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Volume Rate Adjustment for Pesticide Applications against *Aonidiella aurantii* in Citrus: Validation of CitrusVol in the Growers' Practice

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Abstract: *Aonidiella aurantii* is one of the most damaging armored scales in citrus crops worldwide. To control this pest, high water volume rates are conventionally used. In order to rationalize the pesticide applications in citrus, IVIA developed CitrusVol, a tool that recommends the optimal volume rate based on the vegetation, the pest or disease and the active ingredient. In this study the objectives were: (i) validate CitrusVol as a tool to adjust the spray volume to control *A. aurantii* and (ii) quantify its environmental and economical advantages. For this, the spray volume adjusted with CitrusVol was compared with the one conventionally used by farmers in 18 applications in seven orchards during two years. The following parameters were evaluated: (i) spray distribution in the canopy, (ii) *A. aurantii* males trapped per day, and (iii) number of scales per fruit at harvest. CitrusVol reduced the spray volume and the amount of pesticide by 35% on average. Despite this reduction, a satisfactory spray distribution was achieved, and the volume was found to control the pest in a comparable way to the conventional volume. Moreover, CitrusVol saved per application and on average 31.25 h/100 ha of spray operating time, 241.83 L/100 ha of fuel consumption and consequently, the reduction of emissions of CO_2 was 631.18 kg/100 ha. Therefore, CitrusVol allows for efficient, low-input and low-impact pesticide applications.

Keywords: California red scale; coverage; airblast sprayer; spray application; efficacy; integrated pest management (IPM); OVRA tool; decision support tool

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1. Introduction

California red scale *Aonidiella aurantii* (Maskell) (Hemiptera: Diaspididae) is one of the most damaging armored scale insects in worldwide citrus growing and is considered a key pest in the Mediterranean region [1,2]. *A. aurantii* feeds on plant tissues and settles in all the organs of citrus canopies: fruit, leaves, twigs and branches. The main damage is aesthetic because the presence of scales in fruit downgrades its value for fresh consumption. Moreover, it can cause chlorotic spots, defoliation, fruit fall and drying of branches when population density is very high [3–7].

A. aurantii has several generations per year that are generally monitored using sticky traps to collect males during their flights. In the Mediterranean basin, the number of generations varies between three and four depending on temperature [8,9]. First instar nymphs, also known as crawlers, of the different generations infest citrus fruit between May and September settling down in small depressions of fruit skin [10,11]. Once settled, nymphs develop a wax scale that covers their body. Female scales molt twice before they reach the adult stage [7,12]. After several molts, male scales become winged adults that only live about six hours [6].

Nowadays, there are different strategies to manage *A. aurantii* in citrus that include augmentative biological control using the parasitic wasp *Aphytis melinus* Howard (Hymenoptera: Aphelinidae) [13]; conservation biological control of this parasitoid as well as generalist predators [14,15]; and mating disruption [16,17]. Despite the development of these environmentally friendly strategies, insecticides are still used to manage *A. aurantii* when population densities are very high. Chemical control of *A. aurantii* has several problems because it has developed resistance to some active ingredients and its scale protects the insect even from insecticides [18,19]. The most sensitive instar to insecticides is the first nymphal instar. Therefore, plant protection product (PPP) applications should be made when the proportion of this stage is maximum if the economical threshold has been exceeded. This usually occurs three-four times per year in the Mediterranean basin. The first and second maximums of crawlers at the end of May and end of July and beginning of August are generally more homogenous [11].

Since *A. aurantii* inhabits the inner part of citrus trees and overwinter in wood parts, high water volume rates are conventionally used to reach these areas of the tree and control the scale. However, several works have demonstrated that the volume of water sprayed per unit ground area (L/ha) can be reduced without compromising the efficacy of the treatment not only against *A. aurantii* [20–23], but also against other insect pests [20,24,25], mites [26–28], and fungal and bacterial diseases [29,30]. This reduction of water volume is important because it reduces the risk of drift and runoff and, therefore, the risk of insecticide contamination in non-target organisms of different trophic levels. For example, neonicotinoids occur in 93% of organic soils and crops that had not been treated with neonicotinoids for the last 10 years [31]. Moreover, the reduction of water volume also reduces the risk for human health, including farmers, bystanders and consumers. Currently there is a social and political commitment to reduce these risks, as stated in the European Green Deal [32].

