, along with the working parameters and the applied doses.

I – Hypothesis and objectives of the work

The hypothesis of this work is that it is possible to increase the pesticide application efficiency through the adjustment of the operational parameters and of the sprayed volume to the canopy volume, and through the design of the spraying equipment to adapt it to the olive orchard characteristics.

The general objective of this research work is to develop different strategies to improve the efficiency of pesticide applications in olive orchards, by adjusting the volume rate according canopy characteristics, reducing drift and losses to the ground and avoiding environmental damage.

The achievement of those goals is granted by matching the following specific objectives:

1. To develop a methodology of assessment of the application quality and efficiency in olive orchards, comprising traditional, intensive and superintensive plantations.
2. To define appropriate parameters to assess the spray penetration and homogeneity of deposits throughout the olive canopies.
3. To find appropriate working spray parameter ranges in olive orchards, mainly for liquid volume rate and airflow rate.
4. To assess the most adequate methodology for canopy characterization in olive trees, by comparison between manual and electronic methods.
5. To obtain linear models that relation electronic measurements of tree crown with manually-obtained parameters specifically adapted to different plantation systems.
6. To obtain the optimum specific spray volume, i.e., litres of spray mix per cubic meter canopy volume, for isolated olive trees.
7. To identify good strategies to increase the application efficiency in traditional and intensive orchards from the sprayer design point of view.

I – Context of development of the thesis

The present thesis was developed in the research group AGR-126 "Mechanization and Rural Technology" in the Department of Rural Engineering of the University of Córdoba.

The author of this thesis, Antonio Miranda, received a FPU scholarship (Training of University Professorate) from the Spanish Ministry of Education, Culture and Sport in the 2012 edition.

The research line began with a program financed by the Junta de Andalucía Administration, that lasts from 2008 to the date.

This program intended to inform Andalusian farmers and technicians about the new Spanish legislation in pesticide application and, more specifically, about the inspections established by the RD 1702/2011. It also aimed to develop new inspection protocols before having the official Manual for hydraulic sprayers currently in use (MAGRAMA, 2014). The different courses organized in this program showed that farmers were not using airblast sprayers properly as they did not have any objective knowledge about pesticide dosing and sprayer regulation. These aspects, along with the lack of adaptation of the spraying equipment to the olive crown geometry and dimension, made the project to arise as an attempt to make a research on how the main operational parameters could be optimized in conventional airblast sprayers in order to properly advise farmers and technicians and, on the other hand, to develop previous ideas to adapt this equipment to the characteristics of these orchards. This project was entirely funded by the Spanish Olive Oil Interprofessionals (IAOE), what demonstrates the interest of the olive oil sector in making treatments in a more sustainable way.

After six months, this project was cancelled because of the common interest of IAOE and the Spanish Ministry of Economy Innovation in signing a new project to optimize different operations in Spanish olive orchards through the development of new machinery well adapted to their particularities. Thus, a main line in this project, called "Mecaolivar", had the goal to develop three airblast sprayer prototypes to optimize the efficiency in aerial pesticide applications. Thus, the main part of the thesis was carried out during this project, which ended in December 2015.

During the PhD, important collaborations were undertaken with the Unit of Agricultural Mechanization of the Universidad Politécnica de Cataluña. In addition, a collaboration with Professor Gottlieb Basch, from the University of Évora, was undertaken, where the

PhD student went for three months to work on the development of strategies to reduce pesticide applications in conservation agriculture systems, like vegetal covers in olive orchards that are mandatory to reduce soil erosion. Furthermore, the student was also collaborating with the Dipartimento di Science Agrari, Forestali e Alimentari (DiSAFA) of the University of Torino to work on drift reduction with pneumatic nozzles.

I – Links of the objectives with the scientific papers

The specific objectives previously described are developed in four research articles (Papers A – D).

Paper A: Miranda-Fuentes, A., Rodríguez-Lizana, A., Gil, E., Agüera-Vega, J., Gil-Ribes, J.A., 2015. *Influence of liquid-volume and airflow rates on spray application quality and homogeneity in super-intensive olive tree canopies*. Science of the Total Environment, 537:250–259.

Paper B: Miranda-Fuentes, A., Llorens, J., Gamarra-Diezma, J.L., Gil-Ribes, J.A., Gil, E., 2015. *Towards an optimized method of olive tree crown volume measurement*. Sensors, 15: 3671–3687.

Paper C: Miranda-Fuentes, A., Llorens, J., Rodriguez-Lizana, A., Cuenca, A., Gil, E., Blanco-Roldán, G.L., Gil-Ribes, J.A., 2016. *Assessing the optimal liquid volume to be sprayed on isolated olive trees according to their canopy volume*. Science of the Total Environment, 568: 296–305.

Paper D: Miranda-Fuentes, A., Rodríguez-Lizana, A., Cuenca, A., González-Sánchez, E.J., Blanco-Roldán, G.L., Gil-Ribes, J.A., 2017. *Improving plant protection product applications in traditional and intensive olive orchards through the development of new air-assisted sprayer prototypes*. Crop Protection, 94C: 44–58.

The specific objectives achieved and justified in each paper are presented:

- **Objective 1:** papers A, C and D.
- **Objective 2:** papers A and C.
- **Objective 3:** paper A.
- **Objective 4:** paper B.
- **Objective 5:** paper B.
- **Objective 6:** paper C.
- **Objective 7:** paper D.

Figure I-18 shows a summary of the main specific objectives presented in this thesis and their relationship with the four peer-reviewed papers presented in the thesis.

As it can be seen, the specific objectives are organized in five main aspects studied in the PhD:

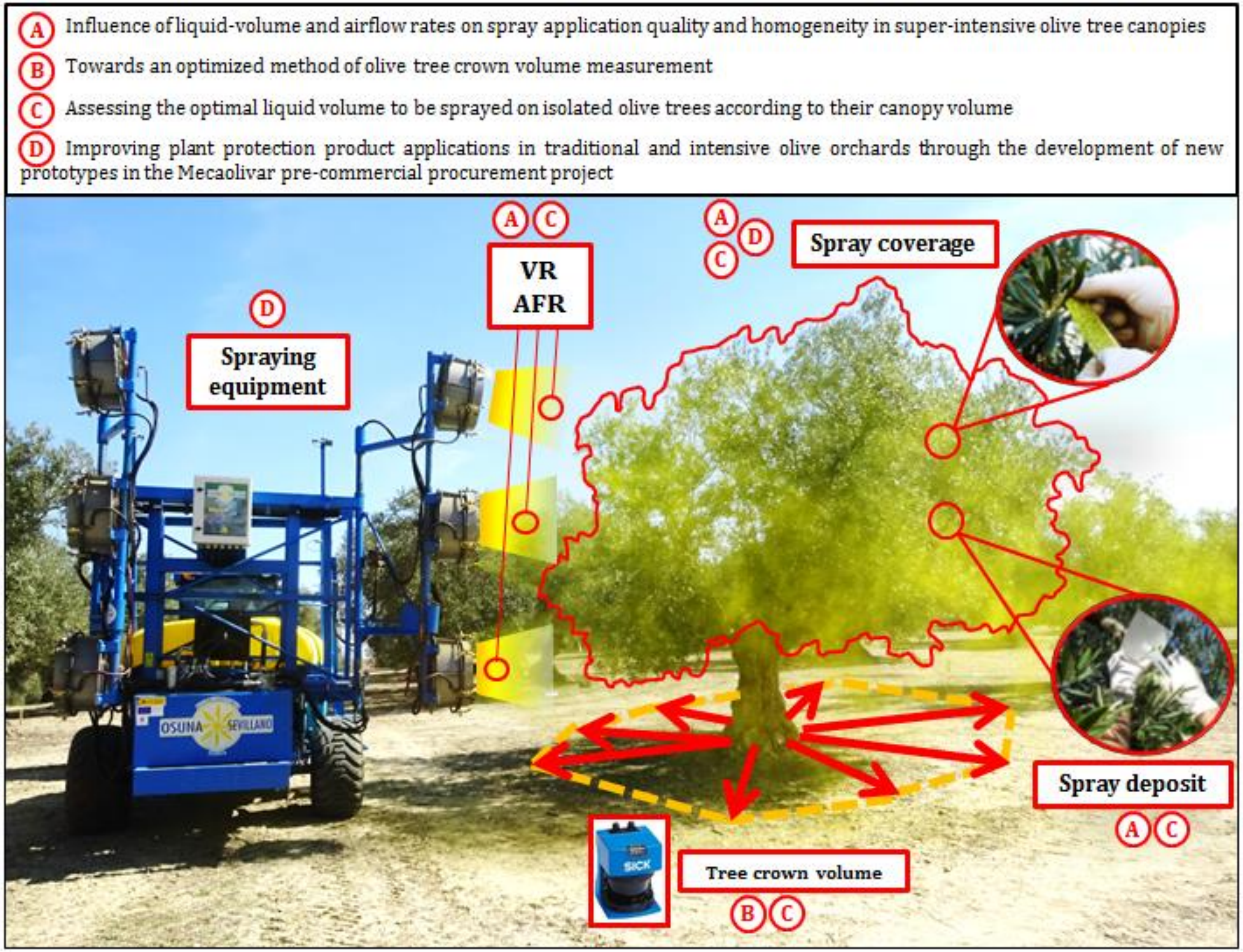

Figure I-18. Connection of the main specific objectives with the four peer-reviewed papers

- **Spray deposit:** the spray deposit is directly linked to the amount of spray that reaches a certain part of the canopy. This parameter has a double purpose in the research trials presented: on the one hand, it is an indicator of the spray efficiency, as the higher the deposit, the higher the efficiency for a certain sprayed volume. On the other hand, it is very useful to determine the spray penetration and homogeneity throughout the canopy, as it allows the researchers to quantify the differences in deposition received by the inner and outer positions. It also enables the calculation of the coefficient of variation of the deposition in different sampling positions in the canopy. This parameter is assessed with a spray tracer by washing leaves or artificial collectors.

  T the adaptation of this methodology to different types of olive orchards was crucial in **papers A** and **C**.
- **Spray coverage:** this parameter is linked to the efficacy of the treatment. Pesticides acting by contact need to have a proper degree of coverage with a minimum number of impacts per leaf square centimeter. The percentage coverage also showed to be a good methodology to quantify spray deposition on leaves. The water sensitive paper, which turns from yellow into blue when wet, along with the image analysis, are the main tools to determine the coverage parameters.

  The coverage parameter evaluation was crucial in **papers A**, **C** and **D**.
- **Tree crown volume:** the canopy volume is the main parameter for adapting the spray volumes to canopy characteristics, with special importance in isolated or globular trees. Precise crown volume measurement is difficult to achieve, but manual canopy characterization methods can achieve good volume estimations for dose adjustment in field conditions.

  Olive crown volume manual characterization methods are analyzed in **paper B**, and spray volume was optimized according to this parameter in **paper C**.
- **VR and AFR:** these two parameters are very important for any treatment, as they determine the applied dose and the air current that transports the droplets to the target canopy, respectively. The analysis of the deposition, the coverage, the penetration inside the canopy and the deposit homogeneity with respect to these two parameters in olive canopies is crucial. In the case of the VR, the achievement of the optimum volume to be applied with respect to the canopy characteristics,

and more specifically, with the crown volume, is the basis of a dosing system in olive.

These two parameters were analyzed in **paper A**, and the optimal VR according to the canopy volume in isolated olive trees was obtained in **paper B**.

- **Spraying equipment:** the sprayer has major importance to optimize spraying once the operation settings and sprayed volumes are optimized according to the canopy volume. The commercial airblast sprayer has shown to be inefficient in big-sized trees with wide row spacing, like intensive and especially traditional olive orchards.

  Paper D describes the development and first tests of three airblast sprayer prototypes especially designed to work in olive orchards.

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CHAPTER II - Influence of liquid-volume and airflow rates on spray application quality and homogeneity in super-intensive olive tree canopies.

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Chapter II - Influence of liquid-volume and airflow rates on spray application quality and homogeneity in super-intensive olive tree canopies

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II - Abstract

Olive is a key crop in Europe, especially in countries around the Mediterranean Basin. Optimising the parameters of a spray is essential for sustainable pesticide use, especially in high-input systems, such as the super-intensive hedgerow system. Parameters may be optimised by adjusting the applied volume and airflow rate of sprays, in addition to the liquid to air proportion and the relationship between air velocity and airflow rate. Two spray experiments using a commercial airblast sprayer were conducted in a super-intensive orchard to study how varying the liquid volume rate (testing volumes of 182, 619, and 1603 l ha^{-1}) and volumetric airflow rate (with flow rates of 11.93, 8.90, and 6.15 m^3 s^{-1}) influences the coverage parameters and the amount and distribution of deposits in different zones of the canopy.. Our results showed that an increase in the application volume raised the mean deposit and percentage coverage, but decreased the application efficiency, spray penetration, and deposit homogeneity. Furthermore, we found that the volumetric airflow rate had a lower influence on the studied parameters than the liquid volume; however, an increase in the airflow rate improved the application efficiency and

homogeneity to a certain threshold, after which the spray quality decreased. This decrease was observed in the high-flow treatment. Our results demonstrate that intermediate liquid volume rates and volumetric airflow rates are required for the optimal spraying of pesticides on super-intensive olive crops, and would reduce current pollution levels.

II-1. Introduction

Olive oil production in Europe represents 71.7% of the worldwide production (www.internationaloliveoil.org), with the olive oil sector being particularly important in southern European countries (surrounding the Mediterranean Basin). According to the Directorate-General of Agriculture and Rural Development of the European Commission (EC), the main areas of olive oil production are in Spain (2.4 million ha), Italy (1.4 million ha), Greece (1 million ha), and Portugal (0.5 million ha). France is a much smaller producer, with only 40,000 ha (http://ec.europa.eu/environment/agriculture/). Of importance, the production process used influences the level of environmental pollution generated by all the inputs used in the crop management. Traditional olive plantations are considered to pose the lowest environmental contamination risk, and still cover the largest surface area (Miranda-Fuentes et al., 2015). In contrast, the area dedicated to intensive and semi-intensive plantations pose high environmental contamination risk (Beaufoy, 2001), with coverage increasing in recent years. For instance, semi-intensive plantations now constitute 22% of the total cultivated area in Spain, representing 550.000 ha; AEMO, 2012). Semi-intensive olive tree plantations are characterised by medium to large row distance (5–8 m), considerable distance between the trees (3–7 m), and low tree density per hectare. The wide spacing of trees hampers the spray application process, while low tree density leads to formation of high canopy volumes that cause crop management difficulties. According to the EC (1999), the olive sector is one of intensified production causing certain negative effects on the environment.

It has been suggested that enhancing the accuracy of the volume rate (VR) represents an important measure to increase spray (i.e. pesticides) application efficiency to crops. For olive trees, this measure represents one of the most crucial parameters for reducing environmental problems. For instance, the adoption of an accurate spray volume that is adapted to the canopy characteristics of different tree crops could reduce the applied volume by 20%, while maintaining the quality of treatment (Pérez-Ruiz, et al., 2011). The authors demonstrated a close relationship between canopy characteristics and optimal application volume, supporting the need to adjust spray application according to tree structure. However, research is required to determine the optimal VR for different tree characteristics. Recently, different methods for canopy characterisation in olive tree plantations have been reported, based on methods established for other tree crops (Llorens et al., 2011; Jang et al., 2008; Tumbo et al., 2002). These methods range from simple, manual approaches to sophisticated procedures using electronic devices (Miranda-Fuentes, et al., 2015; Moorthy et al., 2011). The results of studies on VR optimisation generally indicate that the recommended VR mostly is lower than that currently applied by farmers, and that the use of optimised spraying saves costs and generates environmental benefits through considerably lower pesticide use (Gil et al, 2011; Landers, 2012; Moltó et al., 2001). Manktelow et al. (2004) found that deposit variability between the outer and inner parts of the canopy in a vineyard tended to decline with increasing spray volume, especially when the outer canopy was wetted beyond the point of runoff, which led to an associated reduction in spray efficiency. The authors concluded that if the chemical application rate is held constant and the application volume is adjusted, the highest overall deposits are achieved at low volumes, at which runoff losses are minimised. This conclusion was corroborated by Gil et al. (2005), who demonstrated that the deposition values were not different for VRs ranging from 150 to 800 L ha^{-1} in different vine plantations.

Ozkan (2009) suggested that sustainable agriculture, good water quality, profitability and increasing health, safety, and ecological and sociological concerns require a more prudent use of pesticides. Current methods and equipment have considerably improved the accuracy of chemical application; however, inefficiencies and many unanswered questions remain. Well-adapted spraying equipment, improvement of best management practices, and training seem to be key factors in this process. In 'three-dimensional crops', such as olive trees, precise air-assisted spraying has been identified as one of the most profitable best management practices to reduce drift (ECPA, 2014). Both airflow rate (AFR) and air velocity are directly linked to drift and, subsequently, to environmental contamination (Landers, 2012; Landers and Gil, 2006). Marucco et al. (2008) concluded that medium air velocity and VR generated better spray deposition results on peach trees than high air velocity and VR. In another study, Triloff et al. (2012) adapted the air stream to the canopy structure by altering the fan speed and forward speed, which results, in most cases, in reducing the deposition gradient between the surface and centre of the canopy, thus leading to more uniform spray deposition over the canopy width. Large reductions in volumetric AFR, based on accurate analysis, may substantially reduce spray drift from axial fan sprayers, without adversely affecting the overall spray deposits on the leaf surface (Cross et al., 2003). However, the mean relative amount of spray on the upper versus the lower leaf surface may change substantially. In general, low travel speed and high air output power improve air penetration (Svensson et al., 2003). García-Ramos et al. (2012) showed that high air velocities obtained with a dual-fan orchard sprayer caused vegetation movement to increase, enhancing the penetration and deposition of the sprayed product. However, detailed characterisation of the canopy and the accurate adjustment of all involved parameters are necessary for spray optimisation.

Here, we investigated how varying the volumetric airflow rate (AFR) and applied volume (VR) influences spray deposits and their distribution on leaves, spray coverage. The intention of this research was to determine the effect of air assistance and liquid volume rate on deposition (uniformity and penetration) in olive trees, trying to obtain an objective relationship between those fluids and canopy characteristics.

II-2. Materials and methods

II-2.1. Experimental plots and canopy characterisation

Two experiments were carried out in a commercial farm with the super-intensive cultivation of *Olea europaea* cv. Arbequina. The farm is located in Pedro Abad, Córdoba, Spain (37° 57' 38.94'' N, 4° 27' 57.04'' W). The trees were planted at a density of 1975 trees/ha with a between-row spacing of 3.75 m and a between-tree spacing of 1.35 m. The super-intensive olive tree crop system was chosen because of its geometric regularity compared to the considerable heterogeneity found in traditional olive groves. This phenomenon facilitates studying the homogeneity of spray deposits inside the tree crown. The size of the test field was 3350 m^2. Two rows of 110 trees and three rows of 45, 51, and 117 trees were selected for the VR and the AFR tests, respectively. All of the rows were separated by at least 5 intermediate rows to avoid contamination.

For canopy characterisation, the tree row volume (TRV; m^3 ha^{-1}) (Buyers et al., 1971; Sutton and Unrath, 1984, 1988) was determined by randomly selecting 64 trees from crop rows next to the experimental plots and measuring their maximum height, the distance from the soil to the lowest level of leaves, and the canopy width (Table II-1). Measurements were made using a topographic milestone for manual canopy characterisation as described previously, using the same nomenclature (Miranda-Fuentes et al., 2015). Maximum tree height (H_T), height of the first leaf (H_{fl}), and the canopy width (W) were measured. The canopy height (H_C) was calculated by subtracting Hfl from H_T (Fig. II-1). The leaf area density (m^2 m^{-3}) was measured by inserting a hollow cube of $8{\cdot}10^{-3}$ m^3 into the canopy, picking all the leaves located inside the cube, and determining their total area. Five measurements were taken from each of the sampling positions in the tree canopies (Fig. II-1). The relationship between the leaf surface area and leaf weight was determined as follows: 20 samples from 50 leaves were weighed and subsequently scanned to determine their total surface area with the image processing software ImageJ (National Institutes of Health, Bethesda, MD, USA), and a linear model was fitted by the ordinary least-squares method.

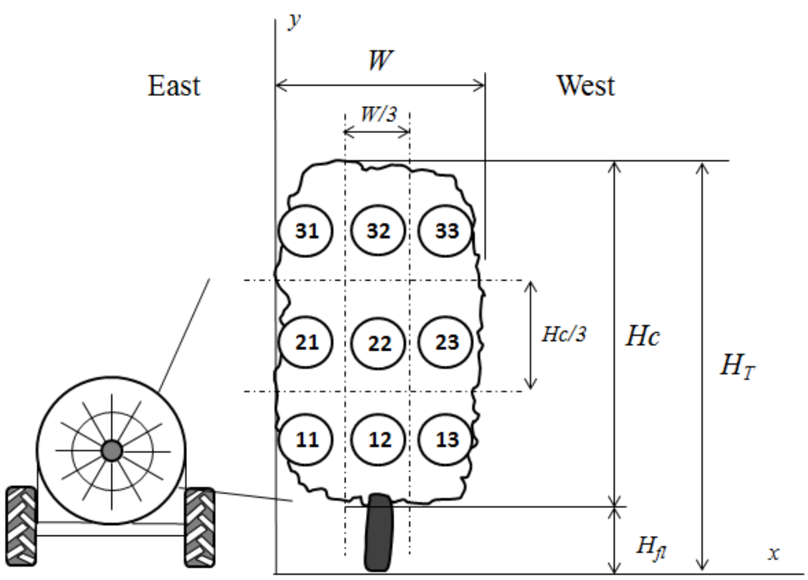

Figure II-1. Sampling positions inside the canopy.

II-2.2. Operational parameters of spray application

II-2.2.1. VR test

For spray application, Albuz ATR hollow cone nozzles (Saint-Gobain Céramiques Advancées Desmarquest, Evreux, France) were used. The working pressures for all the tests were adjusted to obtain a similar droplet distribution based on D_{50} (Volume Median Diameter, VMD), D_{10}, and D_{90} values, which is essential for comparing different application volumes (Sedlar et al., 2013).

VRs of 1603, 619, and 182 l ha^{-1} were used. These VRs were selected based on the one used in the commercial field (1600 l ha^{-1}), which was then reduced by 60% (619 l ha^{-1}) and 90% (182 l ha^{-1}); the three levels were termed 'High Volume' (HV), 'Medium Volume' (MV), and 'Low Volume' (LV) treatment, respectively. The LV treatment was included in the experiment to obtain a wide range of VR. The pressure, nozzle type, and AFR of 12.03 m^3 s^{-1} for the HV treatment were set according to the common practices in the commercial orchard.

The forward speed was selected and kept constant at 6 km h^{-1}, as this is the most frequently adopted value in olive crops and is the value that is commonly used in the commercial trial field. The real forward speed was determined *in situ* by using a 100-m measuring tape and a stopwatch. The rotary power take-off (PTO) speed was adjusted by using a tachometer external to the tractor at 540 rpm.

Table II-1. Parameters used in the VR trial.

Parameter	HV	MV	LV
Nozzle type and colour	Albuz ATR Green	Albuz ATR Orange	Albuz ATR Brown
Number of open nozzles	14 (2 × 7)	14 (2 × 7)	14 (2 × 7)
Pressure (bar)	24.5	11.9	4.7
Liquid flow rate (l min^{-1})	58.0	22.4	6.6
Spray volume (l ha^{-1})	1603	619	182
Forward speed (km h^{-1})	6.04	6.02	5.99
VMD (μm)	159	156	157
PTO speed (rpm)	542	541	539
Airflow rate (m^3 s^{-1})	11.90	11.90	11.90
Fan gear	1	1	1

Because of the structural characteristics and dimensions of the targeted trees, it was necessary to open all of the nozzles on the sprayer (seven on each side) to cover the entire leaf mass. The orientation angle of the nozzles varied between 40° and 50°, with an average of approximately 45°. The working parameters used during the field trials are shown in Table II-1.

II-2.2.2. AFR test

In the second trial, three AFRs were tested: 11.93, 8.90, and 6.15 m^3 s^{-1}, which were termed 'high flow' (HF), 'median flow' (MF), and 'low flow' (LF), respectively. The HF was intended to be set at 12.00 m^3 s^{-1}, to allow comparison of the results with those obtained in the volume rate test; however, the actual measured value was 11.93 m^3 s^{-1}. The MF and the LF were set at 75% and 25% of the HF. To reduce the PTO speed used in the first trial, another fan was used, with the HF reaching 459 rpm, rather than 540 rpm. The VR was set at 770 l ha^{-1}, approximately 50% of the volume applied by the farmer and, consequently, of the HV treatment. The (VMD) values were maintained similar to those obtained in the first trial. Additional operational parameters are listed in Table II-2.

Table II-2. Parameters used in the AFR trial.

Parameter	HF	MF	LF
Nozzle type and colour	Albuz ATR Orange	Albuz ATR Orange	Albuz ATR Orange
Number of open nozzles	14 (2 × 7)	14 (2 × 7)	14 (2 × 7)
Pressure (bar)	15.0	15.0	15.0
Liquid flow rate (l min^{-1})	24.01	23.11	24.71
Spray volume (l ha^{-1})	768.2	744.2	778.2
Forward speed (km h^{-1})	4.90	4.98	5.03
VMD (µm)	136	136	136
PTO speed (rpm)	458	420	280
Airflow rate (m^3 s^{-1})	11.93	8.90	6.15
Fan gear	2	1	1

II-2.3. Sprayer calibration and choice of spray tracer for spray evaluation

The sprayer used in this study was a commercial airblast sprayer with an axial fan (2200 l, Osuna-Sevillano, Jauja, Spain). Before the treatments, the actual liquid flow rate of the sprayer at every working pressure was determined. The relationship between the PTO speed and AFR was determined for the two fan gears.

To measure deposits on leaves, the food dye E-102 (Tartrazine) was used as a tracer at a concentration of 8 g l^{-1}. Although it does not allow multiple treatments on the same surface as metallic chelates do, it is a very suitable tracer because it is not absorbed by the leaves (Murray et al., 2000) and has high extractability and low degradation (Pergher, 2001). Furthermore, the geometrical regularity of the tree crowns enabled us to use different trees, which were assumed to have a similar shape.

II-2.4. Characterisation of the environmental conditions

The wind speed and direction, temperature, and relative humidity were measured *in situ* using an HHF81 multimeter (Omega Engineering, Manchester, UK). Measurements were taken before, during, and after the treatments at three different positions: inside the orchard and between two rows at 2 m height, inside the orchard above the canopy at 5 m height and outside the orchard, at 5 m height. All of the parameters were measured every second for 20 s, and the mean of the measurements was used as the final value for the corresponding parameter.

II-2.5. Experimental design and sampling system

A split-split-plot experiment with three levels per factor was designed. The application volume and airflow rates were the main factors for the first and the second trial, respectively. They were randomly distributed in the three main plots in each of the repetitions: five for the first trial and four for the second. The subplot factor was the depth inside the canopy, and the sub-sub-plot factor was the height, each with three levels, generating a matrix of nine sampling zones (Fig. II-1). The depth of each sampling zone inside the canopy was numbered from one to three. However, the factor depth inside the canopy differed in the two experiments because of the different spray application process used in the trials. Specifically, the test rows were sprayed from one side only in the VR test, whereas the trees were sprayed from both sides for the airflow test to obtain a complete data range to evaluate the effect of air assistance on penetration efficacy.

The nine sampling positions (three heights × three depths) were randomly assigned to nine different trees in the sprayed area (Fig. II-1). From each sampled tree, 50 leaves were collected from the corresponding sampling position, and maintained in containers until further evaluation. In addition, two pieces of water-sensitive paper (26 × 76 mm, Syngenta Crop Protection AG, Basel, Switzerland) were mounted at the corresponding sampling position, one on each side of a leaf, to evaluate spray coverage. Sampling positions inside the trees were defined in accordance with the ISO standard (ISO 22522, 2007). Before the treatments, nine samples of 50 leaves were taken from the rows next to the study plots, to confirm the absence of tartrazine traces. Liquid samples were taken from the sprayer tank before and after each treatment to analyse the real concentration of tartrazine in the spray mix. After treatment, the samples were collected carefully and stored in black bags to minimise tartrazine degradation.

II-2.6. Sample analysis

II-2.6.1. Leaf samples

The leaf samples were analysed in the laboratory. The samples were weighed and washed off with 100 ml distilled water. The tartrazine concentration was determined by measuring the absorbance of the washing solution at a wavelength of 427 nm with a spectrophotometer (Multiskan FC Microplate Photometer, Thermo Fisher Scientific, Horsham, UK) and comparing the results against a calibration curve. For each sample of 50 leaves, six absorbance measurements were taken. Blank samples of distilled water were included in all cases to calibrate the equipment. The spray deposit per unit area was calculated from equation II-1, which was defined by Pergher and Gubiani (1995):

$$d = \frac{T_{cl} \times w}{L_a} \qquad \text{(II-1)}$$

where d is the deposit per unit area (µg cm^{-2}), T_{cl} is the Tartrazine concentration in the washing solution (ppm), w is the volume of extractant used (ml), and L_a is the total area of the sampled leaves (cm^2).

