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Spray and economics assessment of a UAV-based ultra-low-volume application in olive and citrus orchards

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Abstract

Automation is a new frontier in specialty agriculture equipment. Specifically, unmanned aerial vehicles (UAV), machine vision and robotics will increasingly appear in sustainable agricultural systems. The use of small UAVs retrofitted with spraying systems allows precision aerial applications on small targets. These precision applications can result in significant cost savings and reductions in risk to operators during treatments. This paper presents a novel and practical design and development of a small application system capable of being mounted on an unmanned aerial vehicle for agrochemical spraying tasks and an analysis of the quality of the application and economic costs in olive and citrus orchards compared with those of a conventional treatment. Once the equipment had been developed, field trials in super-high-density olive and citrus orchards were undertaken to evaluate the spray deposition efficiency. For comparison with a conventional hydro-pneumatic sprayer, the field tests took into account parameters such as the applied volume rate, spray drift, application time and equipment costs and depreciation. The results obtained indicate that there was a 7 €/ha difference in the application costs between the aerial vehicle and conventional equipment. It is hoped that the conclusions of this work will serve as the basis for a debate about the existing legislation governing this type of aerial work, which can be beneficial in specific cases and should be carried out in a safe and legal manner.

Keywords Agrochemical application · UAV · Sprayer · Economic analysis

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Introduction

In recent years, agricultural UAVs have gained popularity, leading to a paradigm shift in agricultural production (Limnaios 2014). These aerial platforms with computer-based systems for autonomous or semi-autonomous navigation have become relatively affordable tools for widespread use. The wide range of activities that they can carry out in agricultural environments has turned them into increasingly popular tools in agricultural fields. The ability of UAVs to fly at low altitudes carrying airborne sensors, allows data acquisition with both ultra-high spatial and spectral resolutions (Pajares 2015). UAVs also provide easy and fast mission design, reusability, cost-effectiveness and open-source frameworks (Urbahs and Jonaite 2013). Agronomically relevant data can be obtained for tasks such as mapping vegetation cover (Torres-Sánchez et al. 2013), deriving vegetation index data (Agüera Vega et al. 2015; Berni et al. 2009), estimating nitrogen (Zaman-Allah et al. 2015), reconstructing 3D orchards (Nevalainen et al. 2017; Díaz-Varela et al. 2015) and the early detection of diseases using chlorophyll fluorescence (Zarco-Tejada et al. 2012; West et al. 2017). However, the use of UAVs in agriculture is not limited to the imaging or scouting of crop diseases, pests, weeds or water deficits. Recently, UAVs have been used to perform variable rate application tasks such as selective ultra-low-volume herbicide application (Zhang et al. 2016; Giles and Billing, 2015; Huang et al. 2009) or remote aerial controlled seeding and reforesting (Wired Magazine 2015).

Although there is widespread concern regarding the negative environmental consequences of phytosanitary products in liquid form (Panneton et al. 2005), fumigation remains the most common form of application due to its low cost and good efficiency (Giles et al. 2008). The implements and technologies used for this type of application have remained relatively unchanged in recent years. At the European level, the Directive on the Sustainable Use of Pesticides 2009/128/EC (OJEC 2009) has motivated research into precision spraying to find an alternative method of applying these phytosanitary products.

The use of hydraulic and hydro-pneumatic sprayers is undeniably widespread in conventional applications. However, in recent years, variable-dose spraying and selective applications have emerged as satisfactory techniques in terms of product savings, environmental safety and end-use quality. UAV technology has proven its usefulness in crop protection and vector control not only for observation and detection but also for the precise application of agrochemicals (Giles and Billing, 2015). It is in Asian countries, and especially for extensive arable crops such as rice, wheat or barley, where the most important developments in UAV spraying techniques have been generated in recent years. Compared with capturing remote sensing information, applications with UAVs still present a considerable technical challenge. The payload and spraying equipment exhibit different behaviours and the power demand is significantly higher than when using cameras. In this type of aerial application, multi-rotor UAVs have a number of advantages over fixed-wing UAVs or spray UAVs, such as their flexibility and manoeuvrability in complex flight patterns, the non-requirement of a large landing/take-off area and the possibility of hovering over specific points on the ground (Zhang et al. 2016). In addition to these aspects of flight performance, the reduced exposure of workers to chemicals and the ability to apply chemicals in spatially variable patterns in a plot make UAV applications attractive from the point of view of precision agriculture. Previous studies with this type of unmanned system for agricultural tasks such as that carried out by Huang et al. (2009), focused on the use of specific implements mounted on UAVs, such as a rotary electrostatic atomizer Ru et al. (2011) or the co-ordination of a fleet of small multi-rotor vehicles (Wang et al. 2013). Most of these studies reported a common conclusion considered in the present work: the use of UAVs in spraying applications makes sense when used with ultra-low-volume (ULV) doses. These types of applications are considered key to precision plant protection because they result in a higher percentage of the chemical applied being collected on the target surface than when using conventional spraying (Bals 1970). Three key factors must be considered in these treatments: the optimum droplet size, the application strategy and the possible effect on the environment (Mount 1985). ULV treatments represent a significant risk of pollution by plant protection products, as they require the generation of fine, easily transportable airborne droplets that can affect sensitive adjacent areas. Whereas ULV applications are paramount since they provide maximum efficiency in targeted areas, the use of UAVs in this context still presents some technical challenges, such as the relatively large size of the drops from commercial nozzles, the difficulty in calculating the dose of active material to be applied and the small application area to which they are limited (Sheng et al. 2016).

Based on the above considerations, there is a growing interest in the development of application-specific equipment using UAVs. An economic comparison of these equipment with the standard techniques of spraying can reinforce their use in certain situations. The objectives of this study were (1) to develop a low-cost modular spraying system mounted on a UAV (hereafter referred to as Aerial Treatment for a High Orchard System or ATHOS), (2) to study the quality of the application in terms of a droplet and drift analysis and (3) to perform a comparison with a conventional sprayer application in cost-sensitive terms. The results are expected to demonstrate the suitability of the UAVs as tools for low-volume applications, comparing them in economic and quality terms against conventional equipment in a real use case.

Materials and methods

UAV platform

To implement a spraying system capable of applying the insecticide treatment, the DJI s1000+commercial UAV model (DJI, Shenzhen, China) was used for its autonomy and load capacity. This commercial model has a 15 min autonomy with a take-off weight of approximately 6 kg. An embedded GNSS receiver with sub-metre accuracy was used for navigation and route generation based on predefined waypoints. An ad hoc telemetry system consisting of a radio modem and a ground receiving station provided real-time information on the flight parameters (height above ground, horizontal and vertical velocities, position of the UAV), while an analogue video system allowed real-time images to be obtained from a first-person view. The maximum payload was 5 kg, but it was not possible to exceed 11 kg of total mass on take-off. The autonomy of the equipment with the mounted sprayer system described below was measured on several flights with the maximum load, establishing an average flight autonomy of 14 min.