This scenario is boosting strategies to improve the pesticide application through the adequate configuration and calibration of sprayers, implementation of drift reducing technologies, and utilization of optimal volume rate adjustment (OVRA) tools. These tools recommend a spray water volume for pesticide applications adjusted based on different parameters, such as: canopy characteristics, sprayer and active ingredient among others. In recent years, several tools for specific crops have been developed: "Apple Tree-row-volume Spraying Rate Calculator" for apples [33], "Dosage Adapté" for pome and stone fruits [34] and for vineyard [35], "Dosaviña" for vineyard [36], "CitrusVol" for citrus [37], "Dosaolivar" for olive trees [38], and more generic ones for three-dimensional crops such as "Dosa3D" [39]. In addition to reducing the environmental impact of insecticide applications, the use of OVRA tools results in economic benefit to farmers. Reducing the spray volume entails a lower use of pesticides and a lower number of refills of the sprayer tank and, therefore, a reduction in operating time and fuel consumption [37].

CitrusVol is an OVRA tool that recommends a spray volume (L/ha) according to the characteristics of the vegetation (canopy volume, planting pattern, vegetation density and pruning level), the target pest or disease and the active ingredient, for applications with airblast sprayers in adult citrus orchards. This tool calculates the minimum spray volume necessary to obtain the maximum efficacy, based on previous efficacy models determined under laboratory conditions [40,41]. CitrusVol has been validated to control the two-spotted spider mite *Tetranychus urticae* Koch (Acari: Tetranychidae) in the field [28]. This tool is freely available on its website (www.citrusvol.com).

The main objective of the current study was to validate the CitrusVol OVRA tool to control *A. aurantii* in citrus trees under field conditions. For this purpose, the spray distribution on the canopy and the efficacy of spray volume adjusted with CitrusVol was compared with the spray volume conventionally used by farmers in seven clementine orchards and during two consecutive years. Moreover, environmental and economical advantages due to the use of CitrusVol were quantified.

2. Materials and Methods

2.1. Experimental Plots

Field trials were conducted in seven commercial clementine orchards (*Citrus clementina* Hort. *ex* Tan.) of two varieties: "Oronules" (plot P2) and "Clemenules" (the other six plots); during two years (2016 and 2017). Plots were located in Valencia province (eastern Spain) (Figure 1). Canopy dimensions, vegetation density and other characteristics of the experimental plots are shown in Table 1.