To compare the different treatments, it is necessary to normalise the obtained deposits (Llorens et al., 2010). The normalised deposition, d_n, was calculated using equation II-2:

$$d_n = d \times F \qquad \text{(II-2)}$$

where F is a volume factor calculated as the minimum applied volume (LV) divided by the volume applied for the sample treatment.

The penetration coefficient, C_p, was calculated by using equation 3, assuming that the treatment, if applied on both sides of the hedgerow, would be completely symmetrical:

$$C_p = \frac{d_i}{d_e} \times 100 \qquad (3)$$

where d_i is the mean deposit collected in the internal parts of the trees (depth 2) and d_e is the mean deposit collected in the external parts. In the airflow rate trials, in which the treatments were applied on both sides of the test rows, d_e was calculated as the mean of depths 1 and 3 (external parts). Perfect penetration is achieved when C_p equals 1.

The coefficient of variation, *CV*, was calculated for the deposition values at all of the sample points, and was considered an additional indicator of the homogeneity of the deposit distribution (Escolà et al., 2006).

The relationship between the applied liquid flow rate (l min^{-1}) and the airflow rate (m^3 s^{-1}) for every combination of parameters, R, was also calculated and related to the mean deposits.

II-2.6.2. Water-sensitive papers

The water-sensitive papers were collected and scanned at high resolution (600 ppi) to determine the coverage parameters. A special macro was programmed in ImageJ to automatically quantify the percentage of surface coverage (SC) and the number of pesticide impacts in each picture (Zhu et al., 2011). The number of impacts per surface unit, N_i, was subsequently calculated by dividing the number of impacts by the total area of the piece of paper. For SC and N_i, the mean values for both the upper- and lower side of the leaves were calculated. In addition, the homogeneity of the spray distribution over the upper and the lower side, expressed as *HSC* and HN_i, were defined as expressed in equations II-4 and II-5, respectively:

$$HSC = 100 - \left| \left(\frac{SC_{underside}}{SC_{upperside}} \times 100 \right) - 100 \right| \qquad \text{(II-4)}$$

$$HN_i = 100 - \left| \left(\frac{N_{iunderside}}{N_{iupperside}} \times 100 \right) - 100 \right| \qquad \text{(II-5)}$$

II-2.7. Statistical analysis

The data on the studied parameters are expressed as the mean ± the standard error (SE) of the mean. Analysis of variance (ANOVA) was used to establish the effects of the factors, volume rate, and airflow rate on the studied dependent variables, together with depth and height inside the canopy. The variables were the absolute deposit per unit area *d* (µg cm^{-2}), the normalised deposit d_n (µg cm^{-2}), the penetration coefficient C_p (%), the coefficient of variation *CV* (%), the percentage coverage *SC* (%), and the number of impacts per unit area N_i (cm^{-2}). The coverage was considered separately for the leaf upper- and lower side, and was also averaged over both sides. The means were compared by using a Bonferroni post-hoc test (α = 0.05). Prior to analysis, percentage data were subjected to arcsin((Y/100)$^{0.5}$) transformation and the deposition data were log-transformed (Steel and Torrie, 1980). Analyses were performed using Statistix 9 (Analytical Software, Tallahassee, FL, USA) and SPSS v. 20 (IBM, Armonk, NY, USA). A *p*-value < 0.05 was considered significant.

II-3. Results and discussion

II-3.1. Characterisation of the trees

Table II-3 provides an overview of the main geometrical characteristics of the studied trees. The large size and high canopy density of the trees were noteworthy, even though their widths were small in comparison to their height.

Table II-3. Main geometrical characteristics of the studied olive trees.

	H_T (m)	H_{fl} (m)	H_C (m)	W (m)	TRV (m^3 ha^{-1})	Leaf density (m^2 m^{-3})
Mean †	3.96	0.52	3.45	1.25	11474	6.04
Standard deviation	0.21	0.09	0.23	0.29	2201	2.28
CV (%)	5.25	17.18	6.69	23.70	19.19	37.81

† n = 64. H_T: maximum tree height; H_{fl}: height of the first leaf; H_C: canopy height (H_T - H_{fl}); W: canopy width; TRV: tree row volume; CV: coefficient of variation

II-3.2. Characterisation of the climatic conditions

Table II-4 presents the climatic conditions recorded during the field trials. The wind speed was very low and, theoretically, suitable for spraying purposes; thus, it probably did not affect the final results of the study. In addition, the mean values of temperature and relative humidity were regular.

Table II-4. Climatic conditions of the two trials.

VOLUME RATE	DATE	TEMPERATURE (°C)				RELATIVE HUMIDITY (%)			WIND SPEED (km h^{-1})			WIND DIRECTION⊡ (°)
		Position	Z_1†	Z_2††	Z_3†††	Z_1	Z_2	Z_3	Z_1	Z_2	Z_3	
HV	16/12/2013		15.8	15.8	15.4	65.3	61.2	47.5	0.0	0.0	0.0	-
MV	17/12/2013		14.7	14.8	14.8	67.1	66.6	49.3	0.0	0.3	3.6	122
LV	17/12/2013		17.1	17.1	17.3	66.9	66.5	48.3	0.0	0.2	2.5	120
AIRFLOW RATE	**DATE**	**TEMPERATURE (°C)**				**RELATIVE HUMIDITY (%)**			**WIND SPEED (km h^{-1})**			**WIND DIRECTION⊡ (°)**
		Position	Z_1†	Z_2††	Z_3†††	Z_1	Z_2	Z_3	Z_1	Z_2	Z_3	
HF	26/01/2014		9.2	9.3	9.3	58.2	55.5	44.7	0.3	1.1	1.9	120
MF	26/01/2014		15.7	15.8	15.3	59.2	59.9	43.9	0.0	0.0	0.5	99
LF	26/01/2014		11.0	10.7	10.9	55.8	52.3	46.2	0.0	0.2	2.5	118

† Inside the orchard, at 2 m height

†† Inside the orchard, above the canopy, at 5 m height

††† Outside the orchard, at 5 m height

⊡ 0° value was assigned to the North direction, coincident with the crop rows

II-3.3. VR test

II-3.3.1. Absolute and normalised deposits on leaves

The results of the ANOVA (Table II-5) indicated that the VR had a strong influence on the deposition parameters (*p* < 0.0001). Considering the wide range of VRs tested (from 180 to 1600 l ha^{-1}), this result was expected and was reflected in the trial results with mean absolute deposition values of 5.08, 2.98, and 1.74 μg cm^{-2} for HV, MV, and LV, respectively (Table II-6). Yet, the increase in deposits was not linearly proportional to the increase in the applied volume; the mean absolute deposition values for MV and HV were respectively 1.7 and 3.0 times greater than that for LV, while the volumes applied for MV and HV were respectively 2.6 and 8.8 times greater than that for LV. This result implies saturated deposition at high volume application rates (Fig. II-2), which may only be explained by a loss in application efficiency. Similar results have been previously observed in studies of vineyards (Gil, 2001, Unpublished PhD diss.) and greenhouses (Braekman et al., 2009). Our result was supported by the significant reduction in the normalised deposit with increasing application volume. The mean normalised deposition values were 0.58, 0.88, and 1.74 for HV, MV, and LV, respectively (Table II-6). Of note, the difference in normalised deposition was greater between LV and MV than between MV and HV. This result corroborated the loss of efficiency with increasing spray volume, and was in agreement with results observed in similar studies of other crops (Cross et al., 2001; Camp et al., 2007). The wide range covered by the three VRs applied in the current study showed that that the normalised deposition decreased faster at low volumes compared to high volumes.

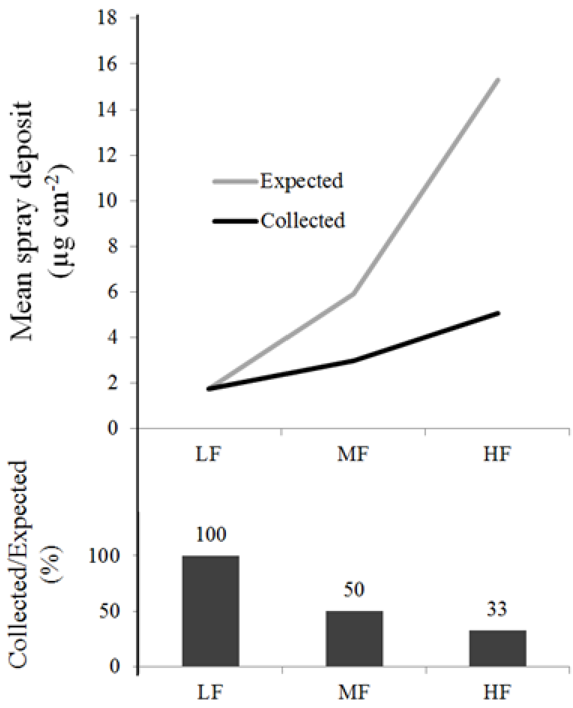

Figure II-2. The mean spray deposits as recorded and as expected according to the applied volume for the five replications. The expected deposit was calculated assuming perfect proportionality between the deposit and the volume according to the deposit obtained for the LV treatment.

The low values recorded for the normalised deposit may be explained by the large size and leaf density of the sprayed trees (mean TRV of 11,474 m^3 ha^{-1} and mean leaf area density of 6.04 m^2 m^{-3}). This result supported studies performed on other tree crops, whereby the higher the canopy density, the lower the normalised deposit; consequently, the greatest deposits were observed during the early season sprayings, when crop density is low (Cross et al., 2001; Solanelles et al., 2007).

The results on the distribution of the spray deposits inside the canopy showed that the absolute deposition values for each VR varied with depth ($p < 0.0001$) and height ($p < 0.003$). The significant interactions indicated that the spray penetration inside the canopy differed for each VR, as shown by Figs. II-3 and II-4. In addition, the results showed significant differences in the penetration for all three treatments (Table II-6). The highest penetration was obtained from the LV treatment (C_p = 123.8%), while the lowest LW was obtained from the HV treatment (C_p = 79.4%). The MV treatment produced intermediate penetration (C_p = 113.6%). Even though this observation was supported by the lowest deposit being detected in the outer zones for the LV treatment, it was unexpected because it was hypothesised that the inner zones would receive no or very low deposit. However, this finding supported the ANOVA results, indicating easier movement of the spray mix throughout the canopy (Table II-6, Fig. II-4). The high values of C_p for the LV and the MV treatments might be because the central zones received much higher deposits than the zones with the greatest depth. Consequently, doubling the deposits to simulate treatment from both sides produced coefficients of more than 100%.

The deposit homogeneity inside the tree crown significantly differed among the three treatments, with the highest and lowest homogeneity being detected for the LV (CV = 36.4%) and HV (CV = 54.0%) treatments, respectively. The MV treatment produced an intermediate value (CV = 39.8%). This result supported the highest penetration by the LV treatment, whereas the ‘wall effect’ (organization of the leaves forming different layers that hinder the spray penetration to the inner parts of the canopy) that occurred in the HV treatment led to the most heterogeneous deposit (Fig. II-4a). This observation might be explained by the proportion of liquid in the spray mix. The AFR was kept constant in all treatments, whereas the liquid proportion changed, being lower at lower application volumes. The higher the liquid concentration in the spray mix, the higher its density; therefore, the movement of the spray through the canopy might be hampered. Consequently, the well-known ‘wall effect’ was shown to be more important as the applied volumes increased.

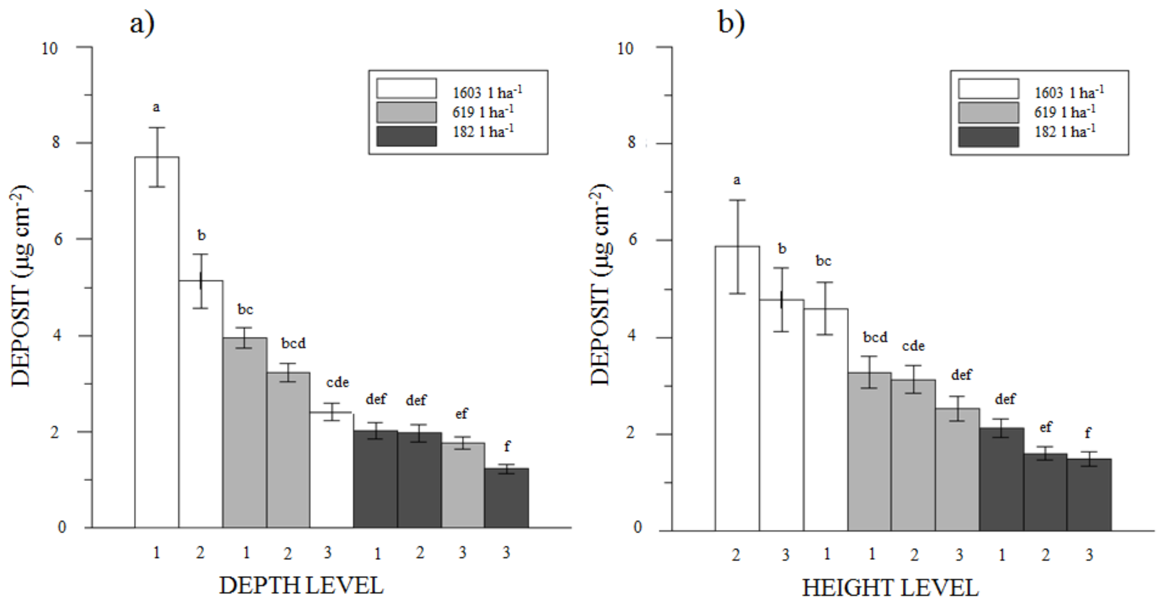

Figure II-3. Absolute spray deposit at different depths (a) and heights (b) in the VR test.

II-3.3.2. Spray coverage

The results of the water-sensitive paper test showed that the VR had a strong influence on the mean absolute deposits on the upper ($p < 10^{-4}$) and lower sides of the leaves ($p < 0.008$) (Table II-5). A significant correlation between the coverage and the absolute deposit was found ($\rho_{sxy} = 0.87$; $p < 0.001$; n = 135). Some samples from the upper side were excluded from the analysis owing to runoff, especially for the HV treatment. The mean coverage for HV and MV was 5.3 and 3.0 times greater than that for LV, respectively, even though the applied volumes were 8.8 and 3.4 times greater, respectively. This fact supported the aforementioned loss of efficiency when applying high spray volumes. The mean upper-side coverage ranged from 9.72% for the LV to 51.36% for the HV treatment, respectively, presenting three homogeneous groups according to the LSD test. Only the MV treatment produced an appropriate value (29.18%) based on the criterion of 30% established by Chen et al. (2013). The highest number of impacts per area unit was obtained from the LV treatment (116 cm^{-2}), while the lowest number of impacts was obtained from the MV and the HV treatments (96 and 81 cm^{-2}, respectively; Table II-6). This phenomenon may be explained by the fact that the biggest droplets remain in the first layers in low-volume applications, causing more impacts to have lower coverage. The lower side of the leaves had much lower coverage values than the upper side (Table 6); values of 15.1%, 9.7%, and 3.5% were recorded for HV, MV, and LV, respectively. None of the treatments conferred appropriate lower-side coverage based on the criterion of Chen et al. (2013), with all three generating under-treated leaf surfaces. Significant differences were found between the three treatments, although all values were low. Nevertheless, these results could be strongly influenced by the fact that treatments were performed by one side.

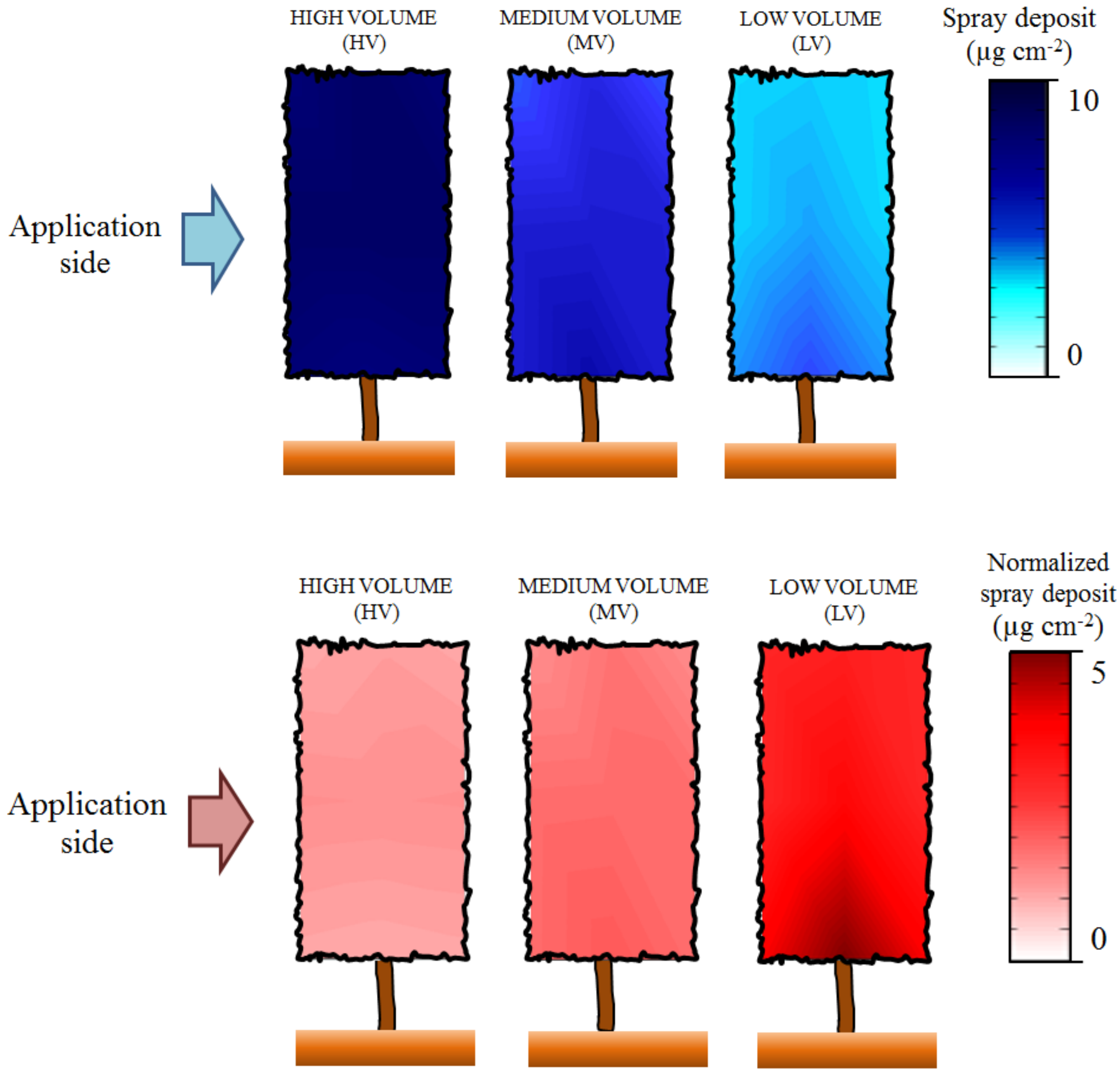

Figure II-4. Absolute spray deposit (a) and normalised spray deposit (b) inside the canopy in the VR test.

The highest number of impacts was found for the MV treatment (100 cm^{-2}), while the lowest number of impacts was found for the LV (60 cm^{-2}). This result showed that, in contrast to the upper side, the lower side received only a small fraction of the spray droplets. Across all three VRs, it was generally observed that the upper side received more impacts as the VR decreased, while the lower side showed the opposite effect.

The *HSC* over the upper and lower side was very similar among all three treatments. The highest and lowest values were obtained for LV (36%) and HV (29%), respectively. This result might be explained by the fact that the upper and the lower side coverage decreased with the applied volume, producing a constant ratio. Finally, the *HNi* was much smaller for the LV (51%) than for the MV and HV (104% and 114%, respectively) treatments, owing to the observed increase in the upper side impacts, which was to the detriment of the lower-side impacts.

Table II-5. ANOVA results for the variables and interactions evaluated in the VR test (p-values).

Sources of Variation	DF	Absolute deposition ($\mu g\ cm^{-2}_{leaf}$)	Normalised deposition ($\mu g\ cm^{-2}_{leaf}$)	Upper side coverage (%)	Lower side coverage (%)	Mean coverage (%)	Upper side impacts (impacts cm^{-2})	Lower side impacts (impacts cm^{-2})
Volume Rate (VR)	2	**$<10^{-4}$**	**$<10^{-4}$**	**$<10^{-4}$**	**0.008**	**$<10^{-4}$**	**0.011**	0.082
VR × Depth (D)	4	**0.001**	0.566	**0.038**	0.412	**$<10^{-4}$**	**$<10^{-4}$**	0.740
VR × Height (H)	4	**0.020**	**$<10^{-3}$**	0.387	0.775	0.706	0.321	**0.043**
VR × D × H	8	0.342	0.546	0.152	0.518	0.091	0.166	0.927

Table 6. Parameters studied in the VR trial.

Table II-6. Parameters studied in the VR trial.

PARAMETER		**HV**	**MV**	**LV**
Mean absolute deposit	d ($\mu g\ cm^{-2}$)	5.08 ± 0.42 a	2.98 ± 0.17 b	1.74 ± 0.10 c
Mean normalised deposit	d_n ($\mu g\ cm^{-2}$)	0.58 ± 0.05 a	0.88 ± 0.05 b	1.74 ± 0.10 c
Coefficient of penetration	C_p (%)	79.40 ± 21.39	113.60 ± 6.58	123.80 ± 12.67
Deposit homogeneity	CV (%)	54.00 ± 5.00	39.80 ± 2.03	36.40 ± 5.90
Upper side coverage	SC **up** (%)	51.36 ± 4.08 a	29.17 ± 2.92 b	9.72 ± 1.36 c
Lower side coverage	SC **lo** (%)	15.12 ± 3.22 a	9.66 ± 1.54 a	3.49 ± 0.84 b
Mean coverage	SC (%)	33.25 ± 2.86 a	19.42 ± 1.73 b	6.60 ± 0.80 c
Coverage homogeneity	HSC (%)	29	33	36
Upper side impacts	N_i **up** (cm^{-2})	81.19 ± 10.37 a	96.22 ± 7.43 a	116.03 ± 11.01 b
Lower side impacts	N_i **lo** (cm^{-2})	92.86 ± 8.84 a	100.03 ± 9.46 a	59.62 ± 8.14 a
Impacts homogeneity	HN_i (%)	86	96	51

Significant differences between means are indicated by different letters.

Table II-7. ANOVA results for the variables and interactions evaluated in the AFR test (p-values).

Sources of Variation	DF	Deposition (µg cm^{-2}_{leaf})	Upper side coverage (%)	Lower side coverage (%)	Mean coverage (%)	Upper side impacts (impacts cm^{-2})	Lower side impacts (impacts cm^{-2})
Airflow Rate (AFR)	2	**0.048**	0.098	**0.046**	0.056	0.311	0.213
AFR × Depth (D)	4	0.742	0.983	0.856	0.940	0.921	0.641
AFR × Height (H)	4	0.195	0.283	0.518	0.631	0.354	0.068
AFR × D × H	8	0.859	0.401	0.451	0.163	0.187	0.208

Table II-8. Parameters studied in the AFR trial.

PARAMETER		TREATMENT		
		HF	**MF**	**LF**
Mean normalised deposit	d_n (µg cm^{-2})	10.5 ± 0.61 a	12.96 ± 0.73 b	11.08 ± 0.70 ab
Coefficient of penetration	C_p (%)	73.25 ± 15.79	94.75 ± 17.12	82.25 ± 8.83
Deposit homogeneity	*CV* (%)	32.2 ± 5.67	34.5 ± 5.04	37.0 ± 4.37
Upper side coverage	***SC* up** (%)	77.4 ± 4.61 a	66.8 ± 5.15 a	57.11 ± 5.82 a
Lower side coverage	***SC* lo** (%)	71.0 ± 4.91 a	57.0 ± 5.68 ab	34.3 ± 4.93 b
Mean coverage	*SC* (%)	74.2 ± 4,10 a	61.9 ± 3,93 a	45.71 ± 3,82 a
Coverage homogeneity	*HSC* (%)	92	85	60
Upper side impacts (cm^{-2})	N_i **up** (cm^{-2})	64.4 ± 12.65 a	89.0 ± 14.22 a	80.44 ± 11.67 a
Lower side impacts (cm^{-2})	N_i **lo** (cm^{-2})	74.7 ± 12.55 a	93.1 ± 14.15 a	116.1 ± 11.31 a
Impacts homogeneity	HN_i (%)	84	85	56

Significant differences between means are indicated by different letters.

II-3.4. AFR test

II-3.4.1. Normalised deposits on leaves

Owing to small differences in forward speed and liquid flow rate (Table II-2), deposit values were normalised. The ANOVA results indicated that the AFR had a significant effect on the normalised deposit ($p < 0.048$; Table II-7). The highest and lowest deposits were obtained from the MF (12.96 µg cm^{-2}) and HF (10.50 µg cm^{-2}) treatments, respectively (Table II-8). The LF treatment generated a deposit of 11.08 µg cm^{-2}, which was not statistically different to that observed for the other treatments. These results supported those obtained by Cross et al. (2003), who found that, at low wind speeds, such as those measured in the present study, decreasing the AFR increased the mean deposit in the canopy of apple trees. Yet, the present study showed that deposition seemed to reach a threshold, which might be explained by the fact that the spray was projected behind the tree canopy at high AFRs, rather than being deposited on the leaves. In contrast, intermediate values resulted in the spray penetrating the inside of the canopy, without passing through. No significant interactions between the AFR and sampling zones (depth and height) were found (Table II-7). However, we observed a significant decrease in spray deposit at the highest tree zones, indicating that a complementary air might be required for the upper parts of the canopy in all treatments (Fig. II-5).

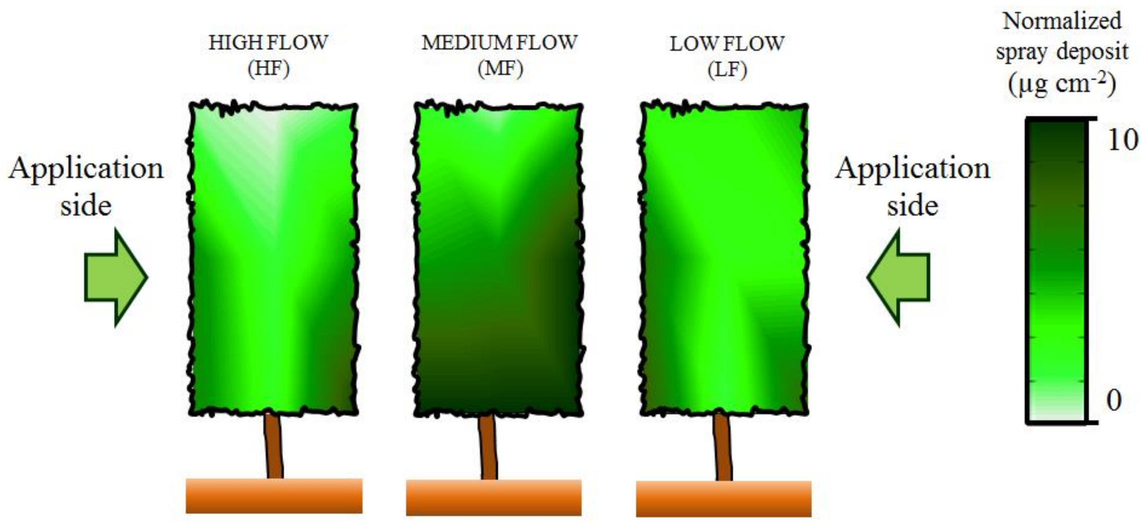

Figure II-5. Normalised spray deposit inside the canopy for the AFR test.

We found large, significant differences in the penetration of the spray inside the canopy among the three AFRs (Table II-8). The highest penetration coefficient was obtained by the MV treatment (C_p = 94.75%), followed by the LV (C_p = 82.25%) and HF (C_p = 73.25%) treatments. These results countered the widespread belief among Spanish farmers that spray penetration in the inner parts of the canopy is improved by using higher AFR levels.

The *CV*s ranged from 32.2% (LF) to 37.0% (HF), and did not significantly differ among the tested AFRs (Table II-8). The *CVs* were lower than those obtained in the first trial, because the treatment was applied on both sides of the test row in this test, resulting in lower differences in deposits inside the canopy.

II-3.4.2. Spray coverage

The results of the water-sensitive paper test demonstrated that the spray coverage of the upper side of the leaves was very uniform among the three evaluated treatments, with no statistically significant differences amongst the treatments (Table II-7). Yet, the results indicated a tendency towards declining spray coverage with reduced AFR (Table II-8). According to the criterion of Chen et al. (2013), the leaf surface was over-treated in all treatments.

No significant differences in the number of impacts were found among the treatments. The highest and lowest values were observed for the MF (89 impacts cm^{-2}) and HF (75 impacts cm^{-2}) treatments, respectively.