Development of the UAV spraying system

The system was designed and built using low-cost materials and considering the payload limitations (Fig. 1a). Five elements compose the sprayer unit: the support structure, the tank to house the plant protection product, the nozzle arm or bar, the set of pipes and pump that make up the hydraulic system and the electrical spray control system (Fig. 1b). The

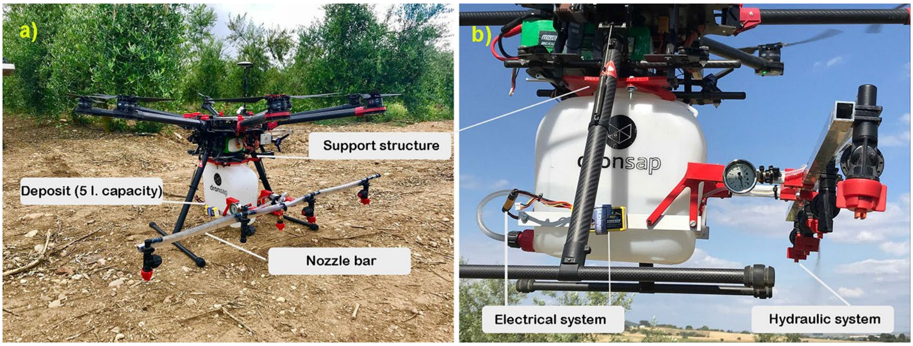

Fig. 1 **a** Application equipment mounted on board the UAV. **b** Detail of the spray system developed

tank, located at the bottom of the UAV, has a capacity of 5 l. The modular nozzle bar was designed to allow two spraying configurations: one with four working nozzles with a 250 mm spacing between them and another with a single central anti-drift nozzle. Both the assembly and UAV coupling frame structures were designed and manufactured using 3D-printed parts. Transparent PVC pipes with an inner diameter of 6 mm were selected for the pipes, while a small, independently supplied electric pump with a voltage of 12 V was used to apply within the circuit a maximum operating pressure of 250 kPa.

The spray control system allows the pump to be driven and its speed to be varied remotely from the UAV remote control station and enables autonomous application in specific areas using pre-established co-ordinates via the electronic system and GNSS. For this purpose, a pulse width modulation (PWM) control system has been designed, in which the radio signal sent from the UAV receiver adjusts the flow rate of the spraying system. This allows the flow rate of the nozzles to vary individually between 0.10 l/min and 0.22 l/min at the maximum pump range. For the complete characterisation of the equipment, laboratory tests were carried out in which the average flow rate of each nozzle in both configurations was determined at different pump regimes, and the liquid quantities were measured with graduated laboratory test tubes. In addition, the battery discharge curves were determined with respect to the weight and time to characterise the autonomy of the equipment with different levels of payload based on the automatic recording of the telemetry received.

Field experiments

To demonstrate the reliability and efficiency of the developed system, a treatment with a commercial insecticide that acts as bait for the olive fruit fly (*Bactrocera oleae*) and common fruit fly (*Drosophila melanogaster*) was conducted in both olive tree and citrus tree fields. The first field test took place in an experimental exploitation of super-high-density olive trees in facilities on the University of Córdoba campus in Córdoba, Spain (Latitude, 37º 56′ 6.3″ N; Longitude, 4º 43′ 1.1″ W). The olive trees in this orchard measured approximately 2.5 m high and were spaced at 1.5 m with a 4 m row separation. Four olive tree rows (50 m long) were selected, over which flights were made with different pre-programmed routes (straight line, flights following a rectangular pattern, etc.), different application patterns and different forward speeds; the treatments were tested at horizontal forward speeds of 2, 3 and 4 m s^{-1} and heights of 0.5, 1 and 2 m above the tree canopy

Table 1 Preliminary test setups for tractor + atomizer sprayer application in citrus orchards

Test setup	Tractor speed (m s^{-1})	Implement working pressure (kPa)
Setup 1	V1 = 2.2	P1 = 1200
Setup 2	V1 = 2.2	P2 = 800
Setup 3	V2 = 2.7	P2 = 800
Setup 4	V2 = 2.7	P1 = 1200

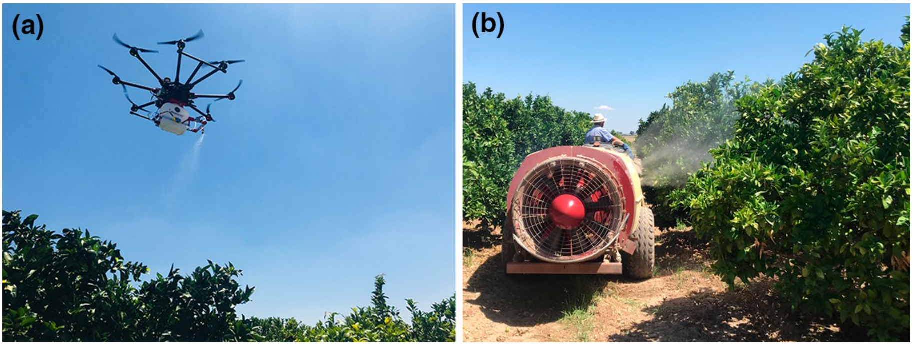

Fig. 2 **a** UAV aerial application using single-nozzle configuration. **b** Conventional spraying application of commercial product in orange trees using tractor + implement equipment

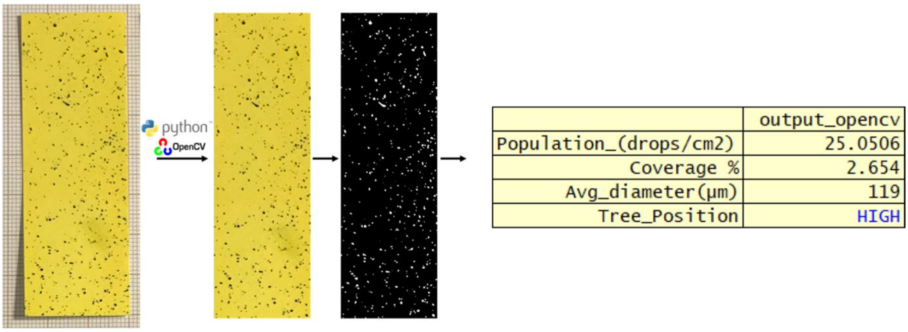

Fig. 3 Image processing of water-sensitive papers. RAW image is first cropped and binarized. Then, the software detects the contours of the elements in the image (droplets) and counts the contours. The final output shows the resulting information in table form

(Fig. 3). Wind conditions were measured with a precision handheld anemometer. During this first test, the wind speed was 1.1 m s^{-1}.