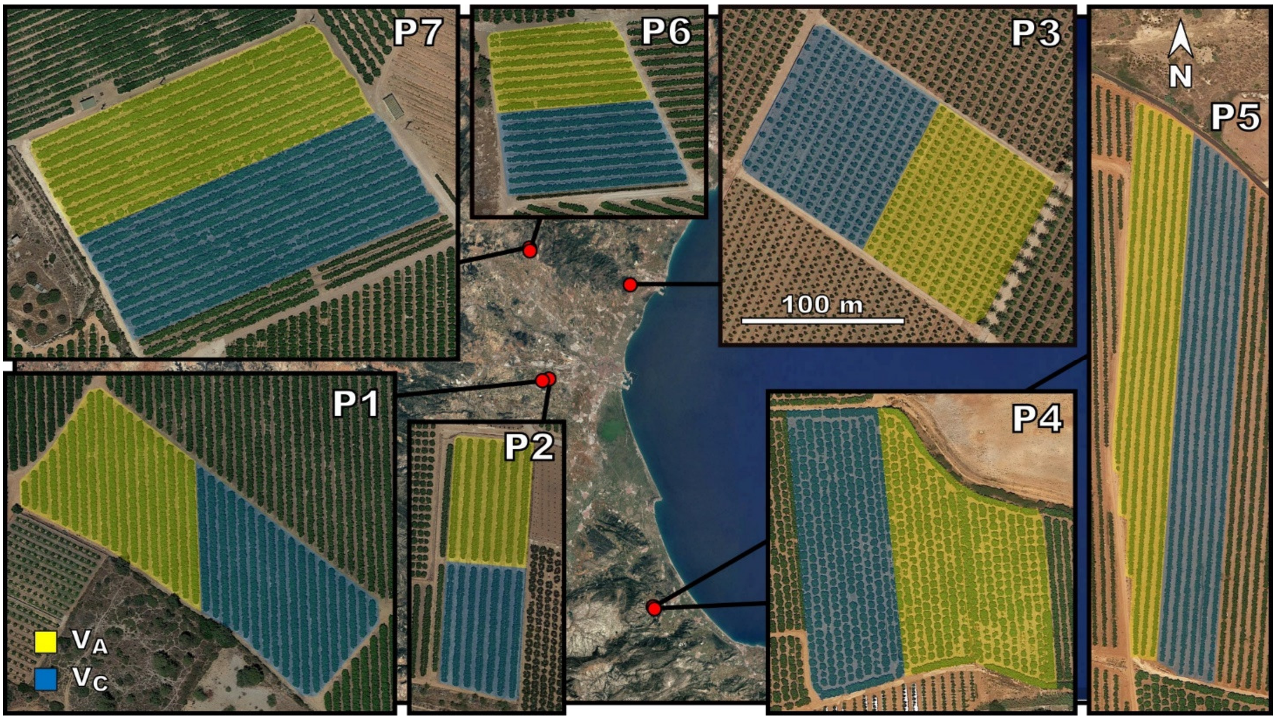

Figure 1. Location and maps of the seven experimental plots (P1–P7). The V_C (conventional volume) block is blue shaded and the V_A (adjusted volume) block is yellow shaded. Date of satellite images: 5 July 2016; source: Google Earth Pro 7.3.2. Geographic coordinates: P1 (39°26′32″ N, 0°33′23″ W), P2 (39°26′43″ N, 0°32′18″ W), P3 (39°39′14″ N, 0°18′26″ W), P4 (38°56′46″ N, 0°14′15″ W), P5 (38°56′56″ N, 0°14′32″ W), P6 (39°43′43″ N, 0°35′28″ W) and P7 (39°43′58″ N, 0°35′33″ W).

Table 1. Characteristics of the experimental plots: area, planting pattern, vegetation density, canopy dimensions, canopy volume, TRV (tree row volume) and pruning level.

Plot	Area (ha)	Planting Pattern [1] (m)	Vegetation Density [2] (m^2/m^3)	Year	Canopy Dimensions [3] (m)	Canopy Volume [4] (m^3)	TRV [5] (m^3/ha)	Pruning Level
P1	1.6	6 × 3	13.56	2016	2.51 × 4.33 × 3.08	17.53	18,114	Normal
				2017	2.60 × 4.03 × 3.05	16.73	17,463	
P2	0.8	7 × 2	11.56	2016	2.12 × 4.26 × 2.30	10.88	12,902	Normal
				2017	2.04 × 3.70 × 2.19	8.66	10,783	
P3	1.7	6.5 × 5	10.36	2016	2.15 × 3.39 × 3.34	12.75	11,213	Severe
				2017	1.93 × 3.10 × 3.16	9.90	9205	
P4	2	5.5 × 5	14.55	2016	2.38 × 4.28 × 4.57	24.37	18,521	Normal
				2017	2.19 × 4.17 × 4.40	20.99	16,604	
P5	2.2	6 × 2	13.46	2016	1.99 × 2.93 × 1.96	5.98	9718	Without pruning
				2017	2.08 × 2.85 × 2.10	6.50	9880	Normal
P6	1	6.5 × 2.5	15.09	2016	2.47 × 3.90 × 2.60	13.11	14,820	Normal
P7	2.7	6.5 × 3.5	17.94	2016	2.45 × 4.84 × 3.70	22.97	18,243	Severe
				2017	2.43 × 4.74 × 3.72	22.49	17,720	Normal

[1] Row spacing × tree spacing. [2] Area of leaves per unit of canopy volume calculated considering the two sides of the leaves and following the methodology of Fonte et al. [28]. [3] Canopy height × diameter across the row × diameter along the row, measured with the methodology indicated in Fonte et al. [28]. [4] Calculated considering citrus canopy as an ellipsoid according to the equation: canopy volume (m^3) = $\pi/6$ × canopy height (m) × diameter across the row (m) × diameter along

the row (m). [5] Tree Row Volume, calculated with the equation: TRV (m^3/ha) = canopy height (m) × diameter of the canopy across the row (m) × 10,000 / row spacing (m).