We found significant differences in the lower-side coverage between HF and LF, with a mean coverage of 71.0% and 34.3%, respectively (Table II-8). Of note, the lower-side coverage was lower than the upper-side coverage in all treatments; however, the lower-side coverage was much higher than the coverage obtained in the VR test. This result may be explained by the fact that both sides were treated, resulting in more similar coverage on both leaf sides. In contrast, the highest and lowest number of impacts was found in the LF (116 cm^{-2}) and HF (75 cm^{-2}) treatments, respectively. However, the lower side received a high number of impacts with low coverage, similar to the VR test.

The *HSC* values were much higher than in the VR trial (Table II-8). The *HSC* was high in all of treatments, except the LF treatment, owing to its low *SC*; thus, *HSC* increased with increasing AFR (Table II-8). The HN_i showed a similar, although more moderate, tendency.

II-3.5. Overall results and discussion

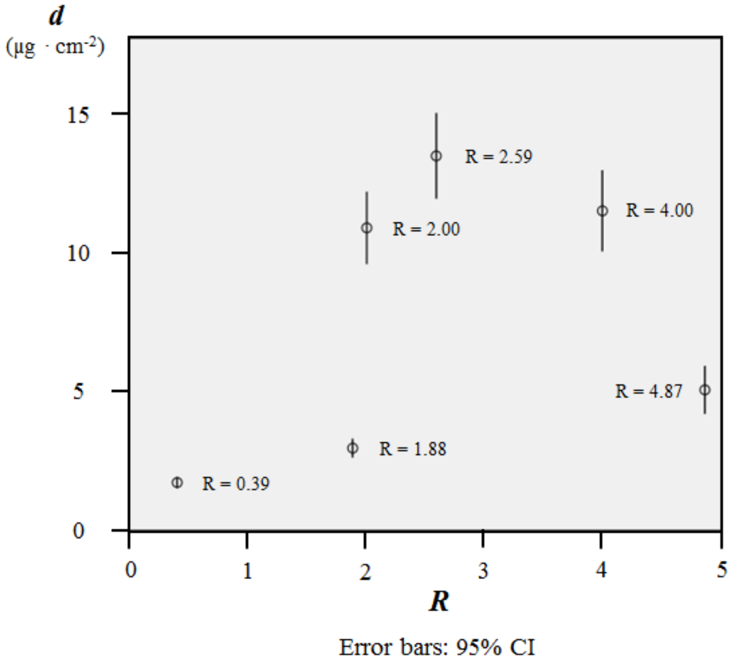

Figure II-6. Spray deposits for different values of R.

The parameter R, calculated as the relationship between the applied Liquid Flow Rate and the AFR, was related to the average deposits on leaves. The results are shown in Fig. II-6. As it can be seen, spray deposits seems to be strongly influenced by R, and present a saturation response that makes that, from a certain value, an increase in R results in a decrease in the deposits. The maximum mean deposit is achieved for the R value of 2.59, corresponding to the MF treatment in the AFR test. This fact has important implications, because when adjusting the spray parameters, attention should be paid not only to the individual parameters, but to their combination as well, trying to achieve R values comprised in the range between 2 and 4, approximately. This is logical if taking into account that very high or low R values indicate the maximisation of one parameter, which shows to not to have a positive effect on the application.

The VR and AFR had a strong influence on the homogeneity and penetration of the deposits and on the coverage parameters. Furthermore, the results showed that the HV treatments were not the most efficient and, in some cases, were not the most effective either. Therefore, when considering both efficiency and effectiveness, the MV and the MF treatments were the most optimal.

The results on deposition obtained in the first trial indicated that the lower the applied volume, the higher the homogeneity of deposits inside the canopy. This observation led us to assume that the spray plume moves more easily throughout the canopy when the air is less charged with liquid; therefore, the ratio of the VR to the AFR should be minimised to obtain high homogeneity. This hypothesis corroborated the results obtained by Randall (1971), indicating that the applied AFR should be maximised for a given air speed to obtain optimal spray uniformity, provided that the speed is equal to or higher than a threshold of 12.2 m s^{-1}. However, this hypothesis was not supported by the results of the second trial, in which the maximum AFR produced the lowest deposits. This finding may be explained by the fact that the speed of the air propelled by the fan rises with increasing AFR. The speed measured at the outlet for the HF treatment was 27.5 m s^{-1}, which was very high compared to the 12.2 m s^{-1} used by Randall (1971). Our measured speed was also higher compared to that observed in a study by Marucco et al. (2008) in a peach orchard, where the authors demonstrated that increasing the air speed above 14 m s^{-1} resulted in a decrease of the mean deposit values. Based on these results, we speculate that optimal results may be obtained with high AFRs and low air-speed values. However, further studies are needed to establish the optimal values for olive orchards.

The spray coverage results showed that it is necessary to obtain a balance between coverage percentage and impacts, with the MV and the MF treatments being the most balanced. However, specific treatment requirements might demand a different choice of parameter settings.

II-4. Conclusions

Three VRs and three AFRs were tested to evaluate their effects on the spray application with respect to homogeneity, penetration, efficiency, and coverage. The VR and AFR had a strong influence on spray penetration, homogeneity of the deposits, and coverage parameters, subsequently affecting treatment efficiency. Increasing the VR resulted in increased deposit, but also in the loss of application efficiency. In addition, even though the percentage coverage increased, the number of impacts per surface unit generally decreased. The best results in terms of efficiency and spray penetration were achieved with the MF in the AFR test. Furthermore, this treatment had the most optimal percentage coverage and number of impacts per area unit. The lower side of the leaves received lower coverage than the upper side in all treatments. When treated on one side, the coverage on the lower side was very low, but this problem was partially solved by treating both sides of the tree row. Our results also indicate the possibility of obtaining good application quality without using excessive application volumes or airflow rates; thus, avoiding all of the negative impacts of pesticide usage efficiency, spray drift, fuel consumption, and noise emission. Commercial treatments proved not to be the best in terms of homogeneity, efficiency, and coverage. Specific needs related to the target crop (i.e. pesticide, etc.) should be taken into consideration, and the working parameters adjusted accordingly. Even though the amount of liquid in the spray proved to be important, the relationship between the air speed and flow rate seemed to be critical for spray penetration and deposit homogeneity. Furthermore, the liquid flow rate and the airflow rate need to be balanced to maximise the deposits on leaves.

II- Acknowledgements

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CHAPTER III - Towards an optimised method of olive tree crown volume measurement

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Chapter III - Towards an Optimized Method of Olive Tree Crown Volume Measurement

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III- Abstract

Accurate crown characterization of large isolated olive trees is vital for adjusting spray doses in three-dimensional crop agriculture. Among the many methodologies available, laser sensors have proved to be the most reliable and accurate. However, their operation is time consuming and requires specialist knowledge and so a simpler crown characterization method is required. To this end, three methods were evaluated and compared with LiDAR measurements to determine their accuracy: Vertical Crown Projected Area method (VCPA), Ellipsoid Volume method (V_E) and Tree Silhouette Volume method (V_{TS}). Trials were performed in three different kinds of olive tree plantations: intensive, adapted one-trunked traditional and traditional. In total, 55 trees were characterized. Results show that all three methods are appropriate to estimate the crown volume, reaching high coefficients of determination: R^2 = 0.783, 0.843 and 0.824 for VCPA, V_E and V_{TS}, respectively. However, discrepancies arise when evaluating tree plantations separately, especially for traditional trees. Here, correlations between LiDAR volume and other parameters showed that the Mean Vector calculated for VCPA method showed the highest correlation for traditional trees, thus its use in traditional plantations is highly recommended.

III-1. Introduction

Increased awareness of the safe use of pesticides has led to substantial developments in the European environmental legal framework. Since the publication of the European Directive for a Sustainable Use of Pesticides in 2009 [1], great efforts have been made by all EU members to reduce the associated risks during the phase-use of pesticides. Of particular importance, is the need to establish procedures for identifying the most suitable dose and volume rate, especially in "three-dimensional" crops, such as orchards, vineyards, citrus and olive tree plantations. Establishing the most accurate volume rate for pesticide application in those crops appears to be one of the most difficult aspects, with most growers using a certain amount of subjectivity. There are several parameters that directly influence sprayer calibrations, and these are in turn, influenced by many external factors. In addition, uncontrollable factors such as weather conditions, pest and/or disease infestation, and crop development and its structure affect the final success of the spray application process. Attempts to improve procedures to identify pesticide dose expression have included recommendations based upon either two (Leaf Wall Area: LWA) or three (Tree Row Volume: TRV) dimensional factors related to the canopy structure [2-4]. The high degree of variability in the crop canopy has hampered the development of general solutions to guarantee efficacy during the spraying process [5] and ensure that the most appropriate amount of pesticide is applied to all leaf surfaces with an even distribution, for crops of all types and in all situations.

According to that it is clear that precise measurements of external canopy dimensions leads to improved identification of pesticide dose. The chosen method for canopy characterisation, such as height and width is therefore of huge importance, and should be arranged by growers before spraying. There are considerable differences between canopy characterization processes for a uniform canopy wall (i.e., vineyard, orchards) and individual, isolated large trees, such as traditional olive tree plantations in the south of Europe. Olive tree plantations and olive oil production represent one of the most important incomes and activities in the agricultural sector on Mediterranean area with a total area of 7.7 Mha and a production over 11.6 MTm per year, and Spain is the largest producer of olive oil globally [6]. New alternative trellis systems have been adopted and developed for new olive tree plantations in recent years, to enable intensive farming. These produce increased tree density and a homogeneous canopy distribution along the row, but this represents only 2% of the olive cultivated area in Spain [6]. Further, traditional olive tree plantations represent 76% of total cultivated area, and intensive plantations represent 22% of cultivated area. Here, single, isolated and in most cases large, wide and heterogeneous canopy shapes can be identified. It is widely accepted that intensive orchards are more profitable than their traditional counterparts, due to the higher plantation density and the possibility of mechanical harvesting. As a result, there have been attempts to convert traditional plantations into intensive ones, by leaving one only trunk per tree, in order to allow the trunk shakers to harvest and plant new trees in between existing trees.

According to previous research, canopy measurement methods to characterise the whole tree structure can be classified in two groups: manual measurements and electronic procedures to estimate the most important tree dimensions. A range of manual methods for canopy characterisation has been widely applied to isolated trees. Among them, the ellipsoid method is the most widely used [7,8]. This method is impacted by the location of the measuring point selected for each tree, and so some authors propose to establish measurements at different heights of the canopy [9] to increase measurement precision.

Alternatively, the method of delimiting and measuring the projected area of the tree crown [10] has been proposed as a manual measurement process. Vertical crown projection onto the soil can be related to canopy volume [11]. Several possibilities for crown projection were established by the same authors, who proposed another canopy characterization methodology named tree silhouette. Tree canopy volume is estimated after applying the second theorem of Pappus Guldinus [12]. Electronic measurement methods use ultrasonic sensors and laser based sensors to estimate canopy characteristics. Ultrasonic sensors have been used for canopy volume measurements in vineyards [13–15], orchard fruits [4,16,17], and citrus plantations [9,18] due to its easy operation and management and affordable real-time data processing. However, there are doubts as to the accuracy of such measurements [19,20]. Further, laser technology has been found to achieve higher precision in comparison with ultrasonic sensors [13,18].

Laser technology is one of the most precise methods for canopy characterization [21] when applied to a range of crops using LiDAR 2D technology [21–25]. Furthermore, laser technology has been well implemented in olive tree canopies, where a complete characterization of the tree crown was achieved with a 3D laser scanner [26]. In this study, 24 trees belonging to four plots with a tree spacing of 7 × 7 m and 6 × 6 m (intensive disposition) were scanned from the top and one side of the crop. Excellent results were obtained for crown height, crown width, tree height, crown volume, and foliar density. Despite its precision, field management of those electronic devices is complex and not very well adapted to real field conditions where PPP must be applied. It may also be unrealistic to propose general implementation of these devices for wide use among the growers, due its complexity and cost. Conversely, accurate protocols for manual canopy characterization seem much more affordable and user-friendly, utilising simple and quick measurements. Whatever the selected method for canopy evaluation, it should guarantee some minimum requirements in terms of precision (as close as possible to the real canopy dimensions) in order to apply the most suitable amount of pesticide. To this end, the aim of this research was to evaluate the accuracy of three different methods for manual canopy characterization (ellipsoid method, shade method and tree silhouette method) in traditional olive tree plantations, and to compare these with 2D LiDAR electronic measurements as a reference. Our objectives were:

(1) Define alternative manual canopy measurement protocol and compare it with electronic methods already in use.

(2) Evaluate the proposed methodologies in three different canopy types in olive tree plantations: intensive, adapted for mechanical harvesting, and traditional.

(3) Identify the most representative parameters for canopy characterization in olive trees.

III-2. Experimental Section

III-2.1. Characteristics of Selected Fields and Tree Plantations

Characterised trees were placed in two different fields, both of them located in the province of Córdoba (Andalusia, Spain), with the first one comprising two study plots: first field (37°45'46.78"N; 5°2'55.82"W) represents intensive and semi-intensive system, whilst the second field (37°43'8.43"N; 4°48'20.55"W) represented the traditional (several trunks) system. Plot numbers 1 and 3 present the Picual variety and plot 2 the Gordal variety (Table III-1 and Figure III-1) of olive trees. Plantation patterns consisted of square distributions (plot 1 and 2), and a quincunx distribution (plot 3). The selected culture systems are the most representative of the Spanish olive tree crop [6].

Table III-1. Main characteristics of parcel and trees selected for trials.

Field number	Plot number	Tree Structure	Plantation distances (rs * ts)[1]	Nº of trees studied
1	1	Intensive	7 m * 5 m	18
1	2	Traditional (1 Trunk)	10 m * 12 m	12
2	3	Traditional (Several trunks)	12 m * 12 m[2]	25

[1]See Fig. 1; [2]Plantation in quincunx structure.

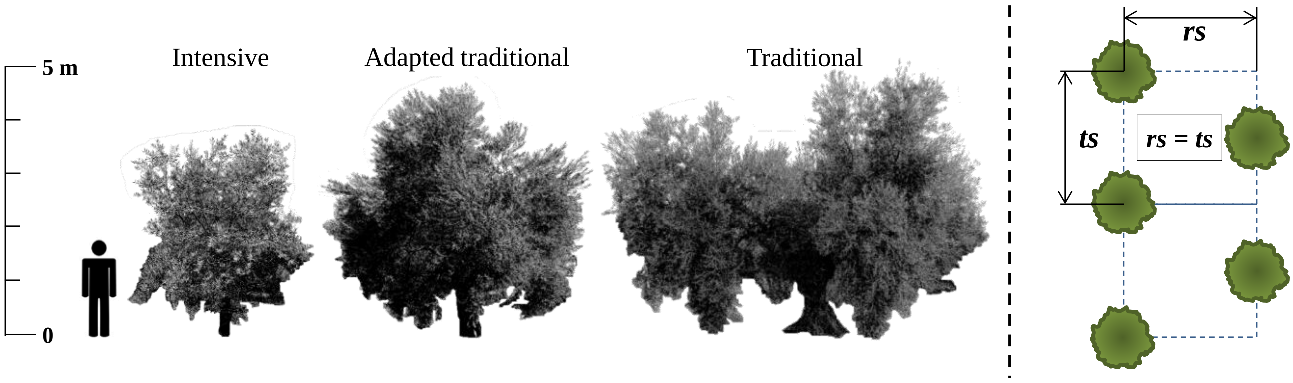

Figure III-1. Olive tree types considered for the study (left) and the traditional trees distribution pattern (right).

III-2.2. Manual crown measurement methods evaluated

Three different manual methods for crown measurement were selected: Vertical Crown Projected Area method (VCPA), Ellipsoid Volume method (V_E), and the Tree Silhouette Volume method (V_{TS}). Measurements corresponding to all the proposed methods and evaluated tree types were done the same day (Intensive: 25 February 2014, Adapted traditional: 19 March 2014, Traditional: 20 May 2014 and 2 July 2014) trying to avoid external and undesirable influences. A detailed explanation of the principles and procedure arranged for every one of the selected methods appears below. Those methods were compared with the results obtained with the electronic measurement method using LiDAR sensor.

III-2.2.1. Vertical Crown Projected Area method (VCPA)

The VCPA method is based on determining the projection of the tree crown onto the soil and determining its area, which can be correlated to its total volume. In order to do so, eight fixed directions (every 45 degrees) related to the north azimuth were selected for all the trees, (Figure III-2) around the entire tree circumference. Vectors were measured from the centre of the trunk with a compass and a plummet placed in the most external point of the profile for each considered direction. If there was only one trunk, it was necessary to add half the Trunk Diameter (T_d), which was obtained from the trunk circumference at 30 cm height. If there were two trunks, the origin of the vectors was set on the medium point between their centres, and if there were three, the origin was set on the barycenter of the triangle formed by the three. The Mean Vector parameter ($\overline{MV}$) was then calculated as the mean of all the measured vectors (V_i) according to Equation III-1:

$$\overline{MV} = \frac{\sum_{i=1}^{n} V_i}{n} \qquad \text{[III-1]}$$

Where: $\overline{MV}$ is the Mean Vector Parameter (m); V_i the single values of the eight measured vectors (m); and n the number of vectors for every single tree (8 vectors for a 45º space angling).

Taking into account the length and direction of every vector, it was possible to determine the coordinates of every single point acting as a vertex of the internal polygon (Fig. III-2) and, therefore, its area (A_{PA}).

The internal polygon’s area was calculated following Equation III-2 corresponding to the Gauss’s area algorithm, also known as shoelace method [22,27].

$$A_{PA} = \frac{1}{2} \cdot \left| \sum_{i=1}^{n-1} x_i \cdot y_{i+1} + x_n \cdot y_1 - \sum_{i=1}^{n-1} x_{i+1} \cdot y_i - x_1 \cdot y_n \right| \qquad \text{[III-2]}$$

Where x_i and y_i are the coordinates of each point i.

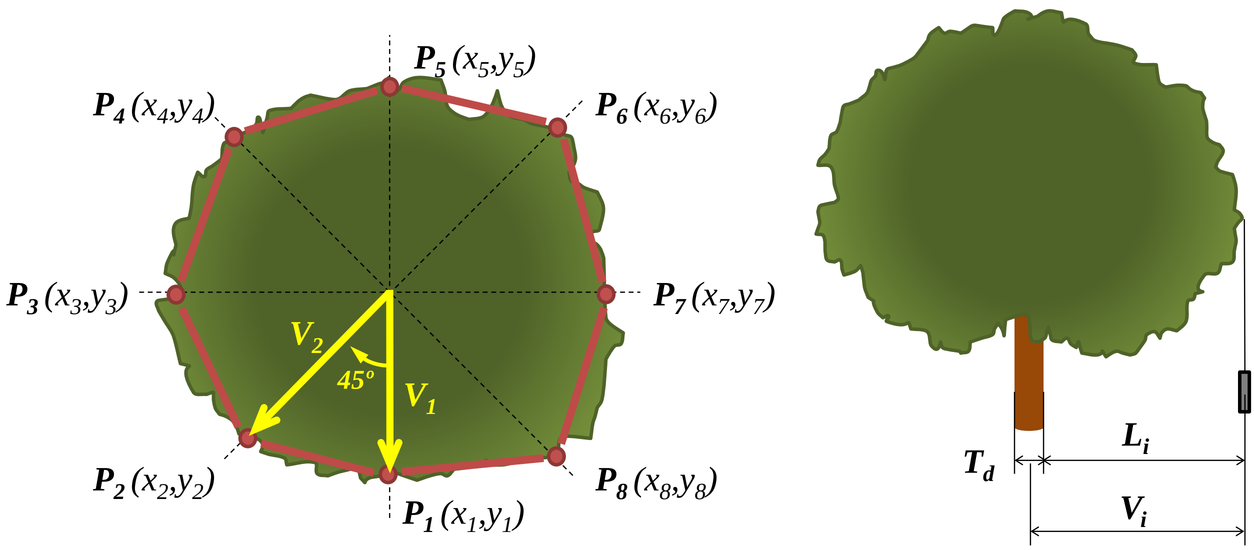

Figure III-2. Vertical Tree Crown Projection's Mean Vector measurement method (left) and Tree crown projection measurement method (right).

III-2.2.2. Ellipsoid Volume method (V_E)

Ellipsoid volume determination is based on assuming the tree crown to be an ellipsoid (defined by three semi axes) and determining its volume. Even though this method has been widely used in other studies [7,8,28], there is not a well-defined standard measurement protocol to obtain the required dimensions.

In the present study, ellipsoid axes (E_a, E_b and E_c, as shown in Figure III-3) were calculated using some of the vectors determined for the VCPA method. Therefore, semi axes E_b and E_c were calculated as the length of their corresponding vectors in North and East directions. In order to obtain semi axis E_a, the total tree height (H_T) and the height of the first leaf (H_{fl}) were measured using a topographic milestone. E_a was calculated as the difference between H_T and H_{fl} and divided by 2. The final Ellipsoid Volume (V_E) was calculated according Equation III-3:

$$V_E = \frac{4\,\pi}{3} \times E_a \times E_b \times E_c \qquad \text{[III-3]}$$

III-2.2.3. Tree Silhouette Volume method (V_{TS})

The Tree Silhouette method (V_{TS}) determines the crown volume by revolutionizing areas delimited on pictures taken from various positions around a vertical axis in the centre of the tree. Pictures were taken in the same orientation as the VCPA method, with a total of eight pictures per tree (P_i). Pictures were scaled according to a reference (a topographic milestone set next to the tree) in the image processing software ImageJ ® (National Institutes of Health, Bethesda, MD, USA). Next, trunk position was determined and the tree canopy contour was manually delimited and automatically divided into two halves.

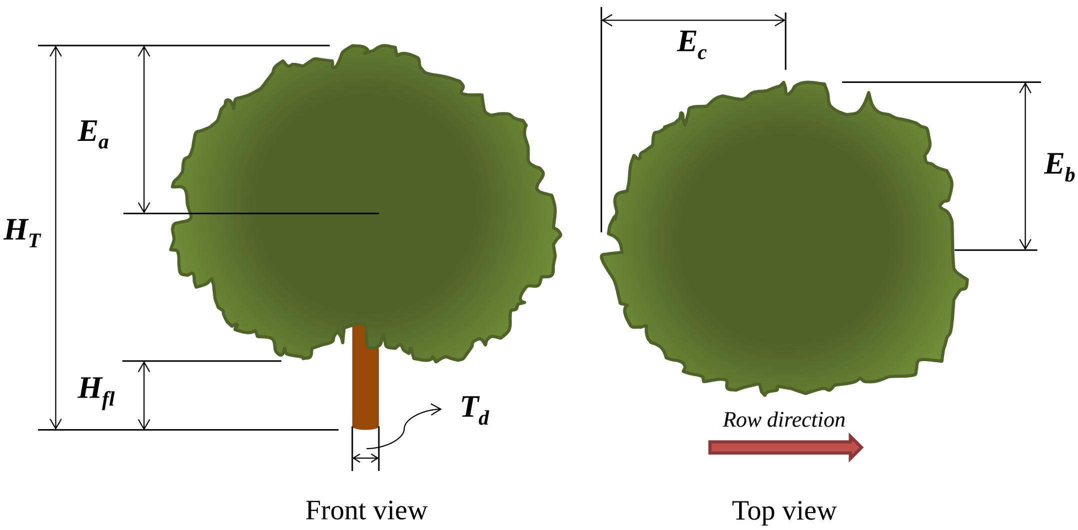

Figure III-3. Parameters defined in the *Ellipsoid Volume* method.

A special program was developed in R software [29] to automatically calculate the surface of both of the crown projection halves and their respective volumes, by revolutionizing it around the vertical axis and using the Pappus Guldinus' second theorem. For each picture, the tree volume was calculated as the mean of the two generated volumes. The final volume of the tree crown was calculated as the mean of all the eight calculated volumes corresponding to the eight pictures (as shown in Figure III-4).

III-2.3. LiDAR canopy characterization

A total of 55 trees randomly distributed on the selected parcels were scanned three times per side from the centre of the row, at a constant speed of 1 km h^{-1}. The LIDAR scanner used in this work was a low cost general-purpose model LMS-200 (Sick, Dusseldorf, Germany), with accuracy of ±10 mm and 5.2 mrad of divergence in a range up to 8 m, a selectable angular resolution of 1°, 0.5° or 0.25° and a scanning angle of 180°. The same device has been used previously [22,30]. It was mounted on a mast attached to a tractor and connected to a laptop via serial RS-232 port (as depicted in Figure III-5). A GPS device AGGPS162 model (Trimble Navigation Ltd., Sunnyvale, CA, USA) with EGNOS correction was placed just above the sensor to determine absolute coordinates of the LiDAR points to relate the points obtained from each side of the tree. Two fixed references were used to correlate the GPS data to the LiDAR data, as described in Llorens *et al.* [22]. Even though the LiDAR sensor allows a maximum 0.25º resolution, speed limitations of the serial port communication meant that 1º resolution was chosen for the scans. However, this resolution is adequate for accurate characterisation of the canopy [21].

LiDAR points and GPS coordinates obtained were processed to georeference each point obtained with the laser sensor. The total data files were filtered to discard those outside the crown (Figure III-6).

A special program developed in R software was used to determine the volume represented by the point cloud. For this purpose, the method used by Xu *et al.* [11] was applied, which consists of calculating the crown volume by dividing the whole tree crown into different horizontal slices with the same height and aggregating all of its individual volumes.

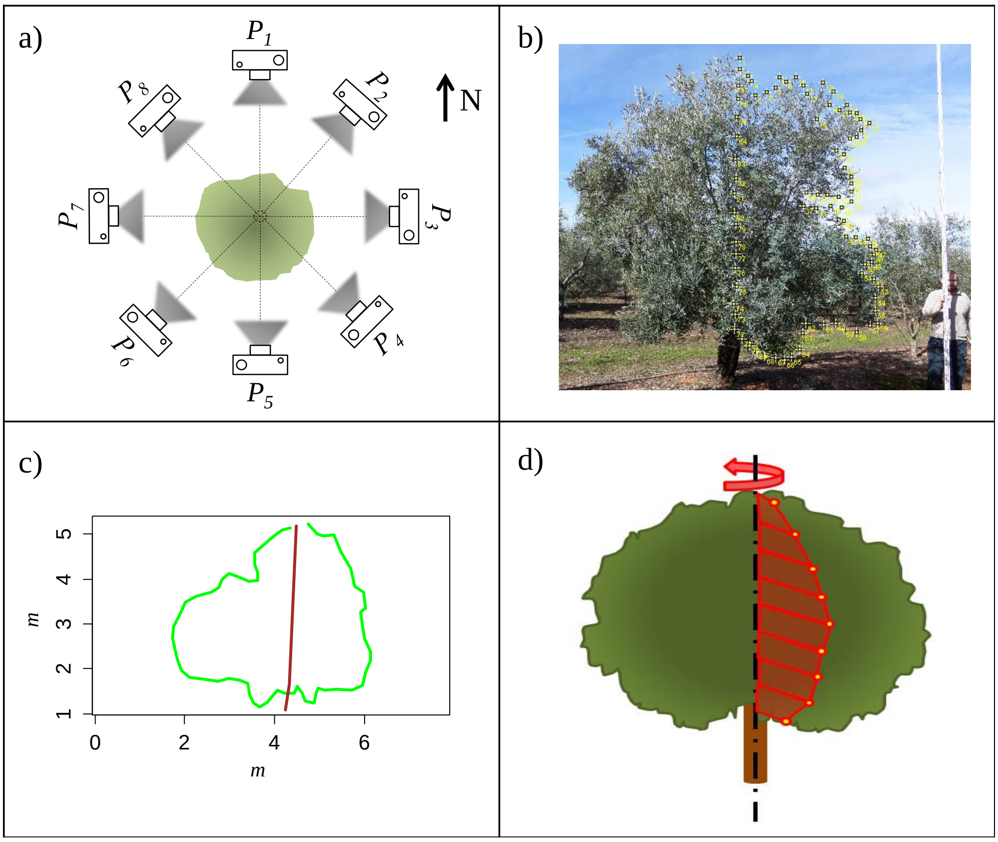

Figure III-4. Procedure to characterise tree silhouette from each picture (P_i) that was taken from all sides (every 45º) of the tree: (a) 8 Picture positions; (b) Manual contour delimitation; (c) Surface automatic calculation; and (d) Surface revolution.

Data were classified into intervals of 0.01 m height each and represented on the same plane (Figure III-7). The convex hull algorithm [31] was used to define a contour with the most external points of each single slice, and its area A_i was then calculated.

Figure III-5. LiDAR sensor and laptop computer in the field, installed on the tractor.