The second test was carried out on a commercial orange grove near Seville, Spain (37 30′ 43.13° N; 5 58′ 12.78° W), whose trees had a separation of 4 m and 5.5 m between rows, with an average height of 2.45 m. During this second test, the wind speed was 2.1 m s^{-1}. In this second test, a John Deere 5510 N (John Deere, Illinois, US) 67 kW tractor and a Hardi Mercury (Hardi, Nørre Alslev, Denmark) atomizer with a deposit capacity of 3000 l was also used for treatments comparison. With the conventional equipment, different treatments were carried out with the usual working speeds and pressures for the application of the commercial formulation, so that different spraying configurations could be obtained, as shown in Table 1 below:

From these four configurations, it was decided to carry out the final tests using the Setup 1 and Setup 3 combinations, which will be hereafter referred to as Treatment 1 (T1) and Treatment 2 (T2) since, according to the tractor operator's criteria, they were the most commonly used possibilities for this type of application. Following the recommendations of the product supplier, only the three nozzles in the middle of the section were used (Fig. 2b). The hydro-pneumatic sprayer used hollow cone Hardi 1299-12 (Hardi, Nørre Alslev, Denmark) commercial ceramic nozzles, specific for fine spraying on orchard crops. In the UAV equipment, Hardi ISO F-110 standard flat fan nozzles were used.

In both application trials, a commercial formulation that acts as bait for the olive fruit fly (Bactrocera oleae) was chosen as the applied ingredient. It is recommended that this insecticide (Spinosad®, Dow Agrosciences), whose active component is 0.024%, be diluted with water at a ratio of 1:10, prepared immediately prior to application, and applied at a rate of 0.25 to 0.5 l ha^{-1} in bands covering 25% of the total surface, which allows 1 ha to be treated with an application from the spraying system.

In the olive and citrus trees, in two non-consecutive rows, two heights (upper and middle crown height) were covered with water-sensitive paper to evaluate the ability to deposit the spray on the tree. To assess the potential drift caused by the ULV application using both spraying systems, tests were conducted under the ISO 22866 standard methodology for field spray drift. Water-sensitive papers were placed on the rows adjacent to the treated trees to capture any drift from both spraying systems (Fig. 3).

A specific software based on Python's OpenCV computer vision module (Bradski 2000) was employed to automatically analyse the water-sensitive paper. The results obtained were analysed by using the R statistics software (R Core Team 2013). The droplet population, mean diameter and area covered were measured using this software. After each flight, samples of the water-sensitive paper were collected and analysed in the laboratory. A total of 150 paper samples were analysed automatically for each field test. The software developed initially takes as an input each of the RGB images, on which using the CopyBorder function of the OpenCV library, it detects the edges of the element due to its difference from the background and performs the automatic cropping of the study area. Once this function is executed, a Gaussian Blur is applied as the only pre-processing, and then the adaptive thresholding is computed using the Gaussian method of the OpenCV library, in which the threshold value is the balanced sum of the neighbouring values. This type of thresholding is done because the lighting conditions in all parts of the water-sensitive paper images were not made with structured light and are therefore different. Afterwards, a binary image is generated on which, using the OpenCV ConnectedComponents function, an analysis is performed based on the shape descriptors, in which the elements that do not belong to the background (the spray droplets) are labelled internally, which allows them to be detected and quantified. Finally, the corresponding outputs are stored in a CSV file for analysis (Fig. 3).

One of the aspects evaluated was the ability of the equipment to effectively apply the product to the crop and to generate relatively uniform coverage while reaching the top and inside-middle parts of the trees. The distribution of droplet populations, the area covered by the droplets per cm^2 and the average diameter of the droplets were obtained automatically for every trial test. The measurements of this software were internally validated by comparison with free software available through the USDA, DepositScan (Zhu et al. 2011), with the only purpose of obtaining the degree of confidence of the program developed. Although this comparison does not fall within the scope of this paper, it should be noted that similar results to those obtained with DepositScan were obtained in the tests performed.

Economic assessment

The aerial platform and conventional application equipment were compared, performing the same type of task, taking into account parameters such as the amount of product applied, the hourly output of the spraying equipment and the cost and payback period of the equipment. For the economic evaluation of the use of conventional equipment for the localised application of fly bait, the calculations were based on the technical considerations proposed by the ASABE (American Society of Agricultural and Biological Engineers) and MAGRAMA (Spanish Ministry of Agriculture), collected by Boto et al. (2004). In these guidelines, the costs of agricultural operations were analysed by including the following: (i) fixed depreciation costs, interest, machinery accommodation, insurance and taxes; (ii) variable cost (VCs), including fuel, lubricants, tyre wear, overall repair and maintenance cost (RMCs), and tractor labour; and (iii) the total hourly cost of operation plus tractor and implementation costs. For the economic evaluation of the application, a theoretical working scenario was established on an intensive olive grove plot similar to that described in the Field Experiments Section, with a planting frame of 1.5×3 m and a number of trees per hectare of approximately 2220. In this scenario, a ULV treatment was proposed, in which both pieces of equipment (the hydro-pneumatic sprayer and the UAV) must cover 50% of the field area (see Fig. 4).

To calculate the application costs, a comparative economic study was carried out on the basis of a tractor with the characteristics listed in Table 2 and the ATHOS system described above.

Based on the preliminary results of the field trials and knowing the design and development costs, an economic assessment of the ATHOS system was carried out with empirical data, and a comparison was made with the previous analysis since no relevant studies or references have been found to date.

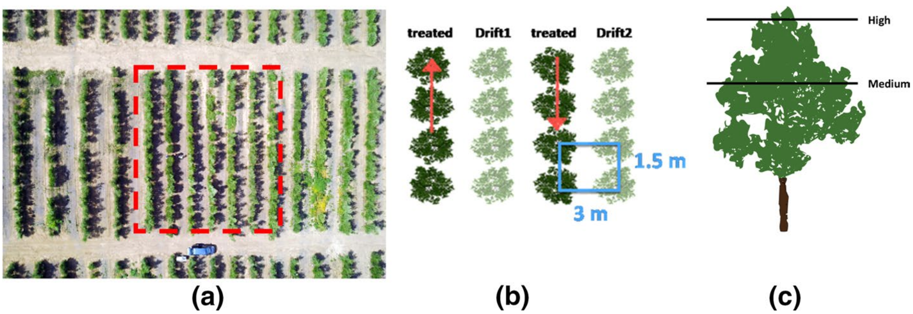

Fig. 4 **a** Aerial image of the field test area in olive trees, **b** diagram of the flight pattern over the olive trees, and **c** measurement heights where water-sensitive paper was located on all the trees

Table 2 Characteristics of the tractor used in the economic assessment

Rated power	78 kW
Max power PTR	70 kW
Acquisition value	30000 €
Annual working hours	1000 h/year
Lifetime period	12 years
Period	12000 h

Results and discussion

UAV spraying system

Achieving a stable and uniform flight behaviour was one of the main challenges once the spraying components were integrated and mounted on the UAV. A number of adjustments had to be made to the centre of gravity and weight compensation, considering factors such as the possible "swell" of the liquid inside the tank during flight and the progressive decrease in the weight of the assembly during operation. The swell limited the maximum forward speed and manoeuvrability of the assembly, while the weight decrease affected the discharge curve of the battery and the power generated by the engines. To avoid these complications, the variations in the system's gravity centre during flight were calculated, and the tank support was built so that it was as close as possible to the structure to prevent swaying in the air, which could cause alterations in flight.