2.2. Experimental Design

The studied independent variable was the spray volume, with two levels: (i) conventional volume (V_C), which is the spray volume commonly used by the technicians of the orchards; and (ii) adjusted volume (V_A), which is the spray volume recommended by CitrusVol tool based on tree characteristics, target pest and active ingredient. Each plot was divided in two blocks of similar size (between 0.4 and 1.35 ha, depending on the plot (Figure 1)). In each block, a different spray volume was applied, V_C or V_A. The response variables were: (i) spray distribution in the canopy, (ii) *A. aurantii* males trapped per day, and (iii) number of scales per fruit at harvest.

In the seven experimental plots (P1–P7) and throughout the two years (2016 and 2017), a total of 18 applications against *A. aurantii* were carried out.

2.3. Sprayers and Spray Applications

The airblast sprayers and the nozzles used to apply the PPPs in the different plots are shown in Table 2.

Table 2. Airblast sprayers used in the applications.

Plot	Year	Airblast Sprayer	Tank Capacity (L)	Number of Nozzles	Trademark and Model of Nozzles	Type of Fan	Fan Diameter (cm)	Air-Jet Emission System
P1 & P2	2016 & 2017	Ilemo-Hardi Arrow XF90	1500	38	Hardi 1553	Axial	92	Circular
P3	2016 & 2017	Mañez y Lozano Twister	2000	30	Albuz TVI	Axial	92	Triangular
P4 & P5	2016	Marisan Duplex Tornado	2000	36	Albuz AMT	Double (axial and inverted)	90	Circular
	2017	Fede Futur	1000	26	TeeJet Disc-Core	Axial	90	Circular
P6 & P7	2016 & 2017	Fede Futur	3000	26	Hardi 1553	Axial	90	Circular

The application parameters were selected by the technicians of the orchards, considering the good agricultural practices [42]: working pressure, forward speed, air flow rate, trademark and model of nozzles. In all cases cone spray nozzles were used as it is recommended for citrus (Table 2). These parameters were used for both treatments (V_A and V_C) (Table 3).

Prior to the spray applications, all the sprayers were calibrated (forward speed, air flow rate, working pressure and the nozzle flow rate). The conventional volume (V_C) was calculated based on the results of the calibration of the sprayer and its set up used by the technician in each orchard (Table 3).

The adjusted volume (V_A) to be used in each application (Table 3) was calculated using the CitrusVol tool. For this, the following characteristics were selected:

- **Foliar density:** Medium;
- **Pruning level:** Normal, Severe or Without pruning (based on Table 1);
- **Pest/disease:** Armored scales (California red scale, oleander scale…);
- **Product:** the active ingredient used in each case (see Table A1 of Appendix A).

V_A resulted always lower than V_C, therefore, the reduction of the spray volume between V_C and V_A was achieved following two steps; first, the spray cloud was adjusted to the canopy shape of the orchard, by orienting or even closing the unnecessary nozzles, in order to reduce both drift (top nozzles) and losses to the soil (bottom nozzles). Secondly, some nozzles with lower nominal flow rate (same trademark and model but different orifice diameter) were selected to get the adjusted volume. Therefore, part of the reduction of the spray volume was due to the decrease of the number of working nozzles. The other part, due to the reduction of the diameter of the nozzle, was attempted to be the minimum possible (Table 3).

Table 3. Operative characteristics of spray applications.