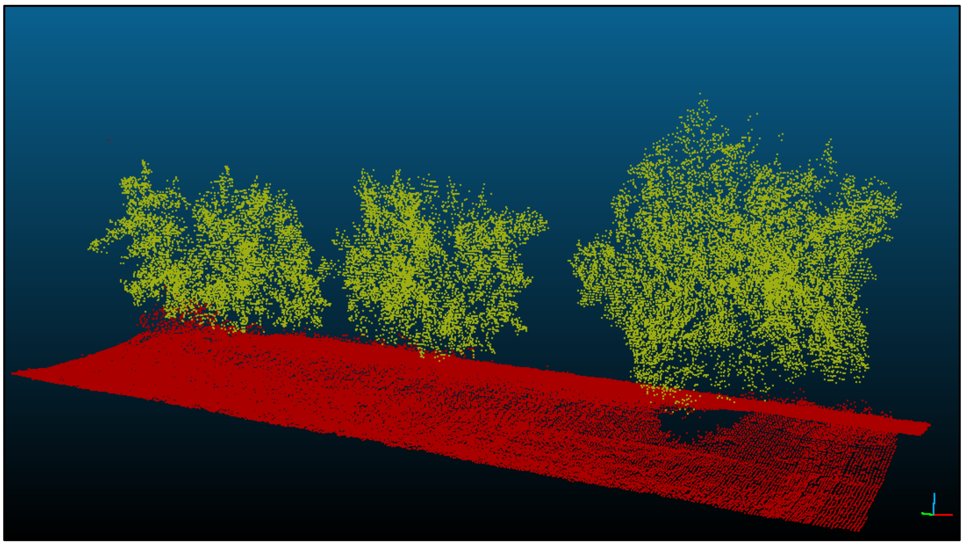

Figure III-6. LiDAR cloud points obtained after scanning three contrasting trees on the same row. This cloud of points was used to estimate the tree volume.

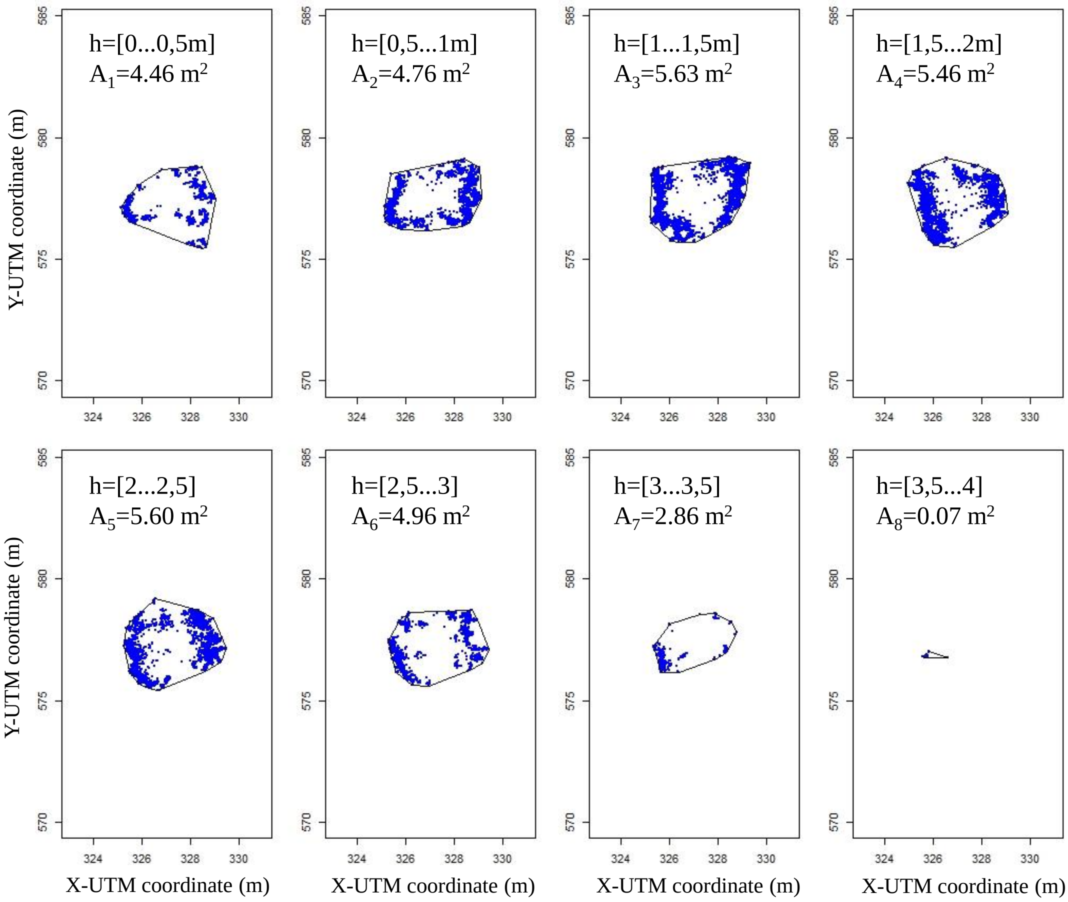

Figure III-7. Projections of the points inside the different slices for a height interval of 0.5 m.

Finally, each area was multiplied for the height interval, giving an individual volume. The sum of every individual volume gave the total LiDAR tree crown volume (V_L), as expressed in Equation III-4:

$$V_L = \sum_{1}^{n} \Delta h \times A_i \qquad \text{(III-4)}$$

Where V_L is the calculated LiDAR volume in m^3; Δh is the height interval (m) and A_i is the area inside the contour (m^2).

III-2.4. Statistical analysis

The statistical analysis adopted was a linear correlation between all measured and calculated parameters, using statistical R-Software with the *Agricolae* package. The data analysis included not only the results obtained by the method, but also the different geometrical parameters measured in order to determine any possible relationship with V_L, assumed the most reliable and used as a reference volume. A Shapiro-Wilk test ($p > 0.05$) [32,33] and a visual inspection of their histograms, normal Q-Q plots and box plots were performed to ensure that the data were normally distributed for all the tree structures evaluated.

III-3. Results and Discussion

III-3.1. Geometrical parameters of evaluated trees

Table III-2 summarises all measured and calculated parameters. Canopies are observed to be large, with large trees ranging from 3.91 m in height in intensive plantations, up to 4.58 m in traditional culture systems. Such tree heights make crown characterisation difficult even with the LiDAR sensor, because the emitter is set to a constant height and thus the laser beam could not reach the upper part of the trees. Nevertheless, this is offset by the high row spacing, which allowed the sensor to be used with no data loss. Another important observation was the variability in trunk diameter amongst the plantations. Trunk diameter as measured in traditional trees was almost four times the magnitude and more variable (higher standard error) than those observed in intensive trees. This makes sense, due to the huge variety of different trunk shapes observed in the trees of traditional plantations.

We observe little variability in all shape parameters, i.e. E_a, E_b, E_c and $\overline{MV}$, reaching 10 cm length in the most variable case. Relative errors are also small, ranging from 1.36 to 4.80%. This is especially true for $\overline{MV}$, due to its characterization of the whole shape of the crown.

Conversely, a large variability was observed in the estimated volume of various tree types amongst the methodologies evaluated. For example, considering V_L, it ranges from 24.60 m^3 for the intensive to 98.08 m^3 for the traditional orchard, which supposes a four times increment of volume. Volume ranges obtained by all other methods were similar in magnitude. Variability within each tree structure was lower than 10% of the mean, even though standard errors were greater than 5 m^3 in most traditional trees. Thus, accuracy of estimated volumes becomes less important with increasing tree volume, specially in traditional trees, which have the biggest sizes.

Table III-2. Mean and Standard Error of all parameters for each tree type.

	Mean and Standard Error		
	Tree type		
	Intensive	*Adapted*	*Traditional*
H_T (m)	3.91 ± 0.09	4.52 ± 0.11	4.58 ± 0.05
T_D (m)	0.19 ± 0.01	0.41 ± 0.04	0.75 ± 0.08
E_a (m)	1.82 ± 0.05	2.09 ± 0.06	2.10 ± 0.03
E_b (m)	2.07 ± 0.09	2.33 ± 0.09	3.24 ± 0.08
E_c (m)	1.96 ± 0.09	2.25 ± 0.07	3.07 ± 0.10
$\overline{MV}$ (m)	2.03 ± 0.07	2.31 ± 0.07	3.27 ± 0.08
V_E (m^3)	31.90 ± 3.00	46.74 ± 3.52	87.64 ± 3.79
A_{PA} (m^2)	11.88 ± 0.83	15.39 ± 0.96	35.58 ± 2.06
V_{TS} (m^3)	29.69 ± 2.32	45.11 ± 3.92	100.26 ± 5.21
V_L (m^3)	24.60 ± 2.19	33.49 ± 3.58	98.08 ± 5.21

III-3.2. Comparison between LiDAR and manual methods for tree volume estimation

Normality for all the tree types was confirmed by Shapiro-Wilk normality tests and visual inspection of their histograms, normal Q-Q plots and box plots. Therefore, data transformations were not deemed necessary. LiDAR tree crown volume (V_L) was compared with volumes predicted by all other methods, as shown in Figure III-8.

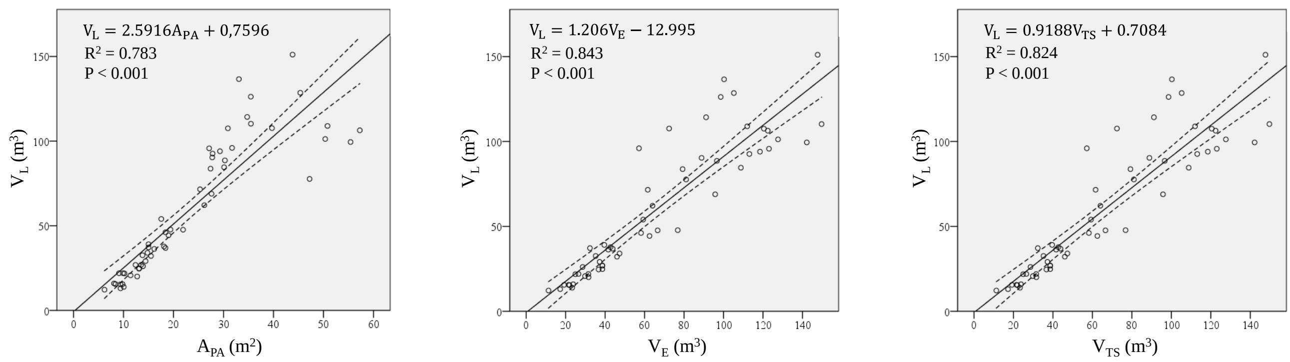

Figure III-8. R^2 values for linear correlations between LiDAR volumes (V_L) and Vertical Projected Area (A_{PA}) (left); Ellipsoid Volume (V_E) (centre); and Tree Silhouette Volume (V_{TS}) (right) for all orchard plantations. Dashed lines represent the 95% confidence interval for the mean.

The three regression models demonstrate that the methods are in good agreement for the whole range of studied volumes (R^2 = 0.79, $P < 10^{-3}$ in all the cases). The Ellipsoid method (R^2 = 0.84) performs best, in reference to the LiDAR measurements, and may therefore be considered the most appropriate method in olive tree volume characterisation after applying a multiplication factor of 1.2, according to the regression model (Figure III-8). The Tree Silhouette method also fits the data with considerable accuracy (R^2 = 0.824), and thus it may be a suitable alternative method. The Projected Area method demonstrated the lowest correlation (R^2 = 0.785) with the LiDAR data. However, this method showed another important characteristic – the vector representation of the trees in all the eight directions identified the differential growth amongst the tree types (Figure III-9). This is especially evident in traditional trees, where the mean Vertical Projected Area reflects a higher growth in a southwest direction.

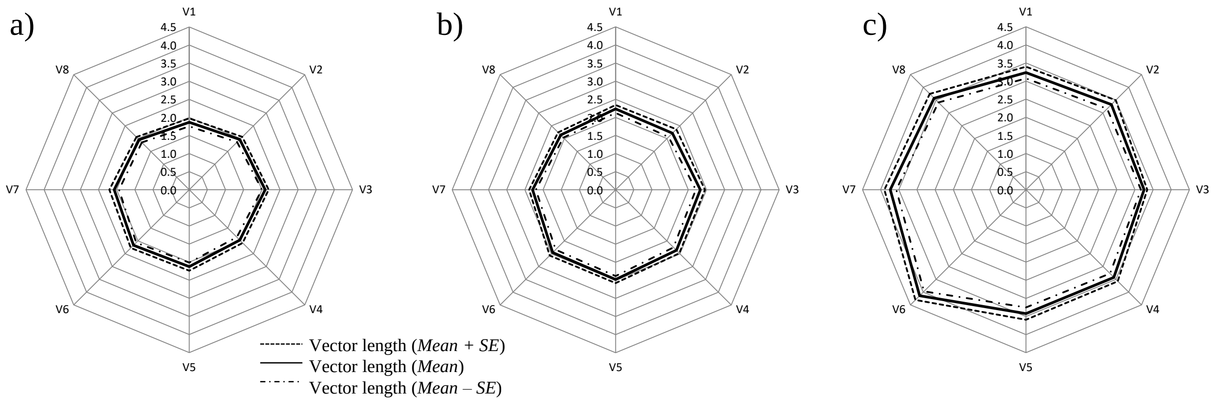

Figure III-9. Mean Projected Area for each tree type: (a) Intensive, (b) Adapted Traditional and (c) Traditional.

We also observed that small tree volumes are more comparable with the V_L data, such as those in the intensive orchard, than for the larger trees belonging to traditional plantations. This could be accounted for by the irregularity of the traditional tree shapes, which are more easily measurable and characterised by the LiDAR sensor than by manual measurements. Electronic measurement by LiDAR easily detects the protruding branches and crown irregularities, which are common in biggest trees, and harder to characterise by any of the other proposed methods. In a decreasing order according their accuracy for irregularities' detection, methods can be ordered as: Tree Silhouette Volume, Vertical Projected Area, and Ellipsoid Volume.

Table III-3. Correlations between LiDAR tree crown volume (V_L) and the other evaluated methods for each tree structure.

Significance: * for p < 0.05 and ** for p < 0.01.

	Intensive	**Adapted Traditional**	**Traditional**
		V_L (m^3)	
A_{PA} (m^2)	0.860**	0.835**	0.242*
V_E (m^3)	0.755**	0.760**	0.399**
V_{TS} (m^3)	0.792**	0.903**	0.275**

Table III-3 summarises the R^2 values for the correlations between LiDAR tree crown volume (V_L) and the other evaluated methods for each tree/plantation type. Tighest correlations between single-trunk trees, i.e., intensive and adapted traditional trees and LiDAR estimates were observed, whilst Vertical Projected Area was the best estimator of LiDAR volume ($R^2 = 0.860$) in orchards. Correlations of ellipsoid method (V_E), and Tree Silhouette method (V_{TS}) with LiDAR data, were very similar ($R^2 = 0.755$ and $R^2 = 0.792$, respectively).

In traditional adapted trees, the Tree Silhouette method presented the highest correlations with LiDAR data ($R^2 = 0.903$), whilst the Ellipsoid method was the least correlated ($R^2 = 0.760$). The highest R^2 values were observed between LiDAR and all of the evaluated methods in the adapted crop system.

Finally, small positive correlation coefficients were observed between the various measured parameters and LiDAR data for traditional tree shapes. As discussed earlier, this may be due to the reduction in measurement accuracy in the manual methods for high tree volumes (Figure III-9). Even though not being very precise, the most accurate method for characterising traditional tree measurements among all the studied was found to be the ellipsoid method ($R^2 = 0.399$), with the highest probability ($p < 0.001$) ($p < 0.013$ for A_{PA} and $p < 0.007$ for V_{TS}).

III-3.3. Correlation between LiDAR volume and simple canopy parameters

We evaluated the use of various parameters used to calculate tree volume or area with LiDAR volume estimates, in order to simplify the field measurement methodology. Correlations of individual parameters with LiDAR volume are shown in Table III-4. All measured parameters, except for the $\overline{MV}$ parameter, are weakly positively correlated with LiDAR volumes ($p < 0.01$). They are especially low for the Projected Area, Ellipsoid, and Tree Silhouette methods.

Table III-4. Multiple correlations between different parameters obtained in the study for all the tree types. Significance: * for p < 0.05 and ** for p < 0.01.

	H_T (m)	**T_D** (m)	$\overline{\boldsymbol{MV}}$ (m)	**E_a** (m)	**E_b** (m)	**E_c** (m)	**V_L** (m^3)
H_T (m)	1	0.129**	0.450**	0.912**	0.326**	0.309**	0.419**
T_D (m)		1	0.403**	0.123**	0.338**	0.413**	0.342**
$\overline{\boldsymbol{MV}}$ (m)			1	0.402**	0.664**	0.748**	0.903**
E_a (m)				1	0.294**	0.299**	0.353**
E_b (m)					1	0.423**	0.676**
E_c (m)						1	0.654**
V_L (m^3)							1

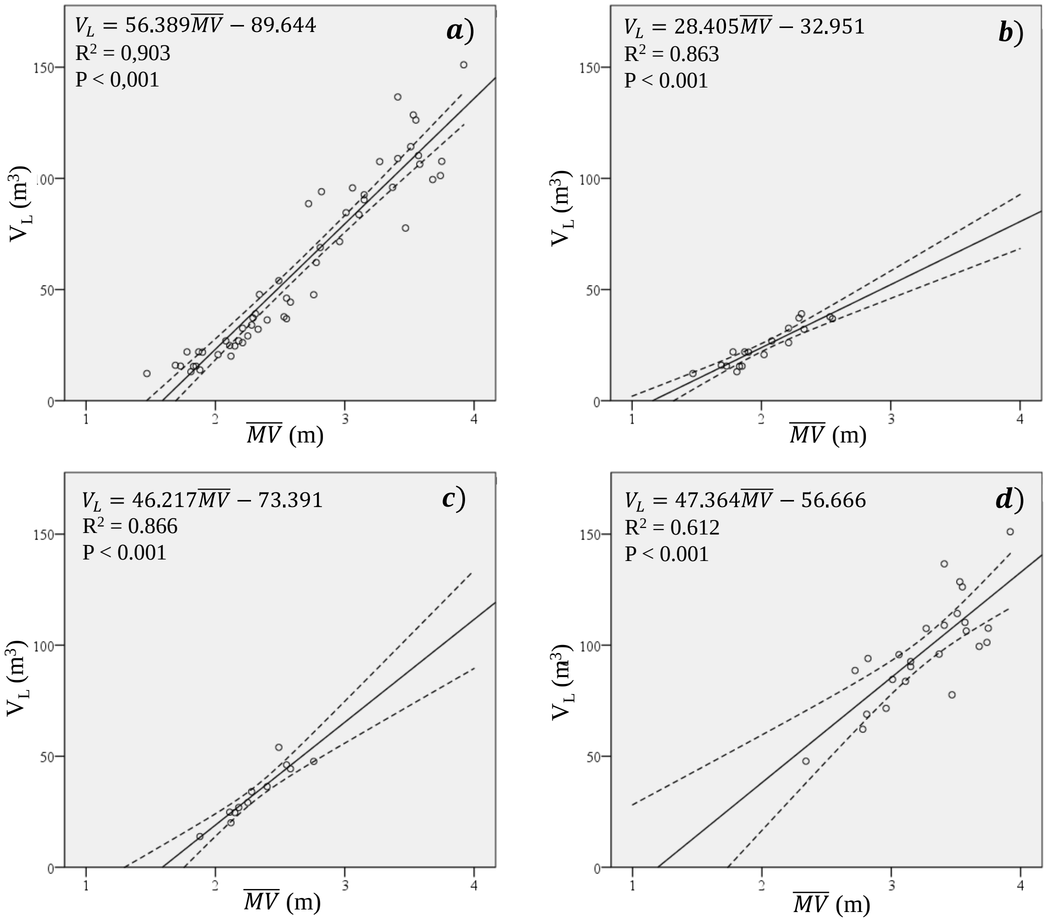

Figure III-10. Correlations between $\overline{MV}$ and LiDAR volume for (a) All studied trees (b) Intensive trees (c) Adapted traditional trees (d) Traditional trees.

Only $\overline{MV}$ in the Projected Area method is strongly correlated with LiDAR volume (R^2 = 0.903) (Table III-4). Comparing this value with those obtained for the studied methods, it is found to be higher (highest R^2 value was 0.845 for ellipsoid method, Figure III-8). This is an important observation, as $\overline{MV}$ parameter calculation is a relatively simple and quick method that could be adopted by farmers or technicians without specialist training, in comparison with other methods such as electronic equipment is needed.

The $\overline{MV}$ parameter correlates well with LiDAR volume across all plantation types, as shown in Figure III-10. For example, correlation coefficients are particularly high in intensive (R^2 = 0.863) and adapted trees (R^2 = 0.866). These coefficients of determination were as good as those obtained with the studied methods for these systems (Table III-3). The most significant result was the coefficient of determination for traditional trees (R^2 = 0.612), which was much higher than those similarly observed using the ellipsoid, tree silhouette and projected area methods. Thus, $\overline{MV}$ provides much more accurate estimations of crown volume than all other evaluated methods.

As to the relationships between each two of all the measured and calculated parameters, significant correlations indicate proportionality in the trees' geometrical characteristics. Positive correlations are observed between H_T and $\overline{MV}$ ($R^2 = 0.450$; $p < 0.01$) that indicates a relationship between crown width and height. Positive correlations are further observed between T_D and $\overline{MV}$ ($R^2 = 0.403$; $p < 0.01$), semi axes E_b ($R^2 = 0.338$; $p < 0.01$), and E_c ($R^2 = 0.413$; $p < 0.01$). However, it must be underlined the low value of those correlations, which could suggest a certain dispersion of the values.

III-4. Conclusions

Three methodologies for measuring tree crown volumes were compared with those obtained with a 2D-LiDAR laser scanner in three types of olive tree plantations. The following conclusions can be drawn:

- All the evaluated methods were able to estimate the tree crown volume with a relatively high degree of accuracy. The best predictions were obtained with the Ellipsoid Volume measurement method, followed by the Tree Silhouette method and the Vertical Projected Area method.

- Correlations were not as good as those found in other three-dimensional crops due to the irregularity in the crown shapes. Determination coefficients were highest amongst low tree volumes, and weakest for high tree volumes.
- Vertical Projected Area method was the most accurate for intensive orchards, whilst the Tree Silhouette and Ellipsoid Volume method yielded the most accurate estimates of tree volume in adapted traditional orchards and traditional orchards, respectively. In traditional orchards, the coefficient of determination was much lower than in the adapted trees.
- Statistical analysis carried out demonstrated that all of the evaluated methods were able to estimate the crown volume in olive tree plantations, though new methodologies could be selected to achieve high accuracy.
- Study of different shape parameters showed that all the evaluated tree shapes have a relationship between their basic dimensions, especially between tree height and crown width.
- Among all the parameters measured or calculated in this study, the Mean Vector used for the Vertical Projected Area method gave the best correlations amongst all trees in total, and for each individual tree shape. For traditional olive trees, the correlation of this parameter with the crown volume was much higher than those obtained with the other evaluated methods, but it is interesting to remark that the accuracy of the prediction is not as good as in the other crop types. In addition, the mean vector method seems to be a simple and quick procedure for canopy characterization, and requires no specialist training to be adopted. Therefore, it has been found to be the one of the most useful methods for estimating tree volume in traditional olive tree plantations. Nevertheless, its accuracy limitations should be considered.
- In general, whilst electronic LiDAR measurements was found to be the most accurate and reliable amongst all methods tested here, more user-friendly methods (such as measurement of the $\overline{MV}$ parameter) could be implemented to accurately characterizeze tree crown volume and dimensions (i.e. shape). However, LiDAR measurement should not be considered as a perfect method. Problems linked to the measurement process itself [34] and collateral errors produced by GPS measurements [22] should be evaluated.

III-Acknowledgments

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CHAPTER IV - Assessing the optimal liquid volume to be sprayed on isolated olive trees according to their canopy volume.

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Chapter IV - Assessing the optimal liquid volume to be sprayed on isolated olive trees according to their canopy volume

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IV – Abstract

The application of pesticides to traditional and intensive olive orchards in Southern Spain has led to environmental problems. More specifically, the lack of an accurate, useful criterion to regulate the spray volume in relation to canopy characteristics has led to spray drift and runoff, which are threats to local ecosystems. The aim of this study was to determine the optimal relationship between canopy volume and the spray application volume, called specific spray volume, CV, through laboratory and field trials.

In the laboratory trial, 6 specific spray volumes (0.05, 0.08, 0.10, 0.12, 0.15, and 0.20 $L \cdot m^{-3}$) were tested in a specially designed structure containing small, live olive trees in order to simulate an intensive plantation system. The model aimed to evaluate the coverage of pesticide application on water sensitive paper (WSP) collectors. In the field trial, the three laboratory specific spray volumes that gave the best coverage values were tested on live, intensively managed trees, whose crown volume was manually measured. Food dye E-102 was used to determine the spray deposition on artificial targets (10 × 10 cm absorbent paper pieces), and WSP was used to evaluate spray

coverage. The spray penetration and deposit homogeneity inside the canopy were also evaluated. Weather conditions during the field trial were monitored with a weather station.

The results of the laboratory trial showed that the three best specific spray volumes were 0.08, 0.10, and 0.12 L · m^{-3}, resulting in mean coverage values of approximately 30%. The ANOVA of the field trial results showed that the 0.12 L · m^{-3} was the optimal specific spray volume for isolated olive trees. This specific spray volume gave the highest mean deposits, the best efficiency (as measured by the greatest normalized deposit), the most favourable penetration and homogeneity, and the highest coverage values.

IV-1. Introduction

Pesticide spray application is an important preventative that helps avoid the yield losses due to organisms and pests that are harmful to crops. Despite this key role, the application of pesticides needs to be accurate because imprecise treatments can lead to serious problems such as environmental pollution, traces of pesticides in food, and health issues in human operators. Olive cultivation, one of the most important agricultural industries in Spain, covering more than 2.5 million hectare (FAO, 2012), is focused in the south in the Guadalquivir river basin (Gómez-Calero, 2009), along the Andalusian provinces of Jaén, Córdoba, and Seville. This basin contains several water reservoirs devoted to human consumption, and studies have reported significant levels of pesticides and herbicides that are commonly used in the olive crop industry in this region (Belmonte Vega et al., 2005; Espigares et al., 1997; Hermosín et al., 2013; Robles-Molina et al., 2014). These problems have led the European Commission (EC, 1999) to conclude that the olive sector poses risks to the environment.

The main losses to the environment created by applying pesticides to olive tree canopies are spray drift and runoff. Spray drift is defined by the standard ISO 22866 (2005) as the quantity of plant protection product that is carried out of the sprayed (treated) area by the action of air currents during the application process. Runoff is created either by overdosing, which is a consequence of not having an appropriate dosing system, or performing low uniformity treatments that result from the inadequate use and poor maintenance of application equipment. Treatments with excessive pesticide doses can contribute enormously to surface and groundwater pollution problems (Barba-Brioso et al., 2010). However, farmers often apply product to the point of runoff as a guarantee of high biological efficacy (Miranda-Fuentes et al., 2015a). In addition, pesticide manufacturers tend to raise the Label Recommended Dose Rate (LRDR) to increase the margin-for-error to mitigate losses produced by different circumstances related to the particularities of the treatment (Russell, 2004; Walklate et al., 2006). Many authors have attempted to quantify spray drift and direct ground losses generated by different circumstances, varieties of equipment, and working parameters by using traditional and new technologies (Arvidsson et al., 2011; Balsari et al., 2005; Derksen et al., 2007; Gil et al., 2013a; Gregorio et al., 2014; Nuyttens et al., 2010; Salyani et al., 2007). Other authors have tried to reduce spray drift by adjusting working parameters or testing new equipment and technology (Ade et al., 2005; Baldoin et al., 2008; Cross et al., 2003, Cross et al., 2001; Derksen et al., 2006; García-Ramos et al., 2012; Jamar et al., 2010; Landers, 2010; Larzelere and Landers, 2010).

Among the different actions that can be taken to reduce the environmental impact of pesticide application, dose adjustment is one of the most important. However, calculating the dose presents a unique challenge when it involves pesticide application to tree crops because they are three-dimensional plants (as opposed to ground crops that have a nearly planar shape to spray), and furthermore, there is a lack of agreement in the dosage systems adopted by the European Union (EPPO, 2012). Rüegg et al. (2001) summarized the different dosing models from a variety of countries in the European Union, including the Crown Height model (CHT model), the Surface Orchard model (SO model), and the Tree Row Volume model (TRV model). The CHT model, also known as the Leaf Wall Area (LWA) (Morgan, 1981), and the TRV model (Byers et al., 1984; Sutton and Unrath, 1984), have the benefits of being straightforward and reliable. The LWA model consists of adjusting the sprayed volume to the tree row projected area (i.e., the lateral surface of the tree row), and may soon be adopted by European pesticide manufacturers (Walklate and Cross, 2012). However, this dosing system does not take into account the crown diameter of the trees; in contrast, the TRV method does include this parameter, which is considered significant for traditional olive plantations because of the ellipsoidal shape of their tree crowns. Other authors have suggested that canopy density must be taken into account in order to efficiently adjust the spray dose (Gil et al., 2011; Gil and Escolà, 2009; Pergher and Petris, 2008; Walklate et al., 2011, Walklate et al., 2003). The challenge of high-volume and isolated tree crops, which include traditional and intensive olive cultivation systems, is that their irregular crown size and shape makes the implementation of established methods difficult.