Regarding the application system, the flow rate of each of the nozzles was tested in the laboratory by collecting samples in graduated laboratory tubes, obtaining an average flow rate of 0.22 l/min for each nozzle at maximum pump speed. The results of the battery discharge tests and the evolution of the weight over time are shown in Fig. 5.

As observed in the curves in Fig. 5, the moment of maximum mass (corresponding to take-off and the first few seconds of flight) corresponded to the maximum power demand of the engines and, therefore, to the most marked decrease in the battery charge voltage. In addition, both curves show that once the entire phytosanitary product was consumed (approximately 5 min or 300 s), the total weight of the system stabilised at approximately 6 kg, while the voltage of the battery remained at 21.5 V. This battery charge still allowed up to 10 more minutes of flight time (software warnings were created to signal when the

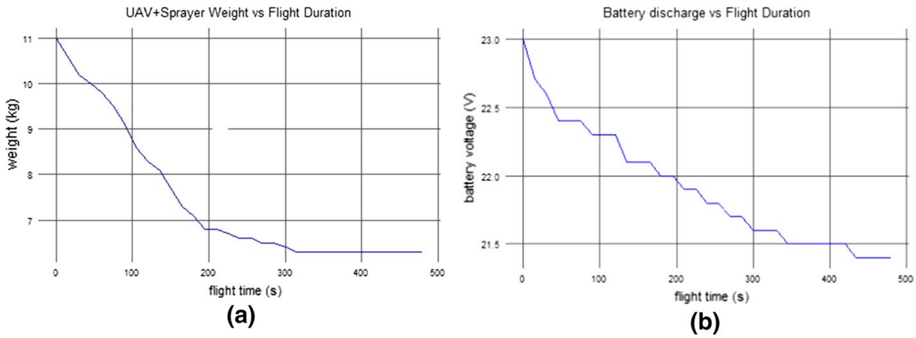

Fig. 5 **a** Curves of the evolution of the ATHOS equipment's weight and **b** the battery discharge over time

battery voltage reached this point) so that if the equipment is far from the operator, there would still be time for a safe return and landing.

Spraying assessment with UAV and conventional equipment

In field tests carried out to verify the performance of the aerial application system, different combinations of forward speeds and flight heights were evaluated. Final test conditions of a 3 m s^{-1} horizontal speed and 1 m height above the canopy were established.

Olive tree spraying

The analysis of the water-sensitive papers used in the first tests carried out in the olive grove using ATHOS gave the results shown in Table 3 below. For the first results in the methodological approach, the drift results were ignored in the calculations.

In addition to the numerical results, it was observed in the field that the air stream generated by the blades of the UAV allowed the penetration of the liquid into the target surfaces inside the tree. Spraying in high-density olive groves is influenced by the structure of the tree, as they are narrow and high in shape. With an aerial spraying system such as the ATHOS, the spray can be applied effectively to the middle part of the tree, one of the objectives of this first field test in the bait product application.

Figure 6 shows how these droplet populations and their mean diameter were distributed over the two different measurement areas. They include the results obtained with respect to the drift. With regard to the population of drops obtained from this application, it was observed that in the upper part of the olive tree, an average deposition of approximately 25 drops/cm^2 was obtained, while in the middle part of the tree, an average of 13 drops/cm^2 was obtained. In addition, a fairly uniform average drop diameter was obtained in both areas of the tree (144 µm in the upper part and 120 µm in the middle part). Although these distributions may be scattered, these results are close to what is demanded by the manufacturer of the commercial fly bait product, as only a tree wetting is sought to attract the insect. It is shown that even under the test conditions with a 2.1 m s^{-1} wind, the drift was very low, almost negligible. This fact is a point that will later be presented in the discussion of the results as a benefit of the ULV application equipment.

Citrus tree spraying

For the second test, where conventional application equipment was available, a comparison was made with the ATHOS spraying equipment. As stated previously in the Field

Table 3 Results of the image analysis of 150 water-sensitive paper samples after the ATHOS spraying application on olive trees

N = 150	Population (drops/cm^2)	Coverage (%)	Avg. drop diameter (µm)
Min	0.1012	0	105
Median	18.2186	2.011	132
Mean	22.9013	4.549	133
Max	76.973	15	206
Std	23.145	3.630	23.234

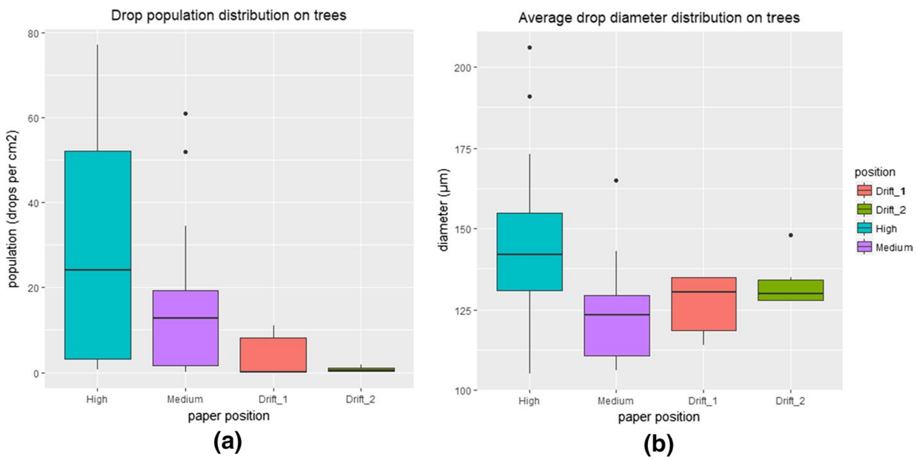

Fig. 6 **a** Drop population pattern and **b** droplet diameter distribution at the different measurement levels established on olive trees. Drift 1 and Drift 2 positions are explained in Fig. 4b. Black dots correspond to the outliers obtained in the statistical analysis of the data

Experiments Section, two different combinations of forward speed and working pressure (T1 and T2) were assessed for the conventional spraying equipment.

Regarding the spraying carried out with the ATHOS equipment in this test on orange trees, the results obtained are shown in Table 4. In comparison with the application in high-density olive groves, a much higher percentage of coverage and a drop diameter almost twice as large were obtained in the orange crop. However, the standard deviations obtained, in some cases above the average, indicate that there are extreme values, which correspond to completely covered papers and others with practically no drops. It should be considered that, for this calculation, no previous selection of the papers had been made, and all those with any drop on them were included.