Plot	Application Date	Working Pressure (bar)	Forward Speed (km/h)	Air Flow Rate (m^3/h)	Number of Open Nozzles		Water Volume (L/ha)		Spray Volume Reduction and PPP Saving (%)
					V_C	V_A	V_C	V_A	
P1	27 May 2016	8	1.32	55,342	38	30	4905	3255	33.64
	27 July 2016	8	1.32	55,342	38	30	4905	3255	33.64
	7 June 2017	8	1.32	74,894	38	30	4899	3487	28.82
	8 September 2017	8	1.32	74,894	38	30	4899	3153	35.64
P2	26 May 2016	8	1.32	55,342	38	28	4204	2800	33.40
	9 August 2016	8	1.32	55,342	38	28	4204	2800	33.40
	22 August 2017	8	1.32	74,894	38	30	4199	2070	50.70
P3	9 June 2016	13	1.75	101,248	26	18	3264	2294	29.72
	23 June 2017	13	2.01	46,467	26	18	3395	1461	56.97
P4	31 May 2016	9	1.92	54,828	34	14	7311	3011	58.82
	26 June 2017	10	1.96	69,385	26	18	4262	2998	29.66
P5	31 May 2016	9	1.92	54,828	34	18	6702	1737	74.08
	27 June 2017	10	1.96	69,385	24	16	3674	1811	50.71
P6	13 June 2016	8	1.53	89,268	26	22	3201	2535	20.81
	12 August 2016	8	1.48	89,268	26	22	3318	2628	20.80
P7	14 June 2016	8	1.53	89,268	26	26	3468	3065	11.62
	11 August 2016	8	1.48	89,268	26	26	3595	3177	11.63
	30 June 2017	10	1.42	82,644	26	26	3932	3290	16.33

V_C: conventional volume; V_A: adjusted volume. PPP: plant protection product.

PPPs were selected by the technicians and were applied at the label concentration. The same product and concentration were used for both treatments (V_A and V_C) in each application (Table A1 (Appendix A)).

The technicians decided the timing for each application based on accumulated degree-days with a development threshold temperature of 11.7 °C. Figure A1 (Appendix A) shows the accumulated degree-days in the seven plots, the treatment thresholds for the first, second and third generation, and the application dates for each plot and both years.

Weather conditions during spray applications are shown in Table A2 (Appendix A).

2.4. *Effects on Spray Distribution on the Canopy*

The effect of spray volume on spray distribution in different zones of the vegetation (height, width, depth and side of the leaf) was estimated through the percentage of coverage on water sensitive papers (WSPs) of 76 mm × 26 mm (Syngenta International AG, Basel, Switzerland).

Coverage (%) was evaluated once per plot and year. In plot P6 in 2017, no applications were carried out, therefore, a total of 13 coverage evaluations were performed. Estimation was conducted in three randomly selected trees per block (V_A and V_C). Before spraying, 72 WSPs per tree were placed in the 18 quadrants in which the canopy was divided (combination of three heights, three widths and two depths; Figure 2). In Plot P3, there were only 12 quadrants, because only two heights were considered due to the small size of the canopies and the severe pruning. In each canopy quadrant, four WSPs were randomly stapled: two on the upperside of the leaves and two on the underside.

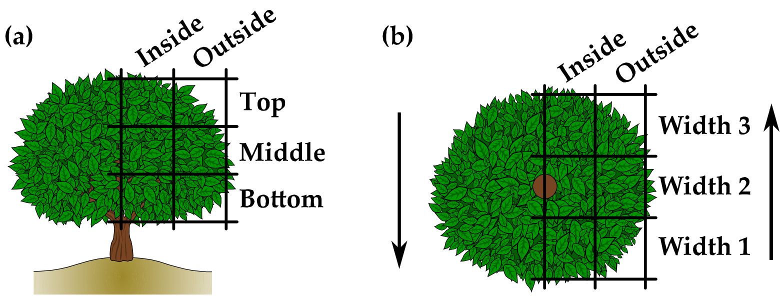

Figure 2. Quadrants of the canopy where water sensitive papers were placed. (**a**) Side view across the row and (**b**) top view of a standard citrus tree. Arrows indicate the forward direction of the airblast sprayer.