For these reasons, an evaluation of canopy features must be taken into account when adjusting spray volume. Different manual and electronic methodologies have been developed to characterize the canopy of tree crops. Electronic methods are more accurate than manual ones, but they are more difficult for farmers and technicians to implement because they require programming and electronic knowledge. Among them, the LiDAR systems are the most accurate, but they are expensive and difficult to use (Rosell and Sanz, 2012). Manual methods are easy to implement and accurate enough that their values can be used in calculating precise recommendations for spray volumes. Miranda-Fuentes et al. (2015b) compared the crown volume obtained with a 2D low-cost general-purpose LiDAR scanner with the volumes obtained by three manual canopy characterization methods, already defined in the scientific literature, in three different cultivation systems in olive. The results of the three evaluated methods, i.e., the Ellipsoid method (Villalobos et al., 1995; Zamahn and Salyani, 2004; Zaman and Schumann, 2005), the Vertical Crown Projected Area method, and the Tree Silhouette method (Iniesta et al., 2009; Xu et al., 2013), were significantly correlated with the LiDAR volume. The Mean Vector method, which was defined in the aforementioned paper (Miranda-Fuentes et al., 2015b) and was easy to use, had a strong correlation with the LiDAR volume for all studied cultivation systems. Therefore, this approach was considered the most appropriate to use in field conditions and was the one applied in this study.

Specific spray volumes relate the spray application volume to canopy volume in order to optimize the spray volume in relation to specific canopy characteristics. Specific spray volumes of 0.095 $L \cdot m^{-3}$ have been used in vineyards (Gil et al., 2013b; Llorens et al., 2010).

The purpose of the present study was first to determine crown volume using the Mean Vector canopy characterization method for isolated olive trees. The next goal was to implement these values in the calculation of an optimum specific spray volume that relates the spray application volume to the canopy volume and that can be used by farmers and technicians to readjust the high spray volumes that are currently being applied in a simple and affordable way.

IV-2. Materials and Methods

Two trials were designed to determine the optimal specific spray volume. The purpose of the laboratory experiment was to determine the three best specific spray volumes among the six analysed, and the field condition trial was set up to test these three optimal values and establish the best specific spray volume under actual work conditions. Before the trials, the airblast sprayer was properly calibrated by measuring the total liquid flow rate for each nozzle and pressure value.

IV-2.1 Laboratory trial

The laboratory trial was set up in the experimental field located on the Campus of Rabanales, in the University of Córdoba (37º55'13" N; 4º43'09" W).

2.1.1 Trial development

A special system was designed to determine spraying quality with different specific spray volumes. Inside the whole tree, the most adverse case for spraying is the deepest tree profile, which is usually placed in the centre of the tree because of its ellipsoidal shape (Villalobos et al., 1995; Zaman et al., 2005). Thus, the system's dimensions were coincident with those of the aforementioned profile. The system consisted of a mobile sampling structure (Fig. IV-1). The purpose of the structure was to have a reference system that permitted the placement of spray collectors in fixed places to ensure that their positions inside the canopy did not vary in the different trials (Fig. IV-1).

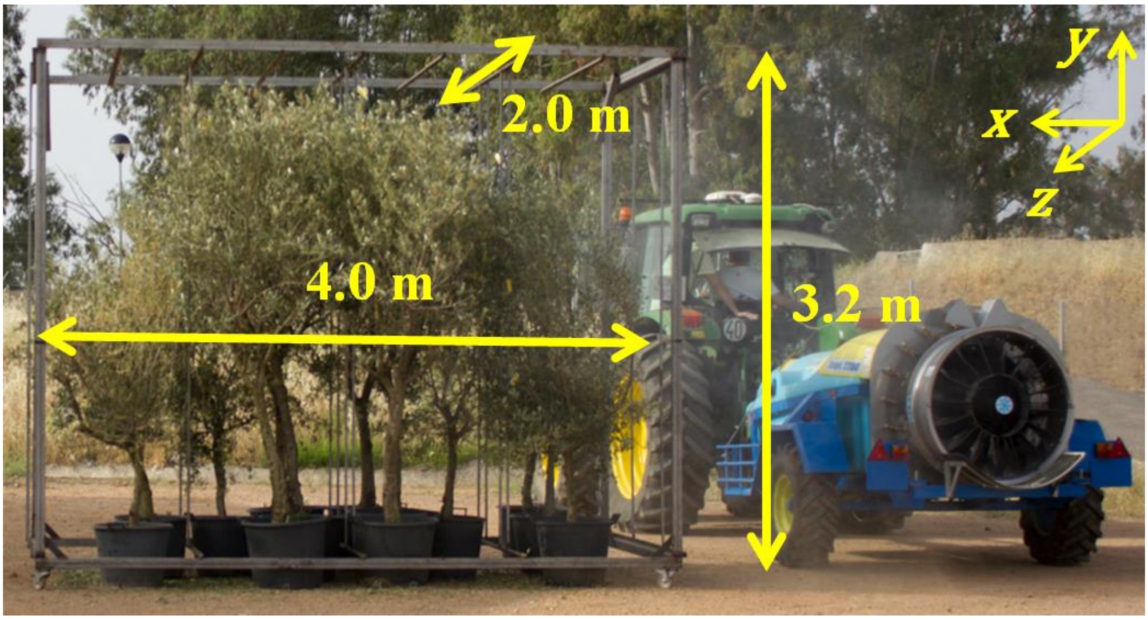

Figure IV-1. Dimensions of the sampling structure for the laboratory trial and coordenates system considered.

In order to obtain a real crown shape, small-sized olive trees were placed inside the structure and allowed to achieve a continuous leaf mass (Fig. 1). The canopy dimensions were coincident with those typically found in trees undergoing intensive management in order to simulate a real canopy profile. The dimensions of the profile (assuming a regular tree shape), generated a tree of 26.56 m^3, which is consistent with this tree type (Miranda-Fuentes et al., 2015b).

IV-2.1.2 Application equipment and spray parameters

Spray application was performed with a commercial airblast sprayer (model Ecojet 2200 l, Osuna Sevillano, Jauja, Spain) with axial fan and hollow cone nozzles (ATR Series, Albuz, Saint-Gobain, Evreux, France) that was pulled by a John Deere 6420 tractor (Deere and Co., Moline, IL, USA) (Fig. IV-1).

Six specific spray volumes (C_V) were tested. A specific spray volume of 0.10 L · m^{-3} was established as the reference based on the findings of previous authors in other three-dimensional crops (Byers et al., 1971; Heijne et al., 1997; Llorens et al., 2010). The remaining specific spray volumes were set higher or lower than this base value (Table IV-1). Most commercial farms implement a specific spray volume of approximately

0.20 L · m^{-3}, resulting in application volumes near 1000 L · ha^{-1} or higher. Such practices aim to guarantee biological efficacy, but result in tremendous product loss.

Table IV-1. Spray parameters selected in the laboratory trial.

Spray Parameter	**Value**					
Treatment ID	1	2	3	4	5	6
Cv (L · m^{-3})	0.05	0.08	0.10	0.12	0.15	0.20
Spray Volume Rate (L · ha^{-1})	270.88	433.41	541.76	650.11	812.64	1083.52
Liquid Flow Rate (L · min^{-1})	15.80	25.28	31.60	37.92	43.34	63.20
Albuz ATR nozzle colour	Yellow	Red	Green	Green	Blue	Blue
Pressure (bar)	12	9	8	12	8	18

Forward speed was experimentally adjusted to be 5 km · h^{-1} This speed corresponded to a constant PTO speed of 421 rpm.

The air flow rate (AFR) was set at 9 m^3 · s^{-1} for all treatments because this rate had the best response in terms of mean deposit, coverage, and homogeneity in previous trials (Miranda-Fuentes et al., 2015b). In order to calculate the spray volume and the Tree Row Volume (TRV), tree and row spacing was set at 7 m, a standard value in intensive plantation patterns (AEMO, 2012) that generates a plantation density of 204 trees per ha. The theoretical crown volume was 26.56 m^3, and thus the TRV of the plantation would be 5418 m^3 · ha^{-1}. The 14 available nozzles (7 per side) were open in all cases to reach the whole canopy.

IV-2.1.3 Weather conditions and canopy characterization

Weather conditions were measured with a weather station (CR800, Campbell Scientific Inc., Logan, UT, USA), which was used to monitor wind speed and direction, temperature, and relative humidity. The 2D ultrasonic anemometer WindSonic 232 (Campbell Scientific Inc.), which measures wind speed and direction, presented a measurement range of up to 60 m · s^{-1}, with a resolution of 0.01 m · s^{-1} and 1º for the wind direction measurement. The sensors were mounted on a 4 m vertical mast and placed 20 m from the sampling structure.

Canopy characterization was performed to ensure that the calculated tree volume was realistic and that the collectors were placed at the correct height. This procedure was carried out using a low-cost, general-purpose, LMS-111 2D LiDAR Laser Scanner (Sick, Dusseldorf, Germany) and software that was specially designed for data acquisition and volume measurement. This software was programmed in R Studio following the procedure described in Miranda-Fuentes et al. (2015b). Five measurements were taken on both sides of the structure (*X* axis direction) with a forward speed value of 1 $km \cdot h^{-1}$.

IV-2.1.4 Sampling system, experimental design, and data analysis

The sampling system was designed to follow the indications of ISO 22522. A grid of 15 sampling positions was placed inside the canopy, with 5 depths and 3 heights. Three profiles on which all the treatments were replicated were used (Fig. IV-2). Water sensitive papers (WSP; 76 × 26 mm in size) (Syngenta Crop Protection AG, Basel, Switzerland) were used as artificial collectors and attached to the leaves. The experimental design incorporated two factors, both with replicated measurements. The first factor was the C_V with 6 levels, and the second was the sampling position inside the canopy (15 levels, Fig. IV-2). The dependent variable was the percentage coverage (*SC*). Two collectors were placed in each sampling zone and each was oriented toward opposite sides of the profile. The mean parameters between both sides were then calculated.

The WSP were analyzed with a specially programmed macro in the free software Image J (Zhu et al., 2011). *SC* data were statistically analyzed with R Studio Software. The main evaluation criterion was to achieve a coverage near 30%, a level considered optimal in other studies (Chen et al., 2013). Analysis of variance (ANOVA) was used to establish the effects of the factors on the dependent variable *SC* (%). The sphericity hypothesis of the model was checked with the W Mauchly statistic (Smith et al., 2009).

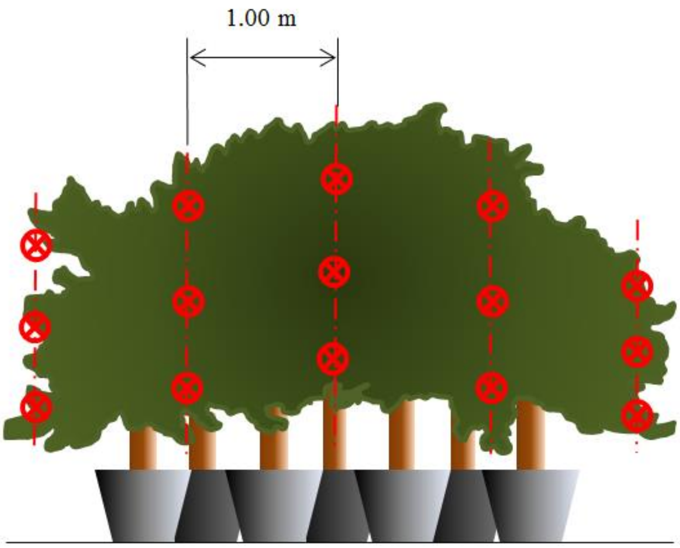

Figure IV-2. Sampling zones distribution in the canopy in the laboratory trial.

In order to evaluate the null hypothesis for the within-subject factors and their interaction, a univariate test based on the Greenhouse-Geisser correction (1959) was used. Prior to analysis, percentage data were subjected to arcsin $[(Y/100)^{0.5}]$ transformation. The means were compared using a Bonferroni post-hoc test (α = 0.05). Analyses were performed using SPSS v. 22 (IBM, Armonk, NY, USA).

IV-2.2 Field trial.

A trial methodology was designed to evaluate the three best performing application coefficients under field conditions. The trial was conducted in a commercial farm in Córdoba province, Spain (37º42'53" N; 4º48'32" W) that has an intensive olive cultivation pattern with row and tree spacing of 7 m.

IV-2.2.1 Canopy characterization

In order to determine the application volumes for each coefficient, crown volumes of the selected trees were measured. The Mean Vector method was used because this analysis gave more accurate results than the LiDAR volume determination method in previous studies (Miranda-Fuentes et al., 2015b). The Mean Vector approach consists of measuring the distance between the centre of the tree and 8 external points of the canopy in eight fixed directions (V_A to V_H). In this way, eight distances, or vectors, were obtained, and the Mean Vector (*MV*) was strongly correlated with the crown volume calculated from the LiDAR points cloud, V_L. The relationship between V_L and *MV* for intensively managed trees with a volume range from 15 to 45 m^3 is described by equation IV-1:

$$V_L = 28.405\overline{MV} - 32.951 \qquad \text{(IV-1)}$$

where V_L is expressed in m^3 and *MV* in m (Miranda-Fuentes et al., 2015b).

The canopy density was also characterized by introducing a hollow cube with 20 cm sides inside different parts of the canopy and removing the leaves contained inside. In this way, the leaf area in a known volume of $8 \cdot 10^{-3}$ m^3 was calculated by weighing the samples and using the relationship between the leaf area and weight, that was previously obtained.

IV-2.2.2 Application equipment and spray parameters

Five olive trees were selected and sprayed with the Eolojet 2200 (Osuna Sevillano) conventional airblast sprayer. The spray parameters are shown in Table IV-2.

Most operation parameters were kept constant with respect to the previous laboratory trial, including the forward speed (5 km $\cdot$ h^{-1}), the Air Flow Rate (9 $m^3 \cdot s^{-1}$), the PTO speed of 421 rev $\cdot$ min^{-1}, and 7 open nozzles per side (14 total). The size and shape of the canopy justified the use of all the nozzles during the spray application.

IV-2.2.3 Tracer extraction rate in absorbent paper

In order to prevent irregular target canopy shape from having a significant effect, the same five trees were sprayed in the three treatments. Food dye E-102 (i.e., Tartrazine), was the spray tracer used to determine spray deposits on 10 × 10 cm artificial absorbent paper collectors. A laboratory trial was designed to determine the Tartrazine extractable portion through washing. Seven Tartrazine doses were tested by applying a varying number of droplets from the same dilution that were either 20 µl or 60 µl in volume, depending on the treatment (Table IV-3), on square 10 × 10 cm pieces of absorbent paper. The liquid was extracted from a 10 g $\cdot$ L^{-1} Tartrazine solution. Three replications were made. All pieces were washed with 100 ml of distilled water for 60 s. Three samples of 200 µl were taken from each washing solution, put on a 96 well plate, and analysed in a previously calibrated spectrophotometer (Synergy HTX, BioTek Instruments, Inc., Winooski, VT, USA) at a wavelength of 427 nm. The obtained concentration was compared with expected values in order to determine the extractability of the method.

Table IV-2. Spray parameters for the field trial.

Spray Parameter	**Value**		
C_V ($L \cdot m^{-3}$)	0.08	0.10	0.12
Spray Volume Rate ($L \cdot ha^{-1}$)	433	541	650
Liquid Flow Rate ($L \cdot min^{-1}$)	25.28	31.60	37.92
Albuz ATR nozzle colour	Red	Green	Green
Pressure (bar)	9	8	12

IV-2.2.4 Sampling system and experiment design

Five trees belonging to the same tree row were selected inside the field of study and underwent five replications per treatment. Sixteen sampling zones were established per tree, again following the indications of ISO 22522 norm, with 3 heights and 4 sectors. For the intermediate height, which corresponded to the largest part of the tree, each sector was subdivided into two subsectors, an inner and an outer one (Fig. IV-3) in order to achieve a higher resolution of the spatial distribution of the spray deposits. Three sampling areas were established per single sampling zone: a 10 × 10 cm absorbent paper piece and two 76 × 26 mm pieces of WSP (Syngenta Crop Protection, Inc.), coincident with the upper and lower parts of the leaves.

For the study of the spray absolute and normalized deposit, the *SC*, and N_i, a two-factor model was designed, with each factor having replicated measurements. The first factor was the spray volume, given by the specific spray volume (C_V = 0.08, 0.10, and 0.12 L m^{-3}), and the second was the position, with 16 levels corresponding to the 16 sampling positions (Fig. IV-3).

Table IV-3. Applied droplets number and volume for the extractability test.

Applied droplets	Droplet volume (µl)	Expected concentration ($mg \cdot L^{-1}$)
0	0	0
5	20	10
6	20	12
7	20	14
8	20	16
9	20	18
10	20	20
10	60	60

The experimental unit was each one of the trees used in the experiment. A one-factor replicated-measurements ANOVA was used to evaluate the penetration specific spray volume because the same trees were sprayed in all of the treatments.

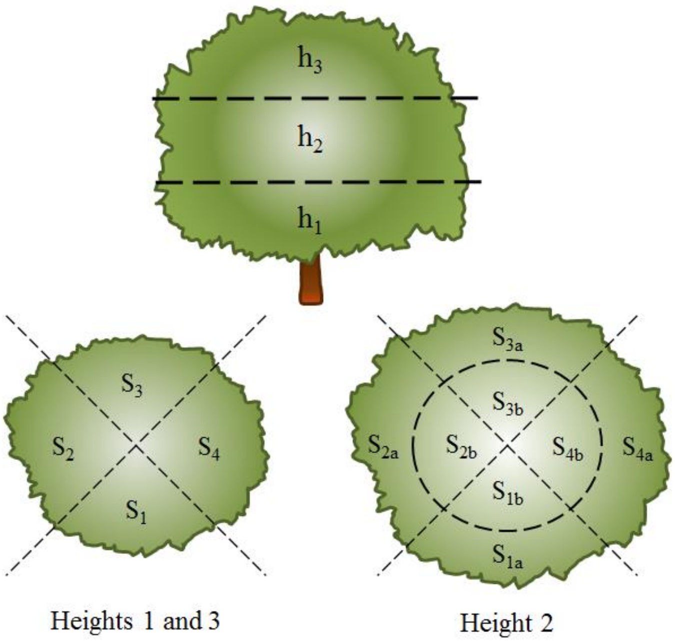

Figure IV-3. Sampling zones distribution in the tree crown for the field trial.

IV-2.2.5 Trial performance and weather conditions measurement

Once the sprayer was properly calibrated, a sample of the spray mix was collected from a nozzle to document the actual Tartrazine concentration in the tank. The treatments were performed by spraying the entire row (not just the selected trees) to ensure that the conditions were as real as possible. The trees were sprayed from both sides. The operators waited for approximately 10 min after application to allow the collectors to completely dry before retrieving them. At this time, another sample of the tank content was taken. Each case sample of the absorbent paper was stored inside a plastic bag and put into a dark environment to prevent photo degradation of the tracer.

The same weather station used in the laboratory trial (CR800, Campbell Scientific Inc,) was set up 20 m from the sprayed row in the field of study. The anemometer was mounted on a mast at a height of 1 m above the ground, and data of wind speed and direction, air temperature and relative humidity were recorded every 2 seconds from the beginning to the end of the trial.

IV-2.2.6 Data analysis

a. Absorbent paper samples analysis

The absorbent paper samples were taken to the laboratory and 100 ml of distilled water was introduced into the storage bags in order to wash the papers. This methodology ensured that the Tartrazine that was initially on the sample and was adhered to the plastic bags was also washed. In this way, there was no loss of spray tracer. The samples were then shaken for 1 min and three aliquots were extracted from each and put into a 96 well plate. Each plate contained three blank wells to correct the values of the remaining samples. All of the concentration values were corrected with the extractability factor obtained in the extractability test.

The calculation of the spray deposit per unit area, expressed in the terminology published by Pergher and Gubiani (1995), was performed with Equation IV-2:

$$d = \frac{T_{cl} \cdot w}{L_a} \qquad \text{(IV-2)}$$

where d is the deposit per unit area (µg cm^{-2}), T_{cl} is the tartrazine concentration in the washing solution (ppm), w is the volume of extractant used (ml), and L_a is the area of the absorbent paper (100 cm^2).

As different spray volumes were used, it was necessary to normalize the deposits obtained in order to compare the different treatments (Llorens et al., 2010). The normalized deposition, d_n, was calculated using Equation IV-3:

$$d_n = d \cdot F \qquad \text{(IV-3)}$$

where F is a volume factor calculated as the minimum spray application volume (C_V = 0.08 L · m^{-3}) divided by the spray application volume [C_V = (0.08 L · m^{-3})/(0.10 L · m^{-3}/0.12 L · m^{-3})] for the sample treatment.

b. Water Sensitive Paper samples analysis

WSP samples were analysed with the same Image J macro used in the laboratory trial. The considered coverage parameters, i.e., percentage coverage SC and impact number N_i, were calculated for the upper and lower parts of the leaf by considering the collectors placed on each surface and their SC (%), N_i (cm^{-2}), and the homogeneity of the aforementioned parameters, HSC (%) and HN_i (%), respectively, calculated as indicated in Equation IV-4 and Equation IV-5:

$$HSC = 100 - \left| \left(\frac{SC_{underside}}{SC_{upper\ side}} \times 100 \right) - 100 \right| \qquad \text{(IV-4)}$$

$$HN_i = 100 - \left| \left(\frac{N_{i\,underside}}{N_{i\,upper\ side}} \times 100 \right) - 100 \right| \qquad \text{(IV-5)}$$

c. Calculated parameters and statistical analysis

A penetration coefficient, C_p, was defined, and calculated by dividing the spray deposits found in the inner sampling zones to the ones obtained in the outer zones (Equation 6) for sampling height 2 (Fig. 3):

$$C_P = \frac{d_{IB}+d_{2B}+d_{3B}+d_{4B}}{d_{1A}+d_{2A}+d_{3A}+d_{4A}} \times 100 \qquad (6)$$

where d_{iB} are the spray deposits collected in the internal parts of each sector *i* (height 2) and d_{eA} represent the spray deposits collected in the external parts. The perfect penetration would be indicated by a C_p value of 100.

The *CV* (%) was calculated with the deposition values of all of the sample points, and was the indicator of the homogeneity of the deposits distribution.

Analysis of variance (ANOVA) was used to establish the effects of the factors on the dependent variables: absolute deposit per unit area (μg cm^{-2}), normalized deposit (μg cm^{-2}), percentage of coverage on the upper side and underside (%), mean coverage (%), C_p (%), impact number at the upper side and underside (cm^{-2}), and mean impact number (cm^{-2}). The sphericity hypothesis was evaluated with the Mauchly W statistic (Smith et al., 2009).

In order to check the null hypothesis for the within-subject factors and their interaction, a univariate test based on the Greenhouse-Geisser correction (1959) was used. Prior to analysis, percentage data were subjected to arcsin $[(Y/100)^{0.5}]$ transformation. The means were compared by using a Bonferroni post-hoc test (α = 0.05). For the C_p (%), a univariate contrast with no sphericity correction was used. Analyses were performed using SPSS v. 22 (IBM).

IV-3. Results and discussion

IV-3.1 Laboratory trial

IV-3.1.1 Weather conditions measurement and LiDAR canopy characterization

The results of the weather conditions measurements are shown in Table IV-4. Importantly, the air speed was relatively low at approximately 1 m · s^{-1} in most cases. This wind speed is not considered high enough to set a drift trial by the ISO 22866 norm about drift quantification and, therefore, it was considered that it did not significantly affect the experimental outcome. In this way, the results can be considered representative and not affected by variations in this parameter.

The variations in temperature and relative humidity values were large enough that they could have potentially created a possible loss from evaporation. Nevertheless, the short distance to the trees and type of collectors used minimized the impact of these differences.

The whole canopy was characterized to produce the point cloud shown in Fig. IV-4a. Using the LiDAR measurements, it was possible to determine the sampling heights in each sampling profile (Fig. IV-4b).

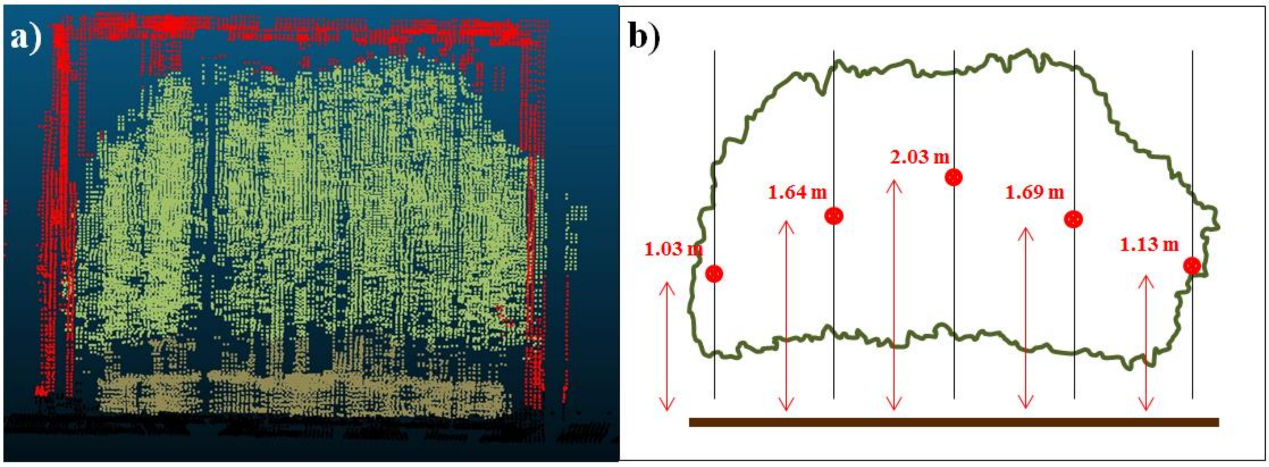

Figure IV-4. a) Point cloud obtained with LiDAR scanner Sick LMS-111. **b)** Sampling heights for the defined profiles.

Table IV-4. Weather conditions during the laboratory trial.

Parameter		Mean value	Coefficient of Variation (%)
Wind speed	[m · s^{-1}]	1.33	30.67
Temperature	[º C]	21.29	23.18
Relative humidity	[%]	48.36	26.83

* 0º direction is coincident with the geographic North

IV-3.1.2 Spray coverage on WSP collectors

A percentage coverage distribution through the different treatments is shown in Fig. IV-5. The values differ among the treatments, with the maximum values at the 0.20 specific spray volume, and the minimum ones with the 0.05 specific spray volume. This rise in spray coverage with the increase in applied volume was previously observed in other works (Miranda-Fuentes et al., 2015c). Similar to that case, the increase is not proportional, not being the coverage values four times greater for Treatment 6 than for

Treatment 1, as the spray application volumes are. There are also differences in the variability of coverage values (Fig. IV-5), with coefficients of variation rising from 80% (Treatment 6) to 122% (Treatment 1). This finding may be explained by the fact that inner deposits are smaller in relation to the outer ones in the low volume treatments.

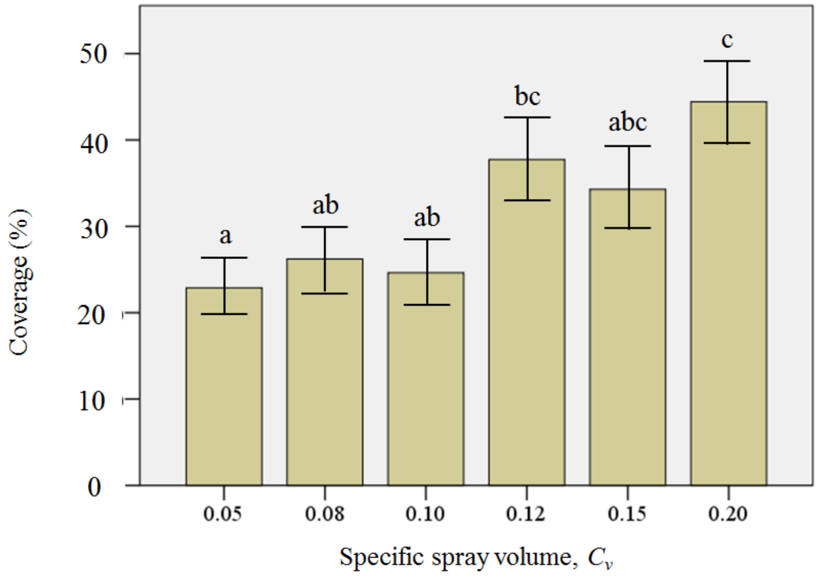

Figure IV-5. Distribution of spray coverage per treatment. Error bars show the 95% Confidence Interval.

The results of the ANOVA with Bonferroni's test (α = 0.05) are listed in Table IV-5, which shows that there are three homogeneous groups. The first one, designated as 'a,' includes the lowest values, with a mean coverage of 27.00%, the second, 'b,' corresponds to the intermediate, with a mean coverage of 30.72%, and the third, 'c,' has the highest values, with a mean coverage of 38.81%. Considering the aforementioned criterion of Chen et al. (2013), the second group, 'b,' would achieve the optimal coverage, with groups 'a' and 'c' under and over treated, respectively (Table IV-6).