As a result of applications using the tractor and implement spraying equipment in the T1 and T2 configurations, it was observed that much more liquid was sprayed during operation and at a greater distance than in the equivalent application using ATHOS. In addition, the air flow caused by the equipment's fan was much more powerful, even affecting the canopy of other adjacent lines. This influenced the drift, which was already much greater than that with the ATHOS equipment, even in windless conditions.

Table 4 Results of the image analysis of 150 water-sensitive paper samples after the ATHOS spraying application on citrus trees

N = 150	Population (drops/cm^2)	Coverage (%)	Avg. drop diameter (μm)
Min	0.101	0.01	95
Median	13.992	7.839	270
Mean	20.255	21.149	270.8
Max	62.75	99.99	409
Std	17.86	32.326	65.44

Regarding the water-sensitive papers obtained in these treatments and those obtained with ATHOS in the different tree positions tested, a completely random selection of three samples for each position and treatment is shown in Fig. 7.

Figure 7 reveals the spraying using the atomizer generated a total coverage (close to 100%) in the middle area of the tree, which can be considered over-treatment and a waste of product. In the upper zone, T1 also generated an inappropriate application of the active matter, with depositions that did not correspond to the manufacturer's instructions for this product. On the other hand, the T2 in the upper part of the tree gave better results in terms of the dispersion, diameter of the drops and their coverage, even though they were slightly high. This second combination could be considered valid in the upper part of the tree, but not in the middle part. As can also be seen in Fig. 7, the drift obtained in the adjacent row with the T1 treatment was significant, practically reaching a coverage of 50% with larger diameter drops than desired, while in T2 a smaller drift occurred, with fine drops and little coverage (approximately 3% on average). In comparison, the results obtained by spraying with the developed ATHOS equipment are much more homogeneous, obtaining, in the case of the citrus test, a greater uniformity in the two areas measured (high and medium zones of the tree), although in the higher part of the tree, there were also areas where the percentage of leaf cover was close to 90%. It is also noted that in the case of citrus fruits with ATHOS spraying, the drops had a larger average diameter than that in the case of the olive groves. This can be attributed either to the tree foliage density of each crop or to their structural morphology. What is evident is that the drift using the ATHOS spray equipment was lower than using the conventional application equipment, as the zenithal air flow

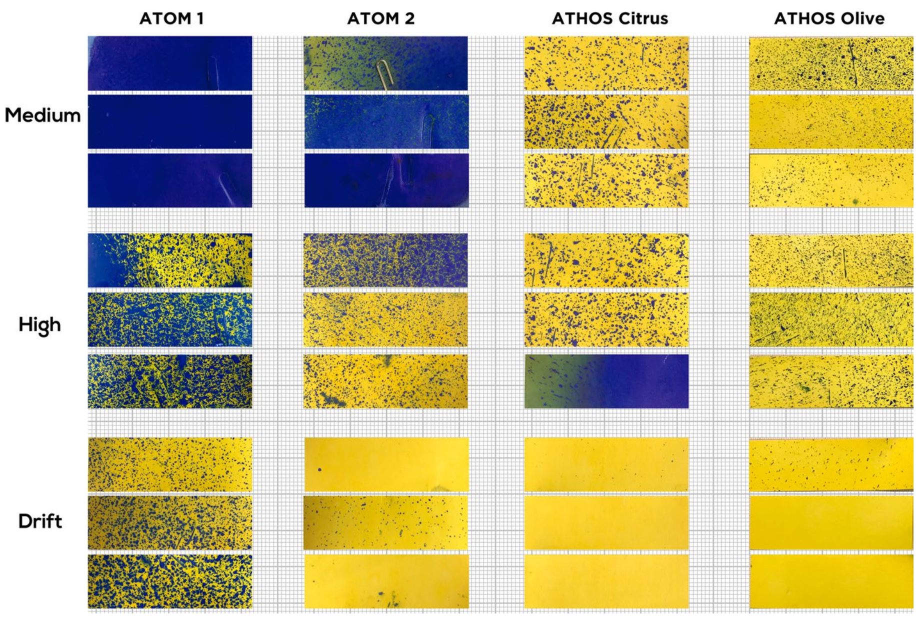

Fig. 7 Sample of hydrosensitive papers collected in each of the field trials using conventional equipment with two different T1 and T2 configurations and the ATHOS equipment in citrus and olive groves. The samples have been sub-divided into the different positions in which they were distributed in the canopy. The selection of the sample of three papers has been made randomly, numbering them and extracting random numbers with the Numpy library in Python

allowed the product to be applied mostly to the tree with virtually no effect on the adjacent trees. In trees with a more spherical structure such as orange trees, the drift was practically non-existent, while in olive groves, as the tress are narrower in width, air vortices were generated on the sides of the tree that generate a small drift. With regard to the distribution of the spraying on the trees, Fig. 8 shows the modelling with respect to a spherical surface on which the data collected on the droplet population and its diameters have been projected on to the set of water-sensitive papers. With the conventional treatment, there is a higher incidence of spraying in the area at medium and high altitudes on the spray side, which decreases considerably on the other side of the tree. However, in the treatment with the ATHOS system, the largest area of incidence, as can be expected, is the highest, but the distribution along the tree in height is notably more homogeneous.

Finally, Figs. 9a–c shows the boxplot diagrams for the coverage of the hydrosensitive papers, average diameter of the drops and droplet population. With respect to the covered