After the spray application and once the WSPs had dried, they were collected. Once in the laboratory, they were photographed with a Canon EOS 700D digital camera (Canon Inc., Tokyo, Japan) under steady light conditions. A digital image of 900 × 350 pixels was generated for each WSP and it was analysed using self-developed software based on Food-Color Inspector [43] to obtain the percentage of coverage. Previously, the program was trained to designate blue range colours of the images as impacted drops and yellow and green range colours as background. Then, the program counted the number of pixels assigned as drops and calculated the percentage they represented respect to the total pixels.

The meteorological conditions during the coverage evaluations are shown in Table A2 (Appendix A).

2.5. Effects on Control of A. aurantii

2.5.1. Monitoring of *A. aurantii* Male Flight

The male flight monitoring is used to check the number of generations of *A. aurantii* per year and in this work it was used to study the seasonal trend of *A. aurantii* in each block and evaluate the applicability of this parameter to study the differences between the two applied volume rates.

It was determined using pheromone dispensers that attract males (product code: PH-057-1RR; Russell IPM Ltd., Deeside, Flintshire, UK). The lure was placed in the center of a white paper adhesive plate protected inside a delta trap (Koppert BV, Berkel en Rodenrijs, The Netherlands). Five traps were uniformly distributed in each treatment block of the plot, and each trap was placed at a medium height inside canopies. The sticky traps were changed fortnightly (and before the PPP applications) between April and October, and the lures were renewed every forty or fifty days. The number of *A. aurantii* males, within an area of 18 cm × 16 cm, was counted in the laboratory using a stereo microscope. Then, based on the number of days the trap had been exposed in the field, the number of *A. aurantii* males per day was calculated.

2.5.2. Number of *A. aurantii* per Fruit

At harvest, 10 trees per block were randomly selected per plot and year. In each tree, 40 fruits evenly distributed in the four cardinal directions (north, south, east and west) and in from inside and outside of the canopy were sampled. In the plots where the tree row formed a hedge (all plots except P3 and P4), with the canopy of adjacent trees touching one another, all the fruits on the tree faces in contact with adjacent trees were considered fruits of the inside of the canopy. In each fruit, the number of *A. aurantii* scales was counted.

Furthermore, in Spain, the economic threshold for the first generation of *A. aurantii* is 2% of infested fruit in the previous season. Infested fruit is considered to have more than three scales per fruit [44]. Therefore, percentage of cull fruit due to California red scale was calculated for each treatment and orchard.

2.6. Economic and Environmental Advantages with CitrusVol

For each plot, the average transit time of the equipment from the center of the plot to the water fill point was measured. On the other hand, the filling time of various tanks in various plots was measured, and an average value of $9.92 \cdot 10^{-5}$ h per liter of tank was obtained. Therefore, the tank refill time (h), including filling time and equipment transit time to and from the water sources, was calculated for each plot and equipment used.

Subsequently, depending on the spray volume applied in each treatment (V_C and V_A) and the capacity of the tank of the sprayer used, the number of tanks necessary to carry out each spray application per unit area was estimated (rounding up to the nearest integer). Then the time savings of tank refill per unit area due to the use of the adjusted volume was calculated. Economic and environmental savings were calculated from these values.

The cost saving due to the service of PPP application with operator (which includes the operator working time and the use of the sprayer, not including the cost of the PPP) was calculated considering an average cost of 33 €/h for the service [45].

The savings in fuel was calculated assuming an average tractor consumption during refill of 10.5 L/h [46] and average price of gasoil B of 0.821 €/L [47].

The reduction of CO_2 emissions was calculated from the reduction of fuel consumptions and knowing that 1 L of diesel fuel consumption produces a CO_2 emission of 2.61 kg [48].

2.7. Data Analysis

A one-way analysis of variance (ANOVA) was carried out to study the effect of spray volume on coverage in each of the 12 canopy zones (combination of three heights, two depths and two leaf sides) considering the 13 coverage evaluations together. For that, coverage in each canopy zone was calculated as the average of the three widths per tree, and the mean coverage of the three replicates per evaluation, corresponding to the three trees per block was used.

Furthermore, a one-way ANOVA was done to study the effect of spray volume on coverage for each of the 13 evaluations (combination of plot and year), and per depth (inside/outside). In this way the results can be compared with the number of scales per fruit that were measured in the two depths.