IV-3.2 Field trial

IV-3.2.1 Weather conditions and manual measurement of the selected trees

Table IV-6 summarizes the environmental conditions present during the field trial. Wind speed was very low for all treatments, which supports the representativeness of the results as they were not affected by this parameter. Temperature values were relatively high, especially for the second and third treatment.

Table IV-5. Mean coverage values and Bonferroni's test homogeneous groups.

Treatment ID	**Cv** (L · m^{-3})	**Mean coverage** (%)
1	0.05	22.88 a
2	0.08	26.22 ab
3	0.10	24.62 ab
4	0.12	37.73 bc
5	0.15	34.29 abc
6	0.20	44.42 c

The manual measurements of the eight vectors for the MV parameter calculation are shown in Table IV-7. Trees had a considerable range in their basic dimensions (Table IV-7 and Fig. IV- 6), which is typical of olive orchards because variability among adjacent trees is usually marked. The variability in the vector length for each direction ranged from 0.12 m for the VF vector to 1.70 m for the VE vector, which produced a variation in estimated tree volumes that went from 27.48 to 39.30 m^3. These results showed that the trees were homogeneous, as is consistent with the findings of Miranda-Fuentes et al. (2015b) in one-trunked trees. The total height of the trees and the height to the first leaf were similar.

Table IV-6. Environmental conditions in the field trial.

Parameter		**Mean value**	**Coefficient of Variation** (%)
Wind speed	[m · s^{-1}]	0.45	12.77
Wind direction*	[º]	23	12.89
Temperature	[º C]	27.13	26.58
Relative humidity	[%]	31.03	5.69

* 0º direction is coincident with the geographic North

Table IV-7. Main measurements of the selected olive trees.

Tree ID		1	2	3	4	5	**Mean**	**SD**
Total height (H_T)	[m]	3.9	4.1	4.1	4.2	4.0	4.1	0.11
Height first leaf (h_{fl})	[m]	0.45	0.40	0.40	0.30	0.40	0.39	0.05
Canopy height (H_C)	[m]	3.45	3.70	3.70	3.90	3.60	3.67	0.16
Trunk diameter (T_D)	[m]	1.10	1.18	1.18	1.24	1.15	1.17	0.05
V_A	[m]	2.76	2.05	2.29	2.83	3.07	2.60	0.42
V_B	[m]	2.51	2.30	1.53	2.10	2.40	2.17	0.39
V_C	[m]	2.31	2.46	2.36	2.41	2.38	2.38	0.06
V_D	[m]	1.15	2.22	2.16	1.87	2.40	1.96	0.49
V_E	[m]	0.97	2.51	1.71	2.32	2.67	2.04	0.70
V_F	[m]	2.42	2.36	2.35	2.30	2.41	2.37	0.05
V_G	[m]	2.50	2.82	2.54	2.92	2.43	2.64	0.21
V_H	[m]	2.0	3.19	2.69	3.06	2.59	2.79	0.33
MV	[m]	2.13	2.49	2.20	2.48	2.54	2.37	0.19
Estimated LiDAR vol. (V_L)	[m^3]	27.48	37.74	29.65	37.39	39.30	34.31	5.35
Leaf density (D_l)	[$m^2 \cdot m^{-3}$]	3.15	3.35	4.92	3.37	3.15	3.69	0.91

V_A to V_H: vectors from the center of the tree to the most external parts of the canopy in eight different directions

MV: Mean Vectors

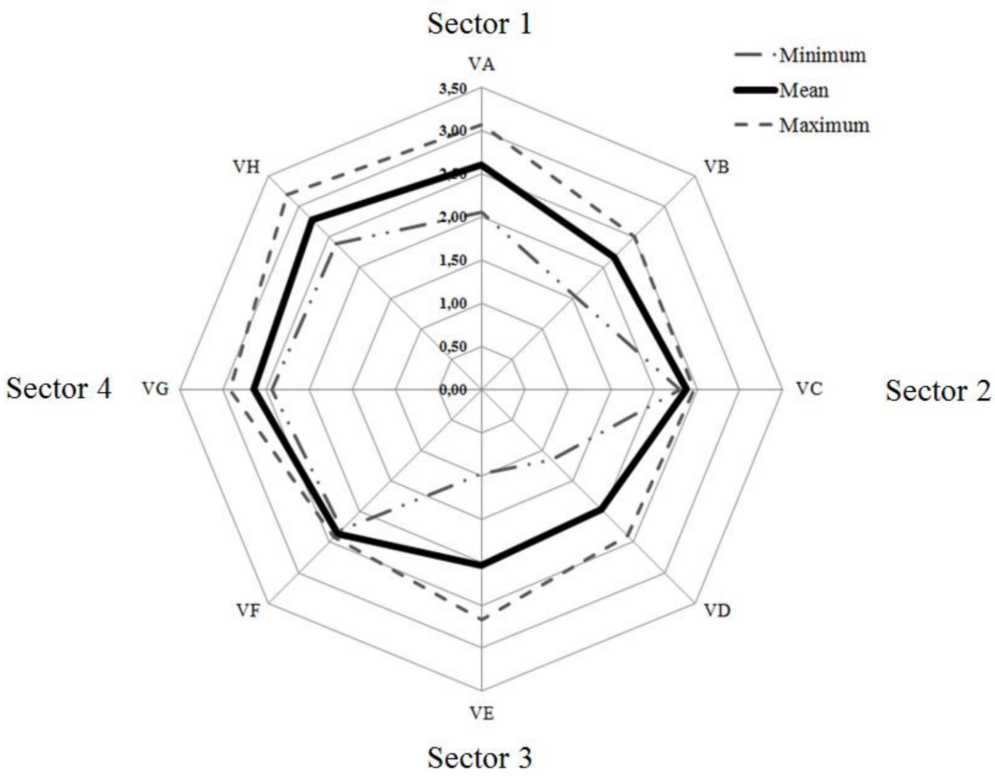

Figure IV-6. Minimum and maximum values of the different measured vectors (VA, ..., VH) for the five selected trees.

IV-3.2.2 Results of the tracer extractability test

The results of the extractability test are summarized in Table IV-8. It was thought that the recovery fraction would be directly proportional to the applied concentration because the absorbent paper would retain a fixed amount of tracer that could not be extracted. In this way, whereas all applied concentrations were reasonable values that were used in other deposition trials, the highest concentration was chosen with the purpose of recovering a high percentage to confirm the expected trend. However, as shown in Table IV-8, the actual results varied from what was expected. The recovery factors were almost constant for the different ranges of concentrations, with values near 60%. Notably, the CV was lower than 10% over a wide range of concentrations. This result, even if unexpected, makes it straightforward to determine the real concentration value of a washing solution in practice because there is a constant recovery factor of 0.59.

Table IV-8. Recovery portion for each expected concentration in the Tartrazine extractability test.

Applied droplets	Droplet volume (µl)	Expected concentration (ppm)	Real concentration (ppm)	Mean recovered portion (%)
0	0	0	0.00	-
5	20	10	5.71	57.06
6	20	12	7.16	59.64
7	20	14	8.85	63.21
8	20	16	9.90	61.87
9	20	18	10.62	59.02
10	20	20	12.15	60.76
10	60	60	60.58	50.49
			Mean	58.86
			Std. Dev.	4.19
			CV (%)	7.12

IV-3.2.4. Spray absolute and normalized deposition

Significant differences were observed in the mean absolute deposit variable, the C_V (p = 0.011), and sampling position in the tree (p = 0.007). However, the interaction of these factors was not significant (p = 0.533), which implies that the distribution of the deposit among the sampling positions was not affected by the application volume. The 0.12 specific spray volume gave the best results (20.51 µg cm^{-2} for C_V = 0.12 L m^{-3}, compared to 15.49 µg cm^{-2} for C_V = 0.10 L m^{-3}, and 12.04 µg cm^{-2} for C_V = 0.08 L m^{-3}), with the latter two not being significantly different. The increment of the mean deposit from applying 0.08 L · m^{-3} to 0.12 L · m^{-3} is 1.7 times higher, which is nearly equal to the increment of volume (1.5 times).

For the mean normalized deposit, there were no significant differences among the varying specific spray volumes C_V (p = 0.499) or factor interaction (p = 0.474), whereas there was a significant difference in sampling position (p = 0.004). The nearly linear correlation between the spray application and the mean deposit had a direct impact on the performance of the operation, quantified by the mean normalized deposit. Even though significant differences among specific spray volumes were not found (p = 0.499), the highest mean value was obtained for the 0.12 L · m^{-3} specific spray volume (Table IV-9). This finding is important because an increase in the applied volume resulting in a decrease in the normalized deposit as a consequence of efficiency loss is a common finding in many tree crops (Braekman et al., 2009; Cross et al., 2003; Miranda-Fuentes et al., 2015a).

When analyzing C_P, the Mauchly W statistic (Smith et al., 2009) gave a significance level of p = 0.13, which therefore does not refute the sphericity hypothesis. The univariate test applied to the C_V factor presented a p-value of 0.846. Therefore, non-significant differences were obtained for the varying volumes, with C_P values of 69.18% for the 0.12 $L \cdot m^{-3}$ specific spray volume, and values of 60.34% and 64.38% for the 0.10 and 0.08 $L \cdot m^{-3}$ specific spray volumes, respectively.

As to the influence of C_V on the spray distribution throughout the canopy, the fact that the ANOVA test showed no significant differences indicates that the movement of spray inside the canopy was similar for the three treatments. The distribution pattern of spray deposits was irregular, with unclear trends in spray distribution (Fig. IV-7). Despite this randomness, the spray deposits consistently decreased with increasing height, a finding consistent with the results of previous, similar experiments (Miranda-Fuentes et al., 2015c). The highest spray deposits were found in heights 1 and 2 in sector 3, a finding that can be explained by the fact that sector 3 was the smallest in volume (Fig. IV-6), and therefore the spray per leaf surface unit was the highest. There were also high deposits in the intermediate height in sector 2, a result that was constant for all treatments. The remaining results are related to the volume of the corresponding sectors, that affects the relationship between the applied liquid volume and target leaf surface.

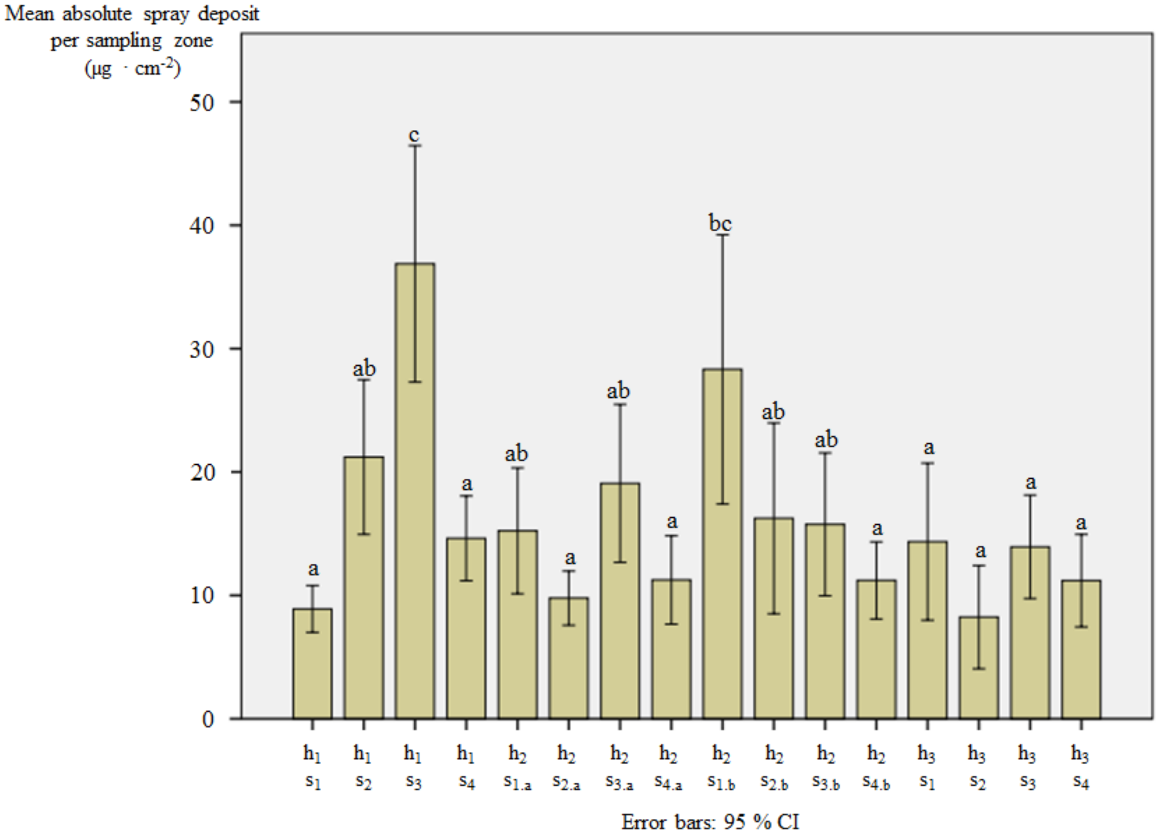

Figure IV-7. Spray deposit distribution for the different sampling positions in the field trial. Error bars indicate the 95% Confidence Interval. h indicates the sampling height and s the sampling sector as indicated in Figure IV-3.

The homogeneity of the spray deposition was also the highest for the 0.12 specific spray volume, as indicated by its lowest coefficient of variation, 61.70%. The high dispersion in the spray deposits is notable and associated with irregularities in the canopy shapes and leaf density values (Fig. IV-6, Table IV-8). Nevertheless, the obtained values can be considered reasonable considering that trials in a super-intensive orchard, which was more regular and less deep, gave coefficients ranging from 36% to 54% (Miranda-Fuentes et al., 2015a).

The results of the post-hoc tests (Bonferroni test, $p = 0.05$) applied to the dependent variables for the different C_V values are summarized in Table IV-9.

Table IV-9. Mean values for deposition and coverage parameters in the field trial with standard errors.

Parameter		Specific spray volume, C_V		
		0.10	0.12	0.08
Mean absolute deposit	$\boldsymbol{d}$ (µg · cm^{-2})	15.49 ± 1.57 a	20.51 ± 1.42 b	12.04 ± 1.01 a
Mean normalized deposit	$\boldsymbol{d_n}$ (µg · cm^{-2})	12.39 ± 1.25 a	13.74 ± 0.95 a	12.04 ± 1.01 a
Coefficient of penetration	$\boldsymbol{C_p}$ (%)	60.34	69.18	64.38
Deposit homogeneity	***CV*** (%)	71.16	61.70	71.96
Upper side coverage	***SC up*** (%)	20.77 ± 2.54 ab	29.15 ± 2.87 b	20.21 ± 2.18 a
Lower side coverage	***SC lo*** (%)	14.31 ± 1.71 a	22.19 ± 2.34 b	11.91 ± 1.37 a
Mean coverage	***SC*** (%)	17.54 ± 1.55 a	25.67 ± 1.87 b	16.06 ± 1.33 a
Coverage homogeneity	***HSC*** (%)	69	76	59
Upper side impacts	$\boldsymbol{N_i}$ ***up*** (cm^{-2})	74.36 ± 4.51 a	102.15 ± 5.88 b	96.36 ± 4.71 b
Lower side impacts	$\boldsymbol{N_i}$ ***lo*** (cm^{-2})	100.76 ± 6.36 a	143.35 ± 8.08 b	100.29 ± 6.76 a
Impacts homogeneity	$\boldsymbol{HN_i}$ (%)	64	60	96

IV-3.2.4 Spray coverage and number of impacts

In evaluating the leaf upper side coverage, significant differences were obtained for the varying spray volumes ($p = 0.002$) and different sampling positions ($p < 0.001$), but not for their interaction ($p = 0.503$). The general results for the coverage values of the WSP samples are shown in Table 9. For the upper leaf surface, the 0.12 specific spray volume gave the highest mean coverage (29.15%), which is significantly different from the values obtained for the other treatments. The 0.10 specific spray volume gave an intermediate value of 20.77%, and 0.08 the lowest, at 20.21%. Only the highest coefficient produced an appropriate value based on the criterion of 30% established by Chen et al. (2013).

The same trend among treatments was found in the lower side. ANOVA obtained a p-value of 0.032 for the C_V. In this case, there were no significant differences for the sampling position ($p = 0.186$) or their interaction ($p = 0.252$). Nevertheless, the mean coverage found in the underside of the leaf was lower in all cases than that found in the upper side, with a maximum value of 22.19% for the highest coefficient. In general, the coverage values of the underside of the leaf were lower than those of the upper side by a percentage ranging from 24% to 42%. In this way, the lower side of the leaves remained undertreated, even when the spray volume was at the highest tested level.

The mean coverage, calculated by considering all of the collected WSP samples, was logically at its maximum in the highest coefficient. The results from the ANOVA indicate significant differences for the C_V (p = 0.001) and sampling position (p = 0.001), but not for their interaction (p = 0.347). The mean coverage produced by the 0.12 specific spray volume resulted in significantly higher results than those of the other two (Table IV-9). Thus, leaves were slightly under covered in the highest coefficient (25.67%), and mostly under covered in the other two. Notably, the coverage values were lower in the field than in the laboratory trial, which may be explained by the fact that tree depth was slightly higher in the field trees. Whereas there was a tree depth of 2 m in the laboratory trial, the mean vector measured in the field trees was 2.37 m, which represents an 18.5% increase. Nevertheless, the 0.12 specific spray volume behaved in a similar way to the first trial, giving a coverage level that could be considered appropriate according to the aforementioned criterion (Chen et al., 2013).

The coverage homogeneity also had its greatest level for the highest coefficient, giving a value of 76% similarity between both sides of the leaf. The intermediate specific spray volume produced a value of 69% similarity, and the lowest specific spray volume, 59%. This fact indicates that the differences in coverage level decreased with an increase in the spray application volume in the studied volumes range.

For the number of impacts per unit area in the upper side of the leaves, significant differences were obtained for the varying volumes (p < 0.001). P-values of the ANOVA for position and interaction were p = 0.035 and p = 0.491, respectively. The upper side received significantly different results for the 0.12 and 0.08 specific spray volumes, and a lower value for the intermediate coefficient, with values ranging from 74 to 102 cm^{-2} (Table IV-9).

The lower side of the leaf received the significantly highest number of impacts in the 0.12 specific spray volume treatment, and the results were similar for the other two treatments (p = 0.001; Table 9). No significant differences were registered for the sampling position factor (p = 0.069), nor for their interaction (p = 0.458). For all treatments, the impact number in the underside was higher than that in the upper side. As to impact homogeneity, the highest was achieved by the 0.08 specific spray volume, with 96%, whereas the lowest by the 0.12 specific spray volume was 60%.

In general, and taking into consideration the results produced by the different analyzed variables (Table IV-9), coverage parameters have the best balance with the highest specific spray volume. These conditions result in acceptable coverage values and the maximum impact number per unit area, which achieve the significantly highest values, especially when considering the variables of upper side coverage and lower side impacts.

IV-4. Conclusions

Two trials were conducted in order to determine the optimum specific spray volume in relation to canopy volume in an intensive olive cultivation system. The following conclusions can be drawn from these experiments. First, the proposed methodology of performing multiple tests in the laboratory with a designed structure can be considered a valid way to replicate results obtained under real field conditions. In addition, the absorbent paper showed to be an appropriate collector when it is not suitable to use natural collectors as leaves, and resulted in the direct correlation between the applied and recovered amounts of tracer, with a constant ratio of 0.58 of extractability for all concentrations tested. Our results also showed that the popular belief that increasing the application volume results in an improvement of the application homogeneity and penetration inside the canopy was not supported by the finding that optimum coverage values resulted in lower liquid volumes, what has a direct impact on the environmental safety of pesticide application. Thus, straightforward guidelines can help farmers to significantly reduce spray volumes in an affordable way. Specifically, among the different tested specific spray volumes, the 0.12 $L \cdot m^{-3}$ specific spray volume was optimal and achieved the best results in almost all measured or calculated parameters considered as indicators of application quality.

IV-Acknowledgments

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CHAPTER V - Improving plant protection product applications in traditional and intensive olive orchards through the development of new prototype air-assisted sprayers.

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Chapter V - Improving plant protection product applications in traditional and intensive olive orchards through the development of new prototype air-assisted sprayers

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V – Abstract

Because of the pollution caused by inappropriate pesticide applications to olive canopies, the Mecaolivar pre-commercial procurement project was undertaken to develop new airblast sprayers to optimise application efficiency and overcome the limitations of conventional sprayers used in traditional and intensive orchards. Three prototype sprayers were developed, evaluated, and calibrated under laboratory conditions and were tested in the field by spraying trees in traditional and intensive cultivation systems. Water-sensitive paper was used to assess the spray coverage achieved. The prototype sprayers were designed to adapt the deposition nozzle positions to the canopy shape to reduce spray drift and off-target application. The first prototype (P1) consisted of a sprayer with a centrifugal fan and adaptable individual spouts, the second (P2) consisted of a sprayer with six small hydraulically-driven axial fans mounted on two mobile structures, and the third (P3) consisted of two axial fans mounted on a tower-like structure with mobile air outlets. The results of the field test showed that the prototypes could be more efficient than conventional equipment. In applying the same liquid volume, the P2 and P3 prototypes increased the coverage by 61% and 46% on average in intensive and traditional systems, respectively, compared to a commercial airblast sprayer, without a significant decrease in the deposit homogeneity throughout the crown.

V-1. Introduction

Olives are among the most important crops grown along the Mediterranean basin, especially in Italy, Portugal, Greece and particularly Spain, which is the world's leading olive producer, with a cultivated area of more than 2.5 Mha (FAO, 2012). Much of the olive-growing area in Spain is concentrated in the south, especially in the Guadalquivir River basin (Gómez-Calero, 2009). This increases the risk of pollution associated with the application of pesticides to olive crops in this region. Several studies have detected the presence of herbicides and fungicides in the river and in nearby reservoirs (Espigares et al., 1997; Barba-Brioso et al., 2010; Hermosin et al., 2013; Robles-Molina et al., 2014).

These problems are typically caused by excessive applications of pesticide without concern for the harm done to the environment or to the economy of the application (Miranda-Fuentes et al., 2015b). It is essential, therefore, to develop appropriate application guidelines to ensure the efficiency of such treatments.

The application of pesticides to so-called three-dimensional (3-D) crops, i.e., to the crowns in tree orchards, is much more difficult than the application of pesticides to arable crops. There are two approaches to dealing with the problems of inefficiency and inadequate coverage associated with applying pesticide treatments to olive canopies: improving the dosing system and improving the application machinery.

However, adjusting the spray dose is useless if the application equipment is not adapted to the target canopy. Therefore, efforts have been undertaken to improve airblast sprayers since their development in the early 1950s (Fox et al., 2008). Conventional airblast sprayers produce problems associated with off-target losses and airborne drift (Salyani and Cromwell, 1992) and work less efficiently in isolated, large-sized trees with high row spacings (Holownicki et al., 2000). These conditions apply to intensive and most traditional olive cultivation systems, which together account for 98% of the olive-growing area in Spain (AEMO, 2012).

The commercial sprayers used in olive production do not include any type of technology for adjusting the spray to the characteristics of the target canopy, except for, occasionally, ultrasonic ON/OFF sensors used to spray only when the tree crown is detected (Giles et al., 1987; Giles et al., 1989). These sensors have been shown to have a significant impact on application efficiency (Ganzelmeier and Rautmann, 2000; Brown et al., 2008), but their use alone is insufficient to adapt spraying equipment to the specific geometries of irregular trees, as the dose remains constant throughout the length detected by the sensor, without the target leaf surface along this track being taken into account. In recent years, various studies have been conducted to assess the performance of airblast sprayer designs for various canopy types and adjust the applied doses to optimise their performance. Most of these studies have compared traditional pesticide application equipment with a prototype or with commercial equipment that incorporates new technology, and various application variables have been examined as well (Holownicki et al., 2000; Pezzi and Rondelli, 2000; García-Ramos et al., 2009; Landers, 2010; Larzelere and Landers, 2010; Foqué et al., 2012).

Escolà et al. (2013) and Gil et al. (2013) developed and validated a new concept for spray application for orchards and vineyards, using a system for canopy sensing, volume setting, and liquid flow rate application that is mounted on commercial airblast sprayers. The canopy sensing is performed using a LiDAR scanner in the case of orchards and by ultrasonic sensors in the case of vineyards. The orchard prototype was shown to be able to adapt the sprayed volume to the canopy volume correctly, and the vineyard prototype was demonstrated to save up to 21.9% of the traditionally applied volume in commercial farms.

Testing of such sprayers is very complex because of the large number of factors involved. Computational fluid dynamics (CFD) modelling has been used to characterise sprayer systems and try to predict their performance under various environmental conditions and for various tree geometries and working parameter values (Dekeyser et al., 2013; Duga et al., 2015).

Other attempts to improve pesticide sprayer application efficiency have involved the use of tunnel sprayers, which surround the whole tree and recycle the excess spray to minimise losses (Ade et al., 20075, 2007; Baldoin et al., 2008; Hogmire and Peterson, 1997; Jamar et al., 2010; Pergher et al., 2013). These types of tunnels are useful for small crops, such as dwarf apples and grapes, but are difficult to use in intensive and traditional olive orchards because of the irregular canopy shapes, the heights of the trees (typically greater than 4 m), and the large crown volumes (typically 100 m3 or more in traditional orchards) (Miranda-Fuentes et al., 2015b).

Because the tunnel system is not suitable for some types of tree crops, other types of system have been developed to attempt to improve pesticide application efficiency. Moltó et al. (2000) designed an electromechanical system for spraying citrus that involved adapting the application elements to the canopy to reduce the spray drift. In this system, a vertical boom with spray nozzles is operated at a fixed distance from the canopy using a signal from an ultrasonic sensor placed in the front part of the prototype. Tests were performed in which the prototype was compared to a handgun sprayer, the most commonly used type of equipment for this treatment, and the results indicated that the new system yielded better coverage for most of the sampling zones and thus better application efficiency. The difference in performance was particularly notable in the inner parts of the canopy, where the handgun sprayer did not achieve proper coverage levels, in contrast to the prototype, which achieved levels similar to those achieved in the outer zones.

In the case of olive trees, it is necessary to find an appropriate solution that fits the special circumstances present in traditional and intensive plantations. The Mecaolivar project arose from various needs identified by the Spanish Government and the olive oil industry in Spain to improve the mechanisation of olive oil production. After a thorough study of the state of the art, the research group AGR 126 of the University of Córdoba decided to develop new airblast sprayer prototypes that would achieve improved application quality and thus do less harm to the environment than conventional sprayers.

This paper describes the prototype development process, the equipment developed, and the results of preliminary tests of the performance of the prototypes.

V-2. Materials and Methods

V-2.1. Technological requirements for the prototypes

The University research team developed a list of the technological requirements for pesticide sprayer prototype designs. These requirements were made to be concise, direct, and measurable to facilitate manufacturers' understanding of the requirements and to facilitate the manufacturer selection process and prototype evaluation stages.

The technical requirements were established by focusing on the four aspects considered to be the most important: application efficacy and quality, environmental and personal safety, adaptation to specific crop characteristics, and economy and practical aspects (Fig. V-1).

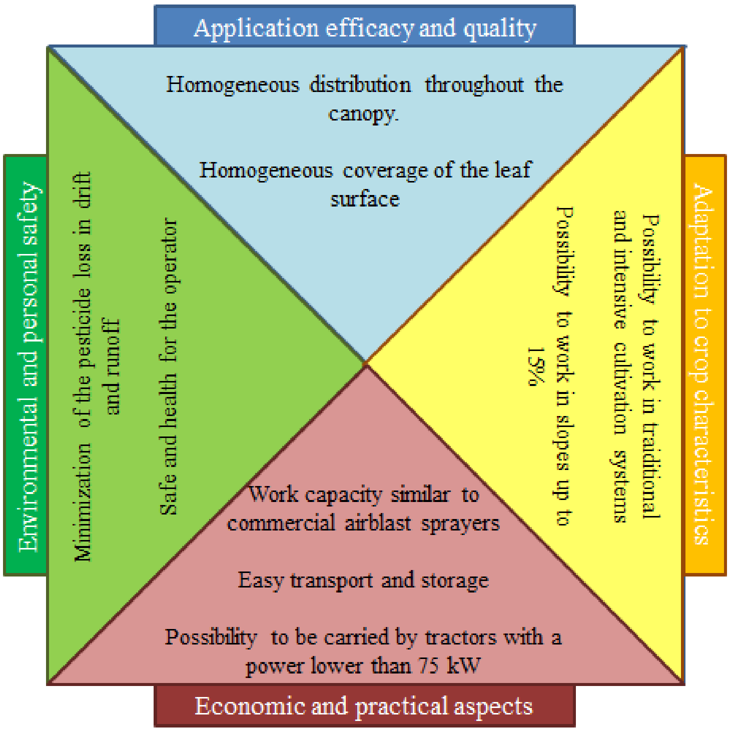

Figure V-1. Technical requirements by category.