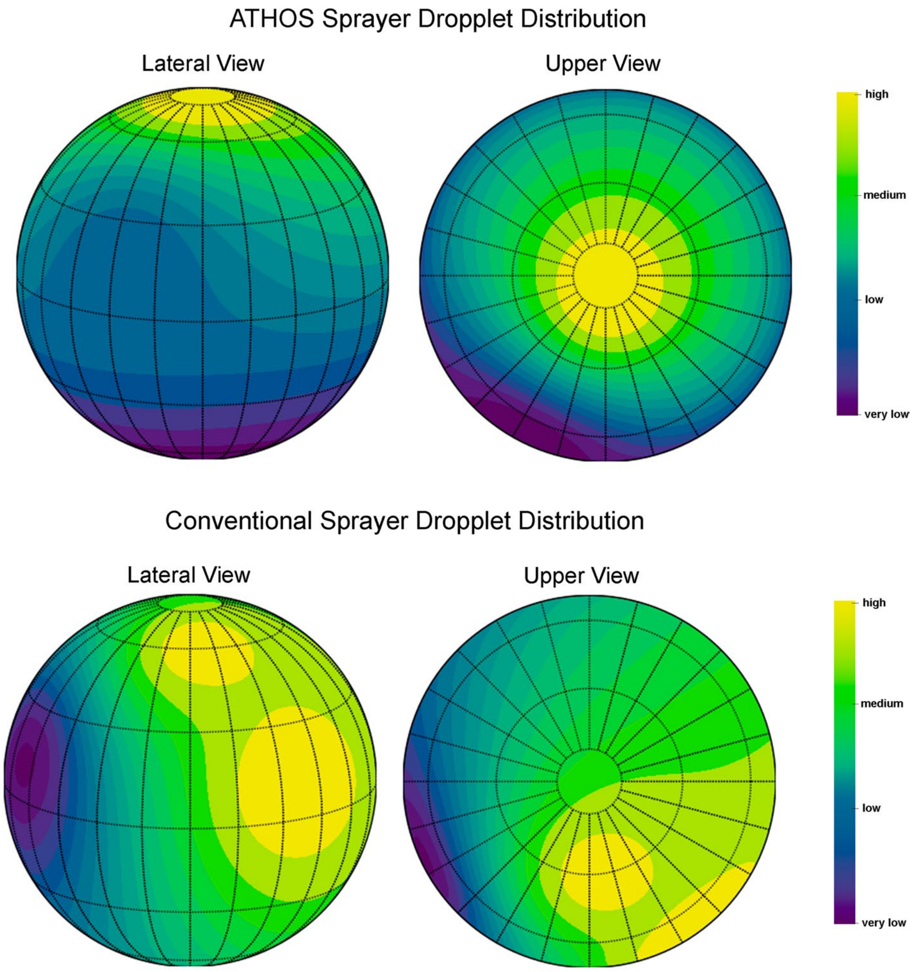

Fig. 8 Comparative representation of the distribution of droplets on a spherical surface from samples obtained in field tests for aerial application with ATHOS (above) and conventional application (below)

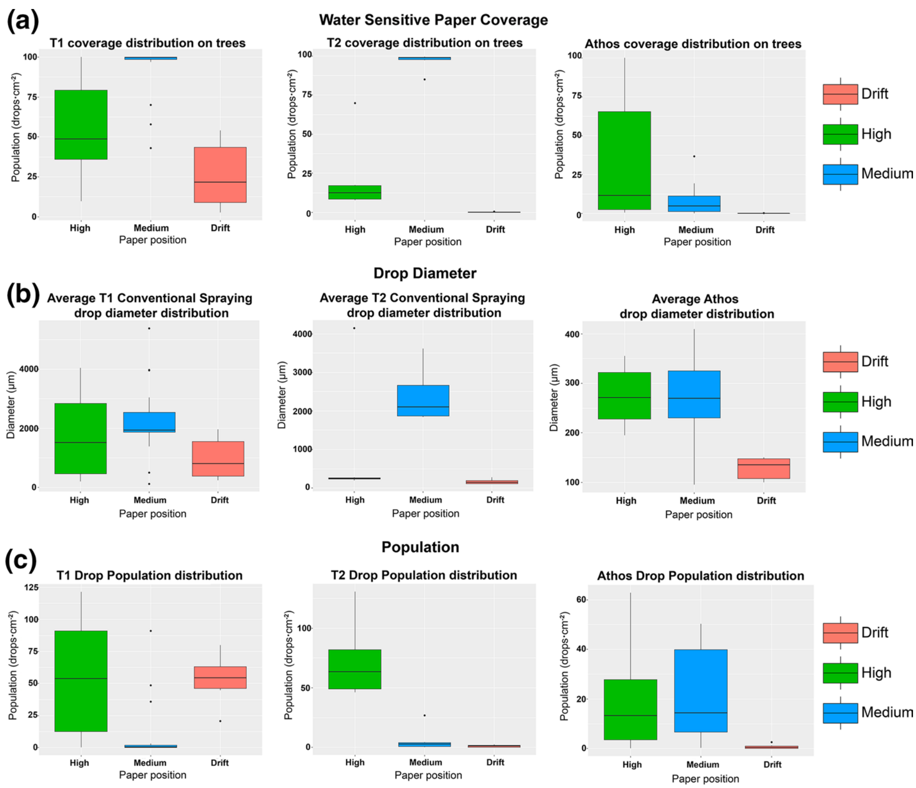

Fig. 9 Comparative representation on different treatments between: **a** percentage of paper covered surface for each tree position of water sensitive papers and drift samples, **b** average of drop diameters for each tree position of water sensitive papers and drift samples and, **c** drop population for each paper position and drift paper samples. Small black dots on the figures represent outliers obtained during field tests

area represented in Fig. 9a, in the average position in both the conventional T1 and T2, almost 100% coverage was obtained in both cases, while the average percentage dropped to approximately 10% in the case of ATHOS. As mentioned above, this result implies that in the case of conventional application, more phytosanitary products may be being distributed than necessary, which implies over-treatment. It also shows that the drift in the T1 case is much greater than that in the other two treatments.

The data analysis related to the average diameter of the droplets shown in Fig. 9b presents anomalous values in the T1 and T2, which can be explained by the fact that the software does not distinguish between the average impact diameters because they have wetted practically the entire surface of the tree leaves. This shows that the digital analysis of the water-sensitive papers is a standard technique that still has limitations in terms of accuracy. An average droplet diameter of 238 µm was obtained in the water-sensitive papers from the conventional spraying. However, the average diameter values obtained with ATHOS showed a much more uniform average diameter between the upper and middle parts, with an average close to 250 µm. In this case, if those papers with anomalous values are not included in the analysis, the average diameter of the droplet population dropped to 130 µm, which represents a value closer to that expected in the ULV applications (Mount 1985).

Finally, the analysis of the droplet population showed anomalous values in the middle part of the tree in T1 and T2. This is due, as in the previous case, to the fact that the entire product coverage of the paper did not allow droplet discrimination, and assumed a low coverage value when it was actually the opposite. In the case of ATHOS, the average droplet population between the upper and middle parts was practically the same. From all the data analysed, it was concluded that the two conventional applications, despite a greater wetting of the canopy, did not generate a uniform and adequate application, giving rise to over-treated areas with a greater drift. However, the application with the ATHOS equipment was more homogeneous, with optimal small diameter drops and uniform distributions.

Economic assessment

Once the machines that carry out the different operations and their capacities had been defined, the operating costs were predicted. First, the economics of the tractor and implement combination were evaluated using the following criteria: FCs (fixed costs), including depreciation (using a 'combined' procedure that considers obsolescence and machine wear simultaneously), interest, accommodation costs and applicable insurance and taxes; VCs, including fuel and lubricant consumption and wear of pneumatic tyres; overall RMCs; and operator and auxiliary labour costs where applicable. Finally, the total hourly costs of the operation, resulting from the sum of the hourly costs of the tractor and implement operation, were calculated.