In all analyses, the homogeneity of the variances was verified by the Levene test and the normality was checked by normal probability plot of the residuals. The Fisher's least significant difference (LSD) test was applied to study the mean differences.

The effect of spray volume on the number of scales per fruit for each depth and year, considering the plots as repetitions, was analyzed using a nonparametric Kruskal-Wallis test because the assumption of normality was not fulfilled. Moreover, a descriptive analysis in each plot and year, and per depth, was performed.

The confidence level considered in all the statistical analyses was 95%.

3. Results

3.1. Effects on Spray Distribution on the Canopy

When the percentage of coverage was compared between spray volumes in 12 canopy zones considering the average result of the 13 evaluations, the coverage was not significantly different between the conventional volume (V_C) and the adjusted volume (V_A) ($p > 0.05$) except in four zones of the canopy, three of them in the top, where coverage was significantly higher for V_C than for V_A (Figure 3) (top-outside-upperside ($F = 9.09$; df = 1, 25; $p = 0.006$), top-outside-underside ($F = 9.92$; df = 1, 25; $p = 0.0043$), top-inside-upperside ($F = 6.61$; df = 1, 25; $p = 0.0168$) and middle-outside-underside ($F = 4,59$; df = 1, 21; $p =$

0.0447)). Nevertheless, the average coverage values for both volumes were higher than 30%. Regardless the spray volume used, the coverage was higher on the outside of the canopy than on the inside, at the three canopy heights and on both sides of the leaves. On the outside of the canopy, the medium height was the one that got the highest coverage, while on the inside, the bottom height was the zone with the highest coverage. The upperside of the leaves had higher coverage than the underside, at both depths, although this difference was more pronounced inside the canopy.

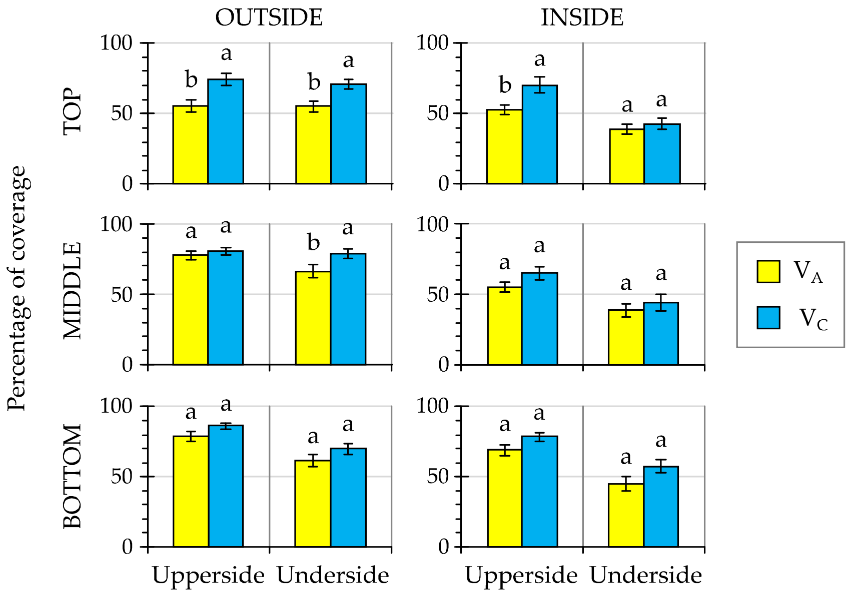

Figure 3. Spray coverage (%) (mean value with standard error bar) obtained on the upperside and underside of leaves at three heights (top, middle, bottom) of the outside and inside parts of clementine tree canopies after application of conventional (V_C) and adjusted (V_A) volume rates considering the 13 evaluations in the orchards on seven locations over the years 2016 and 2017. Different letters above the bars within each height × depth × leaf side combination indicate significant differences (LSD test, $p < 0.05$).