Sprayer manufacturers were selected by assessing the adequacy of their solutions with respect to the technological requirements and the backgrounds and expertise of the companies themselves.

V-2.2. Project organisation

The Mecaolivar project took place from 1 February 2014 to 30 December 2015 and consisted of two phases: a pre-prototyping phase and a prototyping phase. In the pre-prototyping phase, the manufacturers presented their ideas for prototypes that met the technical requirements for the equipment. In the prototyping phase, the manufacturers developed their prototypes, with continuous monitoring by and advice from the University research staff. The prototypes were then tested to assess their performance and evaluate the success of the process as a whole. Figure V-2a illustrates the flow of the project.

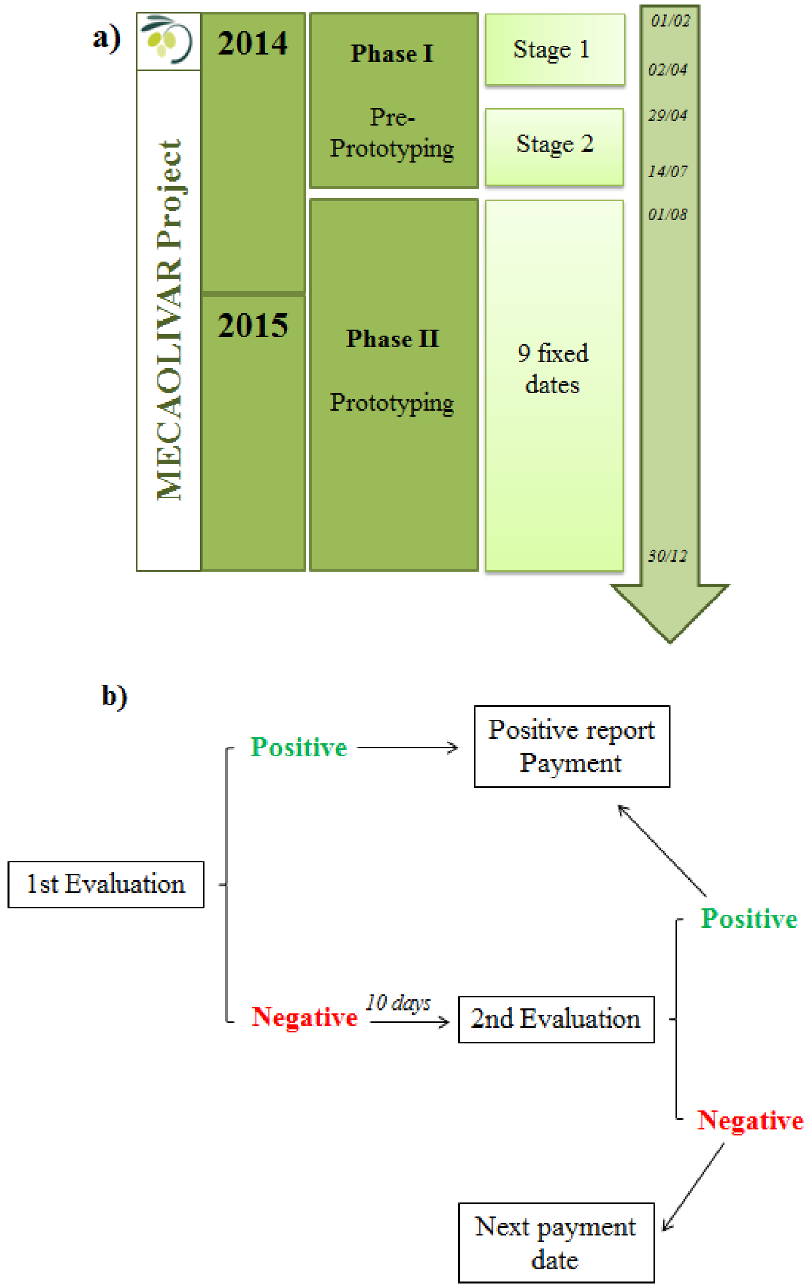

Figure V-2. a) Flow of the Mecaolivar project. b) Evaluation process at the payment dates during the prototyping phase.

Throughout the project, but mainly throughout the prototyping phase, exhaustive technical tracking was implemented for two purposes: technical and scientific support and certification of the work performed by the manufacturers, with payment obligations as milestones were reached.

The tracking process, which was crucial to the development process, was based on a schedule for reaching milestones for each company. All of the companies were given fixed dates to facilitate the certifications and payments for the work performed. At each deadline, a member of the University research staff checked that the planned activities had been successfully completed. If so, a positive report was written and the University paid for the corresponding stage. If not, the company had a period of ten days to repair or complete the work. If the result was still not satisfactory, the payment was postponed until the next payment deadline (Fig. V-2b).

V-2.3. Laboratory calibration of prototypes

After receiving the prototypes on the University premises, the research team carried out a complete laboratory evaluation and calibration of the equipment. The first step was to check that the prototypes met the requirements established for pesticide application equipment (Gil et al., 2011a). The second step was a complete characterisation of each prototype, performed by measuring its main dimensions and checking that all of the components described in the manufacturers' reports were present and of the correct models. To facilitate this, a protocol was developed in which each prototype was described as consisting of the following components:

A. An electrical system
B. A hydraulic system (if any)
C. A pneumatic system
D. A spraying system
E. Auxiliary elements

All of the components were characterised using data sheets like the one shown in Figure 3. The specifications provided by the prototype manufacturers were then compared to those in the component datasheets.

After characterising the individual components of each system, a laboratory calibration of each prototype was conducted. This calibration was of critical importance in establishing the working parameters for each prototype, especially the forward speed, the liquid flow rate, and the air flow rate.

The liquid flow rate and the air flow rate were calibrated. The liquid flow rate was calibrated by checking the real liquid flow rates for the different pressure values in the working range, using a calibrated test tube and a chronometer. The purpose of this calibration was to ensure that there were no pressure losses in the spraying circuit and that the nozzles were in good condition. The air flow rate was calibrated by relating the volumetric air flow rate (AFR) to the power take-off (PTO) speed. A hand-held vane anemometer (HHF81 multimeter, Omega Engineering, Manchester, UK) with a measurement range of 0.30 to 30.0 m s^{-1} and a resolution of 0.1 m s^{-1} was used to determine the AFR at the air inlet, because the inlet section's area was much easier to measure than the outlet section's area for some of the calibrated equipment. The PTO speed was measured with a laser tachometer (RS Pro, Electrocomponents PLC, Oxford, England), with a measurement range from 5 to 99,999 rpm, a resolution of 0.1 rpm, and an accuracy of ± 0.05%.

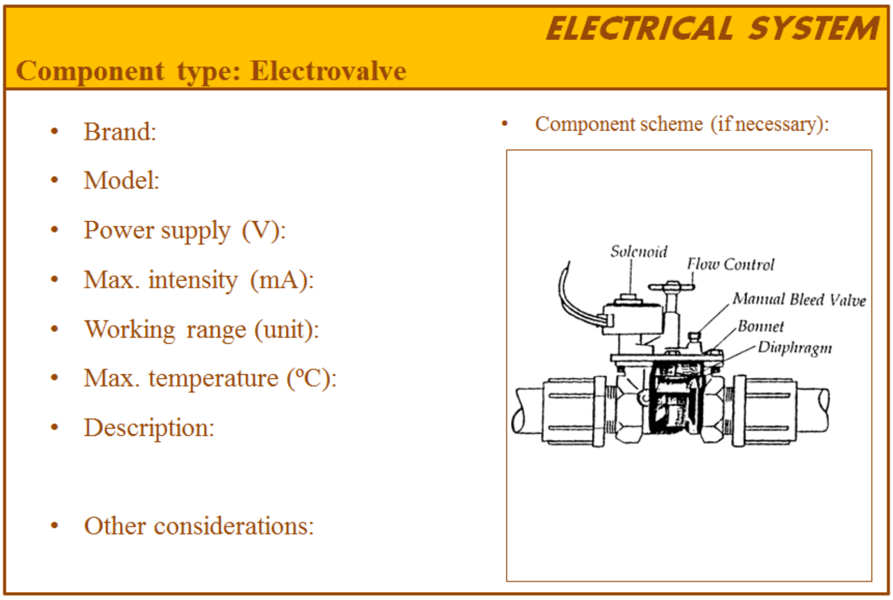

Figure V-3. Datasheet for a component of the electrical system (electrovalve).

V-2.4. Field tests of prototypes

The prototypes were tested under real field conditions on a commercial farm in Córdoba (Andalusia, Spain) (37.715 N; -4.811 W). There was a technical requirement that the prototypes had to be able to work in traditional and intensive cultivation systems, and the selected farm had both such systems in place. The traditional orchard had a row spacing of 10 m and a tree spacing of 11 m, and the intensive orchard had row and tree spacing of 7 m.

Each prototype's performance was compared to that of a commercial airblast sprayer (Eolojet 2200; Osuna Sevillano; Jauja; Spain) that had been used in previous studies of olive spraying (Miranda-Fuentes et al., 2015b).

Before the trials, three trees were selected in each of the two cultivation systems. These same six trees were sprayed using each of the three prototypes to avoid any influence of differences in the tree shape, traditionally grown olive trees in particular being very irregular in shape.

The trees were measured using the mean vector method (Miranda-Fuentes et al., 2015a), which consists of measuring eight radii of the crown projection on the ground and calculating the mean value, referred to as the mean vector (MV), which has been shown to be strongly correlated to the crown volume calculated from LiDAR scanner measurements. A measuring tape and a topographic milestone were used to measure the crown dimensions.

According to the experiment design, three trees were randomly selected in a row that was treated from its beginning to its end and from both sides for all of the treatments. Each tree crown was divided into four sectors, three heights, and two sampling depths for the intermediate height (Fig. V-4), resulting in 16 sampling positions per tree. At each sampling position, two pieces of water-sensitive paper (WSP, Syngenta Crop Protection AG, Basel, Switzerland) 76 × 26 mm in size were attached to the leaves, one on the upper side and the other on the lower side, to assess the coverage on both sides. Each tree was sprayed four times (once per machine). Red paint on the leaves to which the WSP was attached ensured that the sampling positions were the same for each machine and tree. After each application, the operators waited for 10 min before removing and storing the WSP collectors to let them dry.

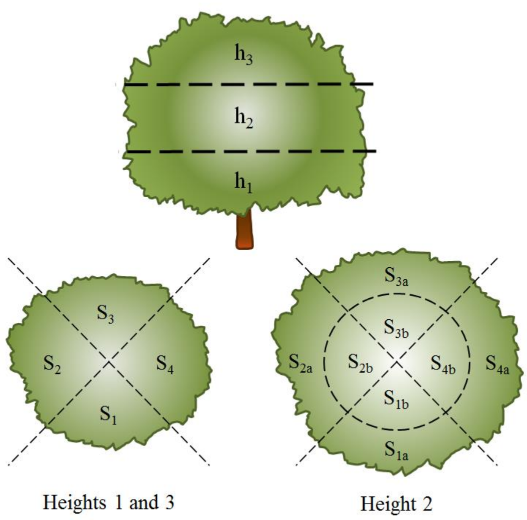

Figure V-4. Sampling positions for the trees used in the prototype tests.

The spray parameters for the trees were established on the basis of the canopy volumes, resulting in an application coefficient of 0.12 L m^{-3}, which has shown to be appropriate for isolated olive trees (Miranda-Fuentes et al., 2016). The application parameters had to be established after the prototype calibrations, as the characteristics of the prototypes were markedly different, and therefore, information about the variability of their performance had to be gathered (see Table V-1).

The forward speed depended on the plantation system and was measured under real field conditions. The spraying pressure was adjusted using a high-resolution manometer, and the PTO speed was checked using an optical tachometer (RS Pro).

The airflow rate was also calculated according to the canopy volume, following the well-established procedure of replacing the canopy inner air with sprayed air, and was checked under field conditions using a hand-held anemometer (HHF81, Omega Engineering).

Table V-1. Operational parameters for the sprayers in the field trial.

	Cultivation system							
	Intensive				Traditional			
Parameter	**P1**	**P2**	**P3**	**Commercial**	**P1**	**P2**	**P3**	**Commercial**
Nozzle colour*	Red	Yellow	Yellow	Green	Blue	Red	Red	Blue
Liquid flow rate per nozzle ($L \cdot min^{-1}$)**	2.17	1.07	1.17	2.79	3.24	1.62	1.73	3.99
Number of open nozzles	18 (2 x 9)	36 (2 x 18)	34 (2 x 17)	14 (2 x 7)	18 (2 x 9)	36 (2 x 18)	34 (2 x 17)	14 (2 x 7)
Pressure (bar)	13	11	13	13	9	7	8	14
Measured liquid flow rate ($L \cdot min^{-1}$)	39.06	38.52	39.78	39.06	58.32	58.32	58.82	55.86
Spray volume ($L \cdot ha^{-1}$)	578.7	585.1	580.7	583.0	1136.1	1170.3	1164.8	1151.8
Forward speed ($km \cdot h^{-1}$)	4.05	3.95	4.11	4.02	3.08	2.99	3.03	2.91
PTO speed (rpm)	540	500	450	520	500	400	350	420
Air volumetric flow rate ($m^3 \cdot s^{-1}$)	2.8	12.7	12.7	12.7	2.7	11.1	11.1	11.1

* All the nozzles were Albuz ATR nozzles
** Values drawn from the Albuz catalogue (accessed December 2015)

The parameters evaluated belonged to two categories, based on the technical requirements: coverage quality and distribution throughout the canopy. The variables in the first category were the coverage percentage *SC* (%) and the number of impacts per unit area N_i (cm^{-2}). The variable in the second category was the coefficient of variation of the coverage throughout the tree crown, *CV* (%). The spray coverage on the WSP can be measured quickly and easily, and despite its limitations, it has been shown to be a valid measure of product deposition on leaves (Cunha et al., 2012; Salyani et al., 2013). Furthermore, in previous studies carried out on olives, it has been shown to be strongly correlated to the absolute deposit value (Miranda-Fuentes et al., 2015b). In the present study, its use allowed the researchers to obtain a large number of results in a short period of time, which was useful in the preliminary assessment of the performance of the three prototypes.

The order of the four treatments was randomised. The three sprayed trees were in the same row, so the row was treated from its beginning to its end and from both sides for all of the treatments. After each application, the operators waited for 10 min before removing and storing the WSP collectors to let them dry.

V-2.5. Samples and data analysis

V-2.5.1. Analysis of samples

The WSP samples were scanned at high resolution (600 ppi) and analysed with a specially programmed macro using the free software Image J (Zhu et al., 2011). The coverage percentage *SC* (%) and the number of impacts per unit area N_i (cm^{-2}) were obtained directly from the analysis for both the upper (*SC up* and *Ni up*) and lower (*SC lo* and *Ni lo*) sides of each leaf.

The coverage homogeneity and impact homogeneity, *HSC* (%) and *HNi* (%), respectively, were calculated using Equations V-1 and V-2, respectively:

$$HSC = \frac{1}{N}\sum_{i=1}^{N}\frac{SCmax_i}{SCmin_i} \times 100 \qquad \text{(V-1)}$$

$$HNi = \frac{1}{N}\sum_{i=1}^{N}\frac{Nimax_i}{Nimin_i} \times 100 \qquad \text{(V-2)}$$

where $SC\,max_i$ and $Ni\,max_i$ are the maximum coverage and impact number, respectively, between the leaf upper and lower sides for each sampling position, and $SC\,min_i$ and $Ni\,min_i$ are the corresponding minimum values. The number of sampling positions (N) was equal to 16 (Fig V-4). The values of HSC and HNi range between 0 and 100. The closer to 100 these coefficients are, the higher the mean homogeneity is between the upper and lower sides of the leaves for the given treatment.

V-2.5.2. Data analysis

The free software R Studio (R Core Team, 2015) and IBM SPSS Statistics version 22 (IBM, Armonk, NY, USA) were used to analyse the data from the field trial. A two-way analysis of variance (ANOVA) with repeated measures was performed to study the dependent variables *SC* and *NI* for both the upper and lower sides of the leaves, as well as their average values for the different prototypes and the coverage homogeneity and impact homogeneity variables, *HSC* and *HNi*. The sphericity hypothesis was checked using Mauchly's test. The coverage percentage was subjected to an arcsin $((Y/100)^{0.5})$ transformation (Steel and Torrie, 1980).

We adjusted the degrees of freedom of the factors and their interaction using Greenhouse and Geisser's epsilon (GG) and the Huynh–Feldt correction. When epsilon's value was lower than 0.75, the Greenhouse–Geisser correction was applied. We used the Huynh–Feldt correction otherwise, according to Girden (1982).

A two-way ANOVA was used to assess the coefficient of variation of the coverage percentage and number of impacts, with the type of plantation as the between-subjects factor and the prototype as the within-subjects factor. Levene's test was used to check the equality of variances among the levels of the within-subject factor. The sphericity hypothesis was checked using Mauchly's test. The equality of the covariance matrices was checked with M statistics using Box's test. For cases in which the M statistics of the covariance matrices of the samples were not invertible, we adjusted the degrees of freedom of the within-subject factor and its interaction with the type of plantation using GG. When necessary, differences among individual means were tested using the least significant difference (LSD) test. The analysis was focused on the prototype factor.

V-3. Results and Discussion

V-3.1. Results of the machinery manufacturers selection process

A total of eight manufacturers provided design ideas at the end of the first stage of phase 1. Although all of the ideas were appropriate and therefore evaluated favourably by the technicians, only the five best were considered in the second stage. These five design ideas were considerably different from each other, which was considered to be very positive for the project.

After the second phase, the three best design ideas were chosen on the basis of the technical reports. The three manufacturers selected for the project were Asesores y Técnicas Agrícolas S.A. (Atasa, Alcantarilla, Murcia, Spain), Osuna–Sevillano S.L. (Jauja, Córdoba, Spain), and Máñez y Lozano S.L. (Valencia, Spain).

The three prototypes differed primarily in their pneumatic systems. Atasa's (ATA) prototype (P1) had a central double centrifugal fan with adaptable air outputs. Osuna–Sevillano's (O-S) prototype (P2) had six individual application modules, an air generation system, and application nozzles. Máñez y Lozano's (MyL) prototype (P3) had two axial fans mounted on a vertical structure, i.e., in the same plane.

V-3.2. Airblast sprayers developed

The three prototypes are described in detail in this section. Note that all of the prototypes met the criteria for the safety of the operator and the environment, according to Directive 2009/127/EC.

V-3.2.1. Equipment based on central double centrifugal fan with adaptable air outputs

V-3.2.1.1. General description

The P1 prototype, shown in Fig. V-5, has six independent application units, three per side, that include an analogue ultrasonic sensor, three hollow-cone nozzles (ATR green, Albuz, Solcera Advanced Materials, Evreux, France), and an air outlet. These application units are placed on carrying elements, called 'arms', at different heights from the ground to reach all of the areas in the tree crown properly (Fig. V-6).

Figure V-5. P1 prototype with central centrifugal fan and individual air outputs.

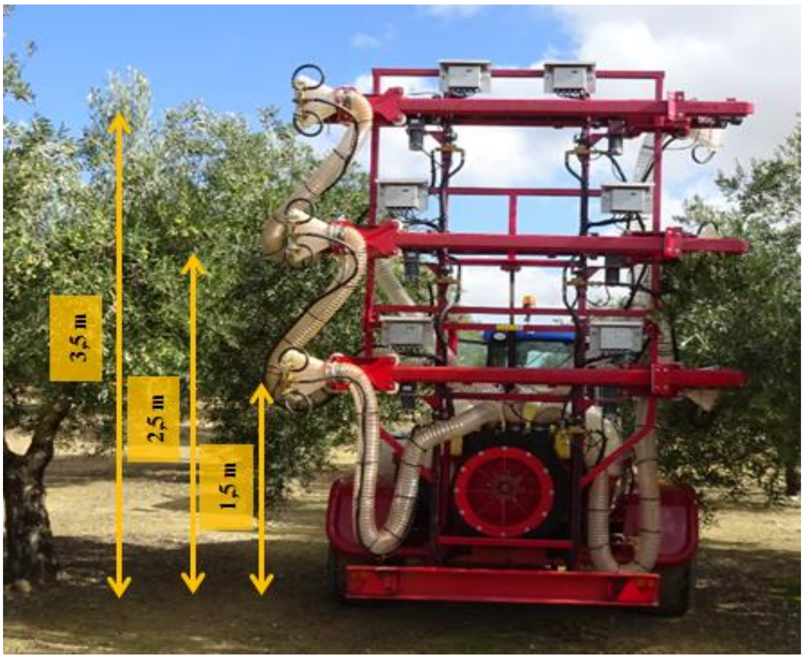

Figure V-6. Application unit positions and heights in P1.

The spray mix is taken from a 2200-l polyethylene tank by a four-membrane pump (maximum pressure: 50 bar). The liquid distribution system is completely manual, as in commercial sprayers, except for the on/off electrovalves located in each application unit, and is controlled by the signals from the ultrasonic sensors. Completely unfolded, the equipment has a total height of 3.58 m and a total width of 5.80 m; folded, its height is 2.50 m, and its width is 2.40 m.

The folding mechanism permits the transport and storage of the equipment by considerably reducing its dimensions and improving its stability. Other important design features of P1 that contribute to its stability are its low centre of gravity, its wide axles, and the presence of a breakwater inside the tank, which makes it possible for P1 to operate on slopes greater than 15%.

V-3.2.1.2. Pneumatic system

P1's pneumatic system begins with a double PTO-driven centrifugal fan (Fig. V-7a) and ends with the air outlets (Fig. V-7b) in the application units. The fan's working principle is to reduce the volumetric air flow to reduce the power required. The fan has two working gears, even though the first one generates a very poor airflow rate.

According to the design hypothesis, the high air pressure produced should be sufficient to penetrate the whole canopy in application at a very close distance. The fan has two identical propellers 500 mm in diameter. Each of the air outlets has an output area of 174 cm^2. The air outlets are made of polyethylene and are thus very lightweight. This is very important in preventing the generation of substantial momentum that would make it necessary to mount strong profiles and thereby increase the prototype's total weight.

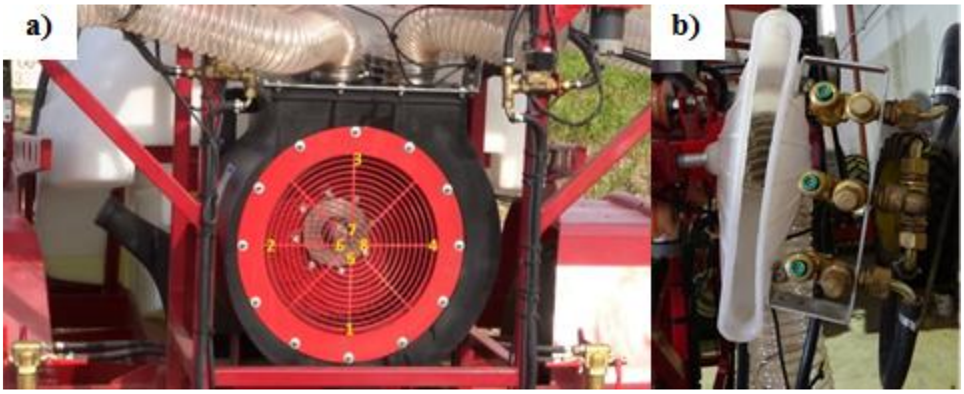

Figure V-7. Components of prototype P1. a) Centrifugal fan. b) Air outlets and nozzles.

The prototype's flexible plastic conduits, 5.5 cm in diameter, are well suited to folding of the structure and to the crown adaptation system.

V-3.2.1.3. Adaptation to the crown

In contrast to the spray application system, the adaptation system is completely automatic. A flowchart of the logic by which the application unit operates is shown in Figure V-8.

The ultrasonic sensor has two purposes: it allows the electrovalves to open, which permits the flow of liquid to the nozzles, and it determines the positioning of the application units through the positioning of the carrying arms. The ultrasonic sensors used (mic+600/IU/TC, Intertronic Internacional S.L., Paterna, Valencia, Spain) have a measurement range from 600 to 8000 mm, a resolution of 0.18 mm, and a sampling frequency of 2 Hz, which corresponds to one measurement each 0.5 m at a forward speed of 1 m s^{-1}.

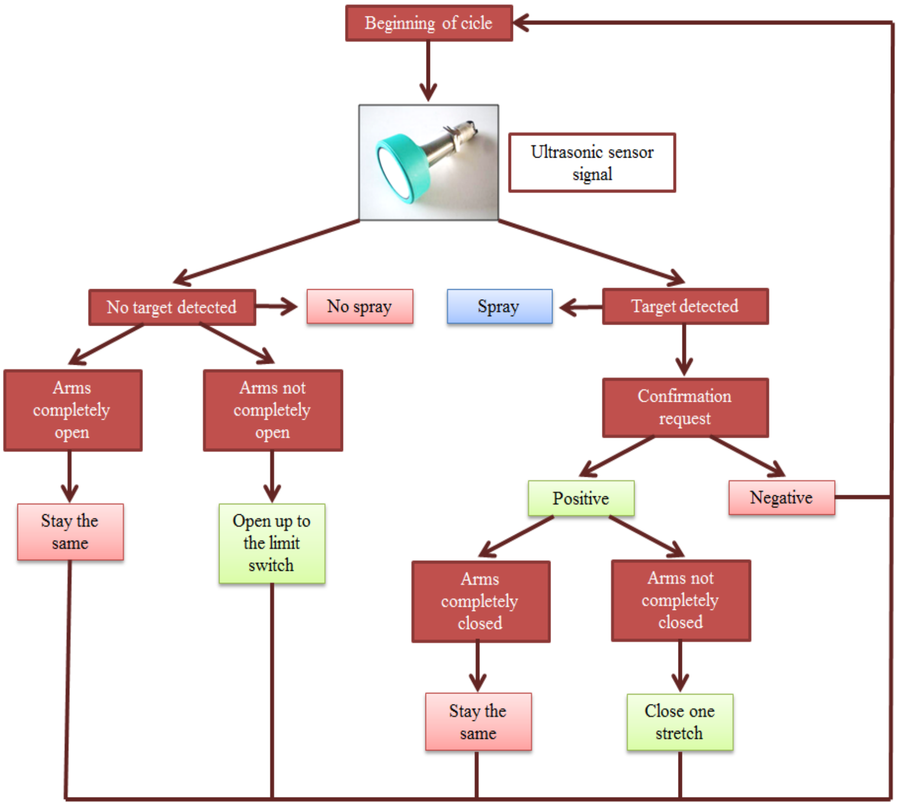

Figure V-8. Flowchart of adaptation to the crown and spraying by prototype P1.

As the diagram shows, the spraying system does not require confirmation to prevent leaving any part of the crown untreated. The movement system, on the other hand, only acts when positive confirmation is received, to avoid unnecessary movements due to nonsignificant measurements from the ultrasonic sensors. The movement system is based on three electrical motors with linear actuators on each side, each of which is moved by a mechanism that combines pulleys and a rack-and-pinion system. The purpose of the movement system is to maintain the application units at a fixed distance of 800 mm from the canopy, which was shown in preliminary laboratory trials carried out by the manufacturer to yield the best results.

V-3.2.2. Equipment based on six hydraulically driven axial fans

V-3.2.2.1. General description

The P2 prototype, shown in Fig. V-9, differs from conventional sprayers in that the central fan is replaced by six small hydraulically driven axial fans. This design idea was first proposed by Furness et al. (2003) and is based on increasing the volumetric AFR ($m^3\ h^{-1}$) while maintaining a constant air speed, so that the spray penetrates into the canopy. This approach has been shown to maximise spray deposition (Randall, 1971). In the case of the prototype, the total AFR is six times that of an individual fan’s, but the air speed remains the same. The individual fans are mounted on two identical structures that allow them to be at a constant distance from the canopy, according to the signals from two analogue ultrasonic sensors, one per structure. Although there are three sensors per side, only the one in the middle is used to control both the movement and the spray of the nozzles; the others just serve as activators of the spraying system.

Figure V-9. P2 prototype with six individual axial fans.

The three fans are positioned at three heights to cover the entire crown (Fig. V-10). The top fan, positioned at a height of 3.45 m, is adjustable in orientation to adapt to different tree heights, from those of intensive (3 m) to those of traditional (4.5 m) cultivation systems. The maximum width of the equipment with the carrying structures completely open is 5.70 m and decreases to 2.30 m when the equipment is folded. The prototype does not have any system for reducing its height, which is a constant 3.70 m. However, a new system will soon be incorporated to lower the top application units, which will considerably reduce the total height.

Figure V-10. Heights of the P2 application units and regulation of the top fans to adapt to different tree heights.

The spraying system has six hollow-cone nozzles around each fan (Fig. V-10), resulting in a total of 18 nozzles per side and 36 nozzles on the whole prototype. The six nozzles around each fan are controlled by a common electrovalve, which in turn is driven by signals from an ultrasonic sensor positioned in front of it (Fig. V-11). Spraying only takes place when the sensor detects the presence of the crown inside its measurement range.