With respect to the FCs, the evaluated items of the equipment amortization, interest, housing and taxes were as follows:

- With respect to the depreciation or amortization of the tractor, Eq. (1) was used to calculate the net value (V_N) at the end of the operating period, and Eq. (2) was used to calculate the value of the application equipment at the end of its operating period, where (V_a) represents the acquisition value and N the years of the operating period.

$$V_N = V_a \times 0.68 \times 0.92^N \tag{1}$$

$$V_N = V_a \times 0.56 \times 0.885^N \tag{2}$$

Once the net values were calculated for both the tractor and the implement, the depreciation cost was calculated using Eq. (3), obtaining an annual depreciation value of 1874.97 € per year.

$$CA_c = \frac{V_0 - V_N}{N} = \frac{30\,000 - 7500.39}{12} = 1874.97 \frac{€}{year} \ (tractor) \tag{3}$$

The depreciation cost for the implement was calculated in the same manner, obtaining an annual depreciation of 632.66 € per year.

- The interest (interest on the investment) represents the opportunity cost applied to the value of the machine. For its calculation, the accounted capital of the machine was valued by calculating half of the sum of the initial value of the machine and the net value at the end of the operating period; an accounted capital value of 18750 € per year was obtained. To determine the net interest rate, the difference between the commercial interest (0.06) and inflation (0.03) was calculated, obtaining 0.03 or 3%

net interest. The total interest cost was obtained from the product of which the capital accounted for, and the interest was 562.51 € per year.

- The annual storage costs were estimated as a percentage of the purchase cost of the tractor or the actual annual cost, which could be for the rental of a garage or cabin to store the tractor. In this case, the cost of accommodation was set at 0.75% of the purchase price or 225 € per year.
- In the same way, the annual cost of insurance and other taxes was calculated as 0.75% of the acquisition value or 225 € per year.

The total annual FCs, understood as the sum of all the above costs, amounted to 3520.14 € per year, which was equivalent to 3.52 € h^{-1}considering the set value of approximately 1000 working hours per year.

The VCs were disaggregated as follows:

- The fuel consumption was calculated using the hourly consumption product (l h^{-1}) and the price of diesel (€ l^{-1}). To calculate the hourly consumption, the average working power (60% of the maximum power) and the specific consumption were estimated. Taking a fuel price of 0.80 € l^{-1}, the consumption resulted in a cost of 10.29 € h^{-1}.
- The lubricant consumption was taken from the tractor's technical data sheet and was valued in this case at 0.21 € h^{-1}. The oil level of the hydraulic system was set at 0.30 € h^{-1}.
- The cost of wheels and tyres was calculated considering that the tractor had four-wheel drive and that the tyres had to be replaced after 4000 h, at a cost of 600 € per tyre. This calculation resulted in a cost of 0.6 € h^{-1}.
- For the RMCs, the average annual cost (RMC average) was calculated, with respect to the acquisition value for each year. In this way, the total RMC over the 12 years of useful life represented 43.2% of the initial purchase value, resulting in an average annual RMC of 1080 € per year or 1.08 € h^{-1}.

With regard to the labour cost of the tractor driver, the estimated cost was 10 € h^{-1}, including salary and national insurance. Table 5 below summarises the total breakdown of costs shown above.

The total cost of the conventional application using a tractor and an implement obtained by adding the FCs, VCs and operating costs was approximately 26 € h^{-1}.

With regard to the ATHOS system, a useful lifetime of 5 years, with 100 flight hours per year, was established. The FCs of this type of system are listed in Table 6.

It should be noted that the accommodation costs were not included in the FCs due to the smaller size of the equipment, although if a fleet of airborne equipment is developed, the authors believe that they should be included.

The VCs of the ATHOS system included the RMCs, with a value of 150 € per year (1.50 € h^{-1}) and the cost of the pilot's salary set at 20 € h^{-1}. The average total cost per hour of ATHOS was therefore 33.80 € h^{-1}.

The area treated per hour or hourly output was estimated using the product of the working width (in m) and the forward speed (in m s^{-1}), divided by ten. In the scenario described above, the working width was 6 m (3 m of separation between rows, treatment of 50% of rows), and the forward speed of both pieces of equipment was set at 2.7 m s^{-1}, which gave a theoretical hourly output of 6 ha h^{-1}.

Table 5 Summary of tractor + sprayer costs

FCs of tractor + sprayer	Depreciation cost of tractor	1874.97 €/year
	Depreciation cost of sprayer	632.66 €/year
	Cost of interest	562.51 €/year
	Shedding costs	225 €/year
	Insurance, taxes	225 €/year
	Total FCs per year	3520.14 €/year
	Total FCs per hour	3.52 €/h
VCs	Fuel consumption	10.29 €/h
	Lubricant consumption	0.21 €/h
	Hydraulic oil consumption	0.30 €/h
	Tyre wear	0.6 €/h
	Repair/maintenance	1.08 €/h
	Total VCs per hour	12.48 €/h
Labour force	Tractor driver (salary + national insurance)	10 €/h
Total cost of conventional tractor application		26 €/h

Table 6 FCs of the developed ATHOS spraying system

Legal declaration operator company/autonomous	300 €
Theoretical/practical/medical pilot licence	900 €
UAV insurance	200 €/year
UAV equipment + remote control	4000 €
Developed spraying system	2500 €
Four batteries	700 €
Total FCs per hour	12.3 €/h

With the tractor, the real capacity could be estimated by multiplying the theoretical efficiency by a factor of 0.8, obtaining a value of 4.8 ha h^{-1}, which implies that application to 1 ha can be completed in 12.5 min.

With the ATHOS system, the real or effective performance factor was increased to 0.9, as turns and manoeuvrability in the field are much faster, requiring less time than those with the tractor. In this way, a real capacity of 5.4 ha h^{-1}, or 11.1 min ha^{-1}, could be obtained. Notably, the speed of 2.7 m s^{-1} set for the study could be increased almost twofold when using ATHOS, thus reducing the estimated time needed to treat one hectare.