Figure V-11. Axial fan with nozzles and commanding ultrasonic sensor on the prototype P2.

The prototype has wide axles and a low centre of mass to allow it to operate on steep slopes.

V-3.2.2.2. Pneumatic system

The six individual fans that make up the pneumatic system were designed by the same manufacturer, according to the crop conditions. The fans are composed of commercial plastic six-blade propellers 500 mm in diameter (500/6-6/45°/PAG/4H L, Multi-wing Ibérica S.L., Mataró, Spain) and outer aluminium housings that converge slightly towards the air outlet (Fig. V-11). Because the fans are driven by hydraulic engines, it was necessary to design a complete hydraulic system for the equipment. The hydraulic circuit has six hydraulic engines (Grupo 2, Bondioli & Pavesi, Suzzara, Mantua, Italy), each with a capacity of 14 cm^3, that move the fans' propellers. The hydraulic system also has a hydraulic unit (Bondioli & Pavesi) with a maximum power of 24.3 kW, a liquid flow rate of 49 $l\ min^{-1}$, and a pressure of 150 bar when working at a PTO speed of 450 rpm; two pressure regulators, one per side; and a fan-based cooling system for the hydraulic fluid.

V-3.2.2.3. Adaptation to the crown

The adaptation to the crown shape is achieved by P2 using an automated system, based on measurements from two ultrasonic sensors. Although there are six sensors in total, only the two intermediate sensors (in height) control the movement of the two carrying structures. The ultrasonic sensors have two types of outputs: digital and analogue. The four sensors with digital output (model 3RG6014-3AD00-PF, Pepperl+Fuchs, Mannheim, Germany) have a measurement range from 600 to 6000 mm and control the opening of their respective electrovalves. The two sensors with analogue output (model UC6000-30GM-IUR2-V15, Pepperl+Fuchs) have a measurement range from 250 to 6000 mm and a sampling frequency of 3 Hz, and they have been proven in previous studies to be well suited to olive canopy detection (Gamarra-Diezma et al., 2015).

The only difference between the logical scheme of P2 and that of P1 is that with P2 there is no confirmation request to begin a movement. Nevertheless, no problems occurred when P2 was operated under field conditions, possibly because of the lower sampling frequency. The linear actuators are moved by two electric engines (L03 CC, MecVel Srl, Bologna, Italy) on each side. The maximum extension per side is 1000 mm. An auxiliary battery is mounted under the equipment frame to supply voltage to the electrical system.

V-3.2.3. Equipment based on two axial fans with tower disposition

V-3.2.3.1. General description

The P3 prototype, shown in Fig. V-12, is the most similar of the three prototypes to commercial airblast sprayers. It has four application units, two per side, that are controlled by analogue ultrasonic sensors and have 12 hollow-cone nozzles each (Albuz ATR red). These are organised in four groups of three nozzles, and any of them can be closed individually. In addition to the 48 nozzles on the side application units, there are two more at the top, one per side, the angles of which can be adjusted with respect to the canopy and the angle of the spray by varying the pressure with an internal pressure regulator. The application units are moved by carrying structures that serve as air outlets, driving the outflowing air from the two axial fans. The height of the application units can be varied from 0.6 to 3.2 m, plus the extra height added by the top nozzle (Fig. V-13).

Figure V-12. P3 prototype with two axial fans.

Figure V-13. Application unit position and height in P3.

Unlike the two previously described prototypes, P3's spraying system can operate automatically, adjusting not only the sections to spray but the circuit pressure as well, by taking into account information obtained by a ground-speed sensor, a liquid flow meter, and a pressure sensor. Pressure regulation is carried out in real time using a motorised valve that automatically adjusts the pressure to obtain a liquid flow rate that is consistent with the spray volume per unit area (l ha^{-1}) and row spacing (m) indicated by the operator through a commercial display (Tronic Volumétrico ®, Máñez y Lozano S.L.), shown in Fig. V-14a. The algorithm used by the program is based on the calculation of a constant liquid flow rate (LFR, L min^{-1}) from the spray volume per area unit (SV, L ha^{-1}), row spacing (RS, m), and forward speed (FS, km h^{-1}), according to Eq. V-3:

$$LFR = \frac{SV \times RS \times FS}{600} \qquad \text{(V-3)}$$

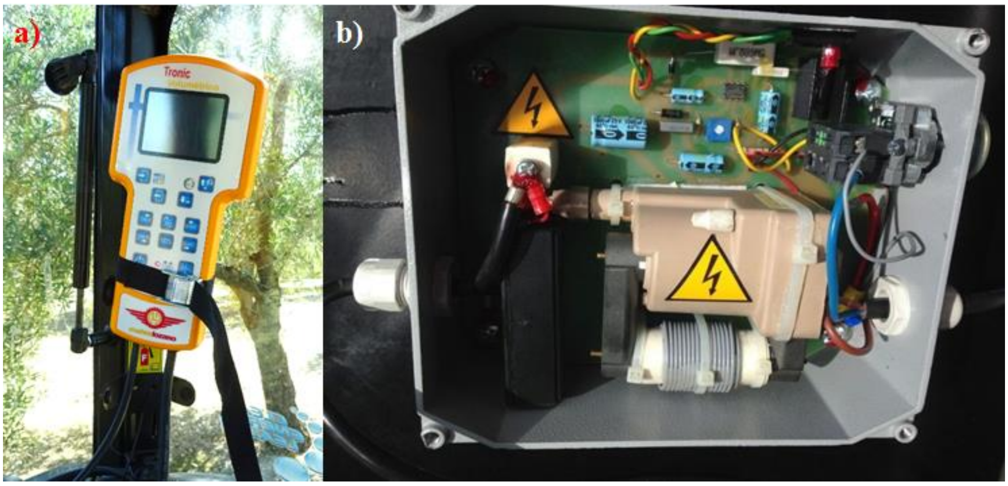

Figure V-14. a) Tronic Volumétrico® for automatically adjusting the spray application rate. b) Electrostatic system's electronic circuit.

Note that even when the constant-rate expression is applied, spraying is only allowed when the ultrasonic sensors detect the presence of canopy within their measurement range. Therefore, the equipment is able to apply the full dose when one tree per side is detected and up to a quarter of the maximum dose if only one sensor detects the canopy. The prototype also has a system to electrostatically charge the droplets to increase the leaf coverage percentage and homogeneity. This system can be enabled or disabled manually (Fig. V-14b).

The rear structure of the prototype is fairly heavy. Nevertheless, the tandem axle (Fig. V-12) provides stability, making it possible for the equipment to operate on steep slopes.

The high-capacity 4300-L spray mix tank markedly reduces the time required for recharging, which increases the field capacity and performance of the prototype.

V-3.2.3.2. Pneumatic system

The pneumatic system is composed of two mechanically driven axial fans mounted on a tower-like structure and four air outlets that direct the airflow towards the tree crown at two different heights. Each fan has an eight-blade propeller 680 mm in diameter and is able to provide a very high airflow rate. The pneumatic system has two working gears, even though the second one generates an excessive airflow rate for olive canopies.

V-3.2.3.3. Adaptation to the crown

The adaptation to the crown shape is based on the adaptability of the four air outlets to the signals from four analogue ultrasonic sensors. The four air outlets can be moved linearly away from their initial positions where they are completely inserted in the tower structure. This movement is carried out by four linear actuators, two per side. These sensors are of the same model as those used by Atasa in the P1 prototype (mic+600/IU/TC, Intertronic Internacional S.L.). The linear actuators used to move the air outlets towards the trees are similar to those used in P2 (ALI2-F, MecVel Srl), with one actuator per air outlet and a maximum extension of 300 mm.

One unique feature of this prototype is the low approach speed of the actuators, which makes the adaptation to the crown less significant than for the other prototypes. Nevertheless, the air enclosure is very effective in directing the air jet towards the target canopy.

V-3.3. Laboratory calibration of the equipment

The three sprayers were calibrated under laboratory conditions. The liquid flow rate calibration results showed a perfect correspondence between the theoretical values shown in the nozzle calibration chart and the measured values.

The results of the airflow rate (AFR) measurements for different PTO speeds are illustrated in Figure V-15. In the cases of P1 and P3, the most appropriate way to spray olive canopies involves using only the second and first gears, respectively. In the case of P2, the hydraulic circuit was set to its maximum capacity to characterise the maximum airflow rate of the pneumatic system.

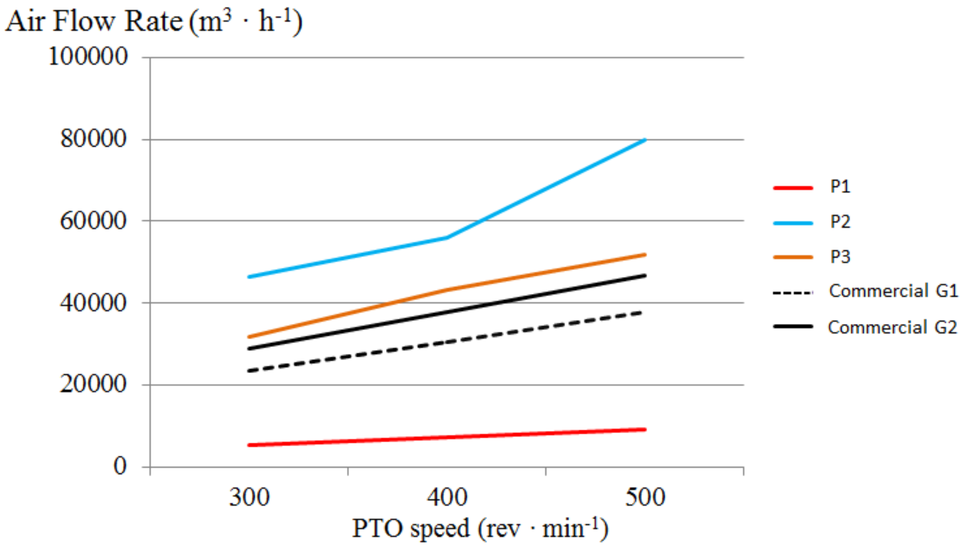

Figure V-15. Measured airflow rates (AFRs) at different PTO speeds for prototypes P1, P2, and P3 (solid red, blue, and brown lines, respectively) and the commercial equipment for the first (dashed black line) and second (solid black line) fan gears.

The AFR values for P1 were much lower than those for the other prototypes for the full PTO speed range considered, because of the centrifugal fan, whose purpose is to produce a high static air pressure so that the air can flow through the tubes to the individual spouts. P2 achieved the highest AFR values over the full range of PTO speeds considered, which indicates that it is the most efficient in terms of airflow generation. In fact, P2 produced AFRs twice as high as the commercial equipment in its first gear. The P3 prototype yielded higher AFRs than the commercial equipment even when working in first gear. It is noteworthy that two fans can work more efficiently than one fan with similar characteristics.

V-3.4. Field tests of the prototypes

The pneumatic system of the P2 prototype was regulated under field conditions by setting the PTO speed and manually modifying the oil pressure and flow rate in the hydraulic circuit. A hand-held anemometer was used for this purpose.

For the intensive olive trees in the study, a mean MV value of 2.42 m with a CV of 4.25% was achieved. According to Miranda-Fuentes et al. (2015a), these values correspond to a mean crown volume of 46.8 m^3. For the traditional trees, a mean MV value of 2.83 m with

a CV of 9.28% was achieved, which corresponds to a canopy volume of 69.94 m^3. The higher CV for the traditional system indicates a higher heterogeneity in the canopy volume for this system, which makes it more difficult to properly adjust the spray volume.
With respect to the coverage, for the intensive olive trees, the results of the trial indicated significant differences among the prototypes for the variable *SC* (p = 0.027) but not for *SC up* (p = 0.124) or *SC lo* (p = 0.074). The means are compared in Table 2. The average coverage percentages ranged from 30% to 48%.
Even though the optimal coverage value is considered to be 30% (Chen et al., 2013), the fact that the applied volumes were the same makes the highest coverage values indicators of spraying efficiency. Only P2 achieved the goal for both the upper and lower sides of the leaves, according to the criterion established by Chen et al. (2013). The other sprayers achieved results that were close to this target value, with coverage values higher than 23% in the worst case, so their performance was considered to be acceptable.
Significant differences were not found in the coverage homogeneity, as expressed by the ratio *HSC* (p = 0.17). The value of this ratio ranged from 27% for P1 to 46% for P2, with values of 35% and 31% for P2 and the commercial equipment, respectively.
The number of impacts *Ni* exhibited significant differences (p = 0.025). For the parameters *Ni up* and *Ni lo*, the numbers of impacts were statistically similar (p = 0.37 and p = 0.11, respectively). Table V-2 shows the results of comparisons of the means of the aforementioned variables. P2 exhibited the best performance, with 117 impacts per cm^2, versus 88, 76, and 94 impacts per cm^2 for P3, P1, and the commercial equipment, respectively. Although not statistically significant, the differences were the greatest in the case of *Ni lo* (Table V-2). Significant differences in the impact homogeneity variable, *HNi*, were not detected among the different sprayers (p = 0.13), with values ranging from 0.32 to 0.53 (Table V-2).
Taking into account the significant differences in coverage and the performance measured in terms of the number of impacts, *HSC* and *HNi*, respectively, P2 was considered the best-performing sprayer, not only with respect to the number of impacts (Table V-2) but also overall. Compared to the commercial equipment, its coverage level was 18% higher.

Table V-2. Average, upper-side, and lower-side values for coverage and number of impacts.

			Intensive system				Traditional system			
Parameter and Position[a]			P1	P2	P3	Conventional	P1	P2	P3	Conventional
Coverage (%)	Average	***SC***	37.2 a	47.5 b	30.9 a	29.5 a	13.5 c	36.0 ab	45.3 a	31.1 b
	Upper side	***SC up***	49.3	55.1	35.5	35.9	19.4 a	44.5 abc	58.9 c	41.3 ab
	Lower side	***SC lo***	25.1	40.0	26.3	23.0	7.6	27.4	31.7	20.9
Coverage homogeneity (%)		***HSC***	27	46	35	31	14	35	38	26
Impacts (cm^{-2})	Average	***HNi***	75.8 a	116.7 b	88.0 ab	94.4 ab	48.4	114.8	73.7	79.1
	Upper side	***HNi up***	75.8	94.9	86.9	87.3	64.4	93.7	49.8	70.5
	Lower side	***HNi lo***	75.8	138.6	89.1	101.5	32.5 c	136.0 a	97.6 ab	87.6 b
Impacts homogeneity (%)		***HNi***	32	43	51	53	26	44	38	50

[a] Values followed by letters are significantly different at the p-values indicated in section 3.4.

Values not followed by letters are not significantly different ($p > 0.05$).

With respect to the trial in the traditional orchard, the strongest statistical significance was detected in the mean coverage values, *SC* ($p = 0.010$). The differences in *SC up* ($p = 0.032$) and *SC lo* ($p = 0.055$) were slightly less significant. The lowest *SC* value (13.5%) was achieved by the prototype P1, which was significantly lower than the *SC* values achieved by P2, P3, and the commercial equipment, which ranged from 31 to 45%, as shown in Table V-2. The ratio between the upper-side and lower-side coverage was superior to that achieved in the intensive orchard, with values ranging from 1.6 for P2 to 2.5 for P1. Unlike P3, P1 never achieved a coverage higher than 30% on the upper sides and lower sides of the leaves. In this respect, the performance of P3 can be considered adequate, according to the criterion proposed by Chen et al. (2013).

In relation to the number of impacts, even though P2 yielded better results than the other sprayers in terms of all of the variables related to this parameter, the results were only significant for N_i *lo* ($p = 0.045$) (Table 2), i.e., not for N_i ($p = 0.066$) or N_i *up* ($p = 0.12$). Taking into account both the coverage and the number of impacts, P2 and P3 can be considered the best sprayers, the former being better for coverage and the latter being better for impacts, although the results did not differ significantly.

The number of impacts was higher on the lower side of the leaves for all cases except for P1 in the traditional orchard, for which a 50% decrease was observed (Table V-2).

Significant differences were not detected for the variables *HSC* ($p = 0.07$) and *HNi* ($p = 0.16$). As expected, the values of these variables were closer to 100% for the intensive system, with 53% being the best value obtained (Table V-2).

With respect to the homogeneity of the treatments applied by the prototypes, expressed by the coefficient of variation (Tables V-3 and V-4), Box's test could not be applied in every case. The determinant of the intensive plantation matrix was equal to $-1.9 \cdot 10^{-40}$ for the coefficient of variation of *SC*, with a zero value for the impacts homogeneity variable (CV of *Ni*).

In this case, we adjusted the degrees of freedom of the within-subject factor and its interaction with the type of plantation using GG. With regard to the homogeneity coefficient of variation of the coverage percentage of the upper- and lower-side coverage values (*HSC*), reflected by the *HSC* variable, significant differences were detected among the prototypes ($p = 0.009$), whereas the prototype × plantation system interaction was not clearly significant ($p = 0.041$). No significant differences between the planting systems were detected ($p = 0.08$). The performance of the prototypes was quite different depending on the plantation system. Thus, significant differences were not detected among the prototypes for intensive trees.

Table V-3. Comparison of mean coefficients of variation of prototypes and plantation systems. Variable: coverage percentage.

	CV (%) of coverage percentage (SC)			
	Plantation system			
Prototype	**Intensive**	**Traditional**	**p-value**	**Prototype factor**[a] (mean)
P1	61 a	111 b	0.01	86 b
P2	51 a	57 a	0.62	54 a
P3	55 a	63 a	0.56	59 a
Commercial	50 a	44 a	0.44	47 a
Plantation system (mean)	55 a	68 a	0.08	

[a] The p-value for this factor is equal to 0.009.

Table V-4. Comparison of mean coefficients of variations of prototypes and plantation systems. Variable: number of impacts.

	CV (%) of number of impacts (N_i)		
	Plantation system		
Prototype	**Intensive**	**Traditional**	**Prototype factor**[a] (mean)
P1	49	67	58 a
P2	49	51	50 a
P3	35	74	55 a
Commercial	40	58	49 a
Plantation system (mean)	55 a	63 a	

[a] The p-value for this factor is equal to 0.32.

In the case of traditional trees, the CV of P1 was almost double those of P2, P3, and the commercial sprayer (Table V-3). In the case of intensive trees, the CV for P1 was 10–22% higher than those of the other sprayers. This can be understood as a lack of homogeneity in the applications performed with the prototype P1 (Table V-3). This may be due to the airflow rate generated by P1's centrifugal fan not being sufficient to carry the sprayed liquid into the canopy, resulting in more liquid being deposited on the outer leaves and poor coverage values being achieved in the inner portion of the canopy. Conversely, the other prototypes did not exhibit statistically significant differences in coverage variability between the two plantation systems.

In terms of the coefficient of variation of the number of impacts, no statistically significant differences were detected among the prototypes ($p = 0.317$), with values of approximately 0.5 in all cases (Table V-4). The prototype × plantation system interaction had a p-value of 0.092, which, though low, was not sufficiently low to reject the null hypothesis of no significant difference.

Figures V-16a and V-16b show the mean deposit per sampling height and sampling sector, respectively, for each prototype and cultivation system. With respect to the sampling height, it can be seen in Figure V-16a that the conventional equipment resulted in a significant reduction in the coverage height for both cultivation systems, as observed in similar studies (Miranda-Fuentes et al., 2016). The three prototypes performed similarly for the two cultivation systems, but they produced different values. In the intensive system, the commercial equipment yielded a very marked reduction, from 42.77% for the lowest height to 18.53% for the highest one. P1 yielded a low coverage for the lowest sampling height (SC = 16.51%) but much higher values for the intermediate and highest heights (SC = 44.57% and 43.20%, respectively). P2 yielded opposite results, with much higher values, ranging from 35.72% to 57.82% from the lowest to the highest height. The results for P3 were similar to those for the commercial sprayer, but the decrease was smaller, with the SC values ranging from 38.34% to 19.19% from height $h1$ to height $h3$. For the traditional system, the coverage values of the conventional sprayer were similar but exhibited a slightly lower decrease (Figure V-16a). P1 exhibited a similar trend but with much lower values. It had its lowest coverage value (SC = 9.53%) at the lowest sampling height $h1$ and higher values at $h2$ and $h3$ (SC = 16.40% and 11.65%, respectively). P2, on the other hand, produced a nearly uniform coverage pattern with respect to height (Figure V-16a). P3 showed a marked decrease with height, from 43.23% for *h1* to 28.31% for *h3*, but the values were nearly always above the 30% limit established by Chen et al. (2013).

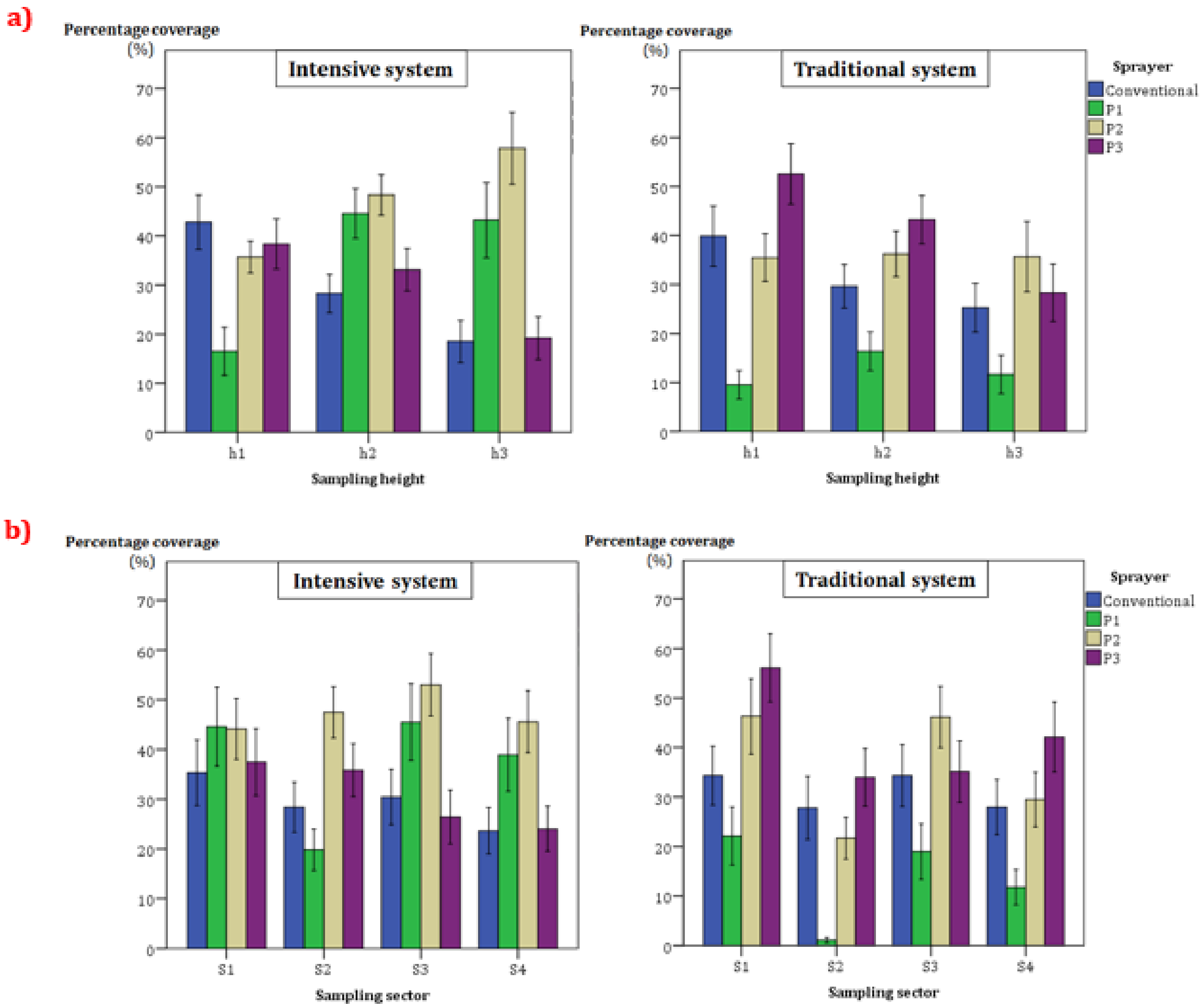

Figure 16. a. Mean coverage values per sampling height for every sprayer in intensive and traditional plantation systems. **b.** Mean coverage values per sampling sector for every sprayer in intensive and traditional plantation systems. Error bars represent the Standard Error.

Figure 16b shows the coverage per sampling sector. S1 and S3 were the sectors perpendicular to the tractor's track; that is, they were the first sectors reached by the spray plume (Figure V-4). The coverage percentages achieved by the commercial sprayer were lower in sectors S2 and S4 than in S1 and S3 in both cultivation systems. This was the case for P1, for which very low values were achieved by the traditional system in S2 and S4 (Fig. V-16b). In fact, these low values are responsible for the low mean coverage values obtained for P1 in the traditional system. P2 was very homogeneous in the intensive system, with very low differences between P1 and P3 and between P2 and P4. Nevertheless, these differences are very important in the traditional system, as evidenced in Figure V-16b. The results for P3 did not follow a clear trend and did not yield a higher coverage for the P1–P3 pair than for the other pair. Its values were more or less similar for the intensive system, but they differed significantly for the traditional trees. P1 and P4 had the highest coverage values (56.10% and 42.13%, respectively), while P2 and P3 had lower values (33.95% and 35.15%, respectively).

In general, the prototypes all improved the application efficiency, achieving higher coverage values than the commercial sprayer for the same sprayed volume, except for P1 with traditional trees. The P1 solution does not seem to be well adapted to the traditional planting system, for which much higher airflow rate values are needed. P2 and P3, however, performed better than the commercial equipment for this planting system. In the case of intensive planting, the three prototypes and the commercial sprayer performed similarly, except for P2, which significantly improved the coverage values and achieved a high impact number. Therefore, P3 was concluded to be the best sprayer for traditional trees, and P2 was concluded to be not only the best sprayer for intensive trees but also the most versatile sprayer.

In conclusion, this paper presents the results of the Mecaolivar project, including the prototypes developed and the results of preliminary tests of their performance. The Mecaolivar project can be considered a successful example of innovation achieved through a pre-commercial procurement project conducted as a public–private partnership. The Mecaolivar project was successful in attracting the participation of equipment manufacturers who were very involved in the design process and accomplished all of the objectives as required and on schedule. The most satisfactory outcome of the project is the fact that the manufacturers intend to include the new sprayers that they developed for this study in their commercial catalogues. All of the prototypes developed represent a high level of innovation and are completely original in their conception. Furthermore, they are well adapted to use with both traditional and intensive olive canopies and sufficiently durable for use under real field conditions. The final prototypes fulfilled all of the technical requirements established in this study. Two of the prototypes, P2 and P3, are very efficient in generating high airflow rates at low power take-off speeds, which can contribute to reducing the power needs of the tractor In general, the prototypes all performed well under field conditions. P3 performed very well under traditional orchard conditions, achieving the highest coverage for a given spray volume. P2 performed well under both intensive and traditional orchards conditions, improving in both cases on the performance of the commercial sprayer. P1 performed well under intensive orchard conditions but cannot be recommended for traditional orchard conditions. The three prototypes can contribute to reducing pesticide doses applied to olive canopies and thus have the potential to have a positive influence on environmental conditions.

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CHAPTER VI – General conclusions.

Chapter VI – GENERAL CONCLUSIONS

Regarding the results and conclusions of the different works presented here, the following general conclusions can be drawn:

1. Pesticide applications in olive orchards can be markedly improved by increasing their efficiency without compromising their biological efficacy, what has the potential to generate important environmental, personal and food security outcomes (papers A and C).
2. Both volume rate (VR) and airflow rate (AFR) have optimal values that are lower than those used by the farmers. A reduction in this parameters could lead to an increase in the spraying efficiency by reducing spray drift and runoff from leaves and, in addition, to a reduction in the fuel consumption and the power needs of the tractors performing the treatments. The environmental save is, therefore, closely linked to the economic one (paper A).
3. Manual canopy characterization methods can contribute to estimate the crown volume accurately. The different methods vary their accuracy depending on the cultivation system. The Mean Vector (MV) method showed to fit reasonably well to the three evaluated orchard types, and can be considered as an accurate estimator to be used in any general dosing system for olive (paper B).
4. It is possible to find an optimal specific spray volume for isolated olives that relates the spray volume to the tree crown volume. This parameter can be the basis on which others could be added to improve pesticide applications in olive orchards (paper C).
5. The laboratory approach for multiple spray volumes testing resulted very useful as it reduced the number of treatments that were taken to the field. The sampling structure made the work easy as it allowed the researchers to easily change the samples by respecting the coordinates of each one. This setup can make researchers to save time and money, and to optimize the working settings in the field trials (paper C).

6. It was shown that improving spraying efficiency is possible through the use of adapted equipment. The difficulties present in the crop make necessary to adapt the spraying machinery, what makes possible to significantly reduce spray losses and, therefore, to perform treatments in a safer way (paper D).