Conclusions

The design and construction of a low-cost hydraulic sprayer model (ATHOS) capable of performing specific ultra-low volume applications was successfully completed. Its performance in flight and ability to apply chemicals was field-tested on olive and citrus trees. The droplet population, distribution on canopy, covered leaf area and droplet diameter were measured. In addition, a comparative analysis of the application costs between conventional equipment and the developed ATHOS system was carried out. The following conclusions can be drawn from the present work:

- The results obtained from the aerial application with the ATHOS system demonstrated that this type of application equipment can perform variable spraying tasks at specific locations in a uniform manner and with an acceptable quality in terms of coverage, population and droplet diameter. In the comparison with the conventional application, the conventional treatment equipment generates an over-population of drops and a wetting that can lead to over-treatment and, therefore, product waste. However, the treatment using the UAV showed uniformity in both the droplet population and diameter, both being sufficiently homogeneous to consider that an effective treatment had been carried out. As shown in the results, a combination of both systems could lead to an optimised treatment in the side and top parts of the tree.
- Drift in crop protection applications represents a problem when dealing with conventional equipment, especially in windy conditions. In this work, it is clear that the conventional application equipment, in a normal working setup and in low wind conditions, generated a drift large enough to be an environmental problem. In this respect, the use of UAVs has significantly reduced the drift. This reduction in drift is mainly due to two factors: the lower power of the airflow generated by the flight equipment with respect to the atomizer fan and the direction of the atomizer fan with respect to the structure of the tree. Another important consideration in terms of sustainability is that UAV applications avoid the soil compaction problems caused by machinery.
- There was not much difference in the application cost of the aerial platform and conventional equipment (33.80 € ha^{-1}compared to 26 € ha^{-1}, respectively). The costs of the developed equipment were analysed on the basis of estimates from the team's own experience, to the best of the author's knowledge, no economic studies of this type of application have been carried out.
- The capacity in hectares per hour of equipment such as ATHOS was calculated to be greater than that of conventional equipment because the treatments can be carried out at a higher rate of advance and with greater manoeuvrability.

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References

Agüera Vega, F., Carvajal Ramírez, F., Pérez Saiz, M., & Orgaz Rosúa, F. (2015). Multi-temporal imaging using an unmanned aerial vehicle for monitoring a sunflower crop. *Biosystems Engineering, 132,* 19–27.

Bals, E. J. (1970). The principles of and new developments in ultra-low volume spraying. In *Proceedings of the fifth British insecticide and fungicide conference* (Vol. 1, pp. 189–193). Alton, UK: British Crop Protection Council.

Berni, J. A. J., Zarco-Tejada, P. J., Suárez, L., González-Dugo, V., & Fereres, E. (2009). Remote sensing of vegetation from UAV platforms using lightweight multispectral and thermal imaging sensors. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 38*(6), 6.

Boto, J. A., Pastrana, P., & Suárez de Cepeda, M. (2004). *Consumos energéticos en las operaciones agrícolas en España (Energy Consumption in Agricultural Operations in Spain).* Madrid, Spain: Spanish Ministry of Agriculture, Fisheries and Food.

Bradski, G. (2000). The opencv library. *Dr Dobb's Journal of Software Tools, 25,* 120–125.

Díaz-Varela, R. A., de la Rosa, R., León, L., & Zarco-Tejada, P. J. (2015). High-resolution airborne UAV imagery to assess olive tree crown parameters using 3D Photo reconstruction: Application in breeding trials. *Remote Sensing, 7,* 4213–4232.

Giles, D., & Billing, R. (2015). Deployment and performance of a UAV for crop spraying. *Chemical Engineering Transactions, 44,* 307–312.

Giles, D. K., Akesson, N. B., & Yates, W. E. (2008). Pesticide application technology: Research and development and the growth of the industry. *Transactions of ASABE, 51,* 397–403.

Huang, Y., Hoffmann, W. C., Lan, Y., Wu, W., & Fritz, B. K. (2009). Development of a spray system for an unmanned aerial vehicle platform. *Applied Engineering in Agriculture, 25,* 803–809.

Limnaios, G. (2014). Current usage of unmanned aircraft systems (UAS) and future challenges: A mission oriented simulator for UAS as a tool for design and performance evaluation. *Journals of Computation and Modelling, 4*(1), 167–188.

Mount, G.A. (1985). Ultra Low Volume Application of Insecticides for Vector Control. Geneva, Switzerland: World Health Organisation, WHO/VBC/85.919

Nevalainen, O., Honkavaara, E., Tuominen, S., Viljanen, N., Hakala, T., Yu, X., et al. (2017). Individual tree detection and classification with UAV-based photogrammetric point clouds and hyperspectral imaging. *Remote Sensing, 9*(3), 185.

OJEC. (2009). Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for community action to achieve the sustainable use of pesticides (Text with EEA relevance)

Pajares, G. (2015). Overview and current status of remote sensing applications based on unmanned aerial vehicles (UAVs). *Photogrammetric Engineering & Remote Sensing, 81,* 281–330.

Panneton, B., Lacasse, B., & Piché, M. (2005). Effect of air-jet configuration on spray coverage in vineyards. *Biosystems Engineering, 90,* 173–184.

Sheng, W., Yubin, L., Jiantado, Z., Shenghua, L., Haiyan, Z., & Hang, H. (2016). Analysis and experiment on atomization characteristics of ultra-low-volume swirl nozzle for agricultural unmanned aviation vehicle. *Transactions of the Chinese Society of Agricultural Engineering, 32*(20), 85–93.

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Torres-Sánchez, J., López-Granados, F., De Castro, A. I., & Peña-Barragán, J. M. (2013). Configuration and specifications of an unmanned aerial vehicle (UAV) for early site-specific weed management. *PLoS ONE, 8*(3), e58210.

Urbahs, A., & Jonaite, I. (2013). Features of the use of unmanned aerial vehicles for agriculture applications. *Aviation, 17,* 170–175.

Wang, Z., Lan, Y., Hoffmann, W.C., Wang, Y., & Zheng, Y. (2013). Low altitude and multiple helicopter formation in precision agriculture. Paper no 131618681, St Joseph, MI, USA: ASABE.

West, J. S., Canning, G. G. M., Perryman, S. A., & King, K. (2017). Novel Technologies for the detection of Fusarium head blight disease and airborne inoculum. *Tropical Plant Pathology, 42*(3), 203–209.

Wired Magazine (2015) Re-Planting a Forest, One Drone at a Time. Retrieved August, 2018, from https://www.wired.com/brandlab/2015/07/re-planting-forest-one-drone-time/

Zaman-Allah, M., Vergara, O., Araus, J. L., Tarekegne, A., Magorokosho, C., Zarco-Tejada, P. J., et al. (2015). Unmanned aerial platform-based multi-spectral imaging for field phenotyping of maize. *Plant Methods, 11,* 35.

Zarco-Tejada, P. J., González-Dugo, V., & Berni, J. A. J. (2012). Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection using a micro-hyperspectral imager and a thermal camera. *Remote Sensing of Environment, 117,* 322–337.

Zhang, P., Deng, L., Lyu, Q., He, S. L., Yi, S. L., Liu, Y. D., et al. (2016). Effects of citrus tree-shape and spraying height of small unmanned aerial vehicle on droplet distribution. *International Journal of Agricultural & Biological Engineering, 9*(4), 45–52.

Ru Y., Zhou, H., Fan, Q., & Wu, X. (2011). Design and investigation of ultra-low volume centrifugal spraying system on aerial plant protection. Paper No. 11-10663, St Joseph, MI, USA: ASABE.

Zhu, H., Salyani, M., & Fox, R. D. (2011). A portable scanning system for evaluation of spray deposit distribution. *Computers and Electronics in Agriculture, 76*(1), 38–43.