In the analysis of the effect of spray volume on coverage for each of the 13 applications using the three trees per plot as replicate, the results, differentiating by canopy depth, showed that the differences on coverage between V_C and V_A were not significant in most of the cases except in four cases (Figure 4) where higher coverage was obtained with V_C: P1 2017 outside ($F = 16.58$; df = 1, 5; $p = 0.0152$), P2 2017 outside ($F = 19.16$; df = 1, 5; $p = 0.0119$), P3 2017 outside ($F = 12.03$; df = 1, 5; $p = 0.0256$) and P4 2017 outside ($F = 33.95$; df = 1, 5; $p = 0.0043$) and inside ($F = 9.59$; df = 1, 5; $p = 0.0364$).

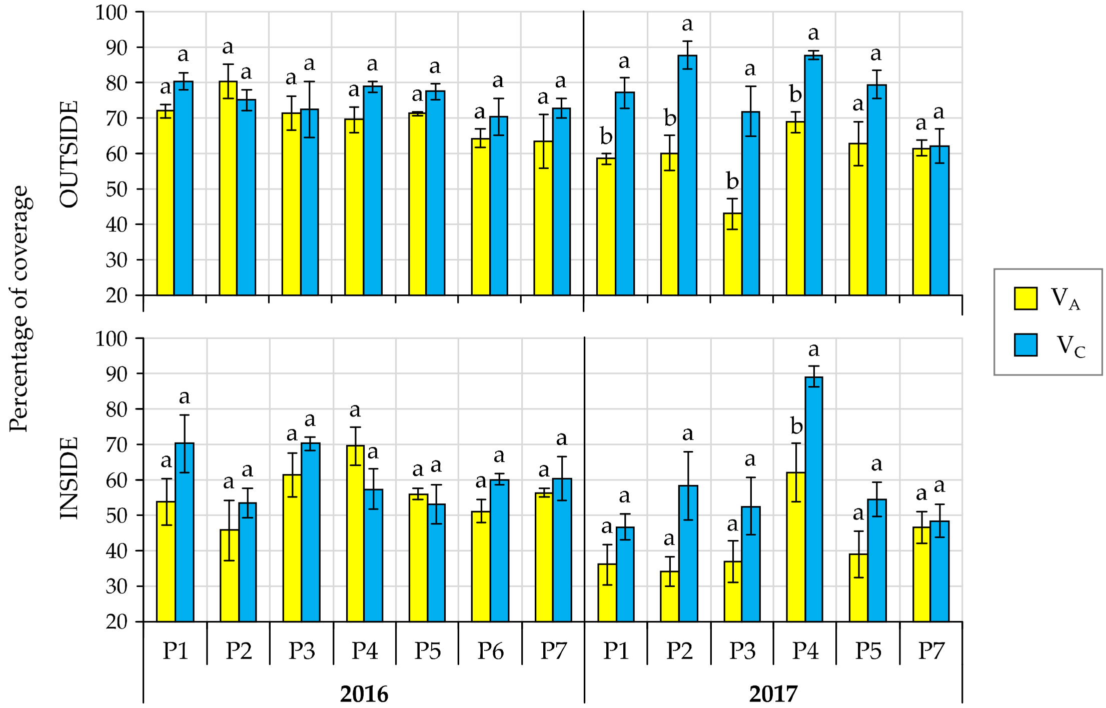

Figure 4. Spray coverage (%) (mean value with standard error bar) obtained on the outside and inside parts of clementine tree canopies after application of conventional (V_C) and adjusted (V_A) volume rates in each orchard on different locations (P1–P7) over the years 2016 and 2017. Different letters above the bars for each coverage evaluation indicate significant differences (LSD test, $p < 0.05$).

3.2. Effects on Control of A. aurantii

3.2.1. Monitoring of *A. aurantii* Male Flight

The number of *A. aurantii* males caught with pheromone traps per day in each plot in 2016 was very low between April and May in all the blocks (Figure 5). The number of *A. aurantii* males began to increase in June. The highest mean number of males trapped was 800.15, and it was obtained in the block treated with V_C in plot P7 between June 14 and July 1. After the summer, the number of males began to decrease in most of the plots. When comparing between treatments, there was not a clear trend, while the density of *A. aurantii* males was similar for both V_C and V_A in some orchards (P3 and P5), others had higher densities in some blocks indistinctively of the treatment. Therefore, this parameter was not considered useful to determine differences between different spray volumes and in 2017 the traps were not evaluated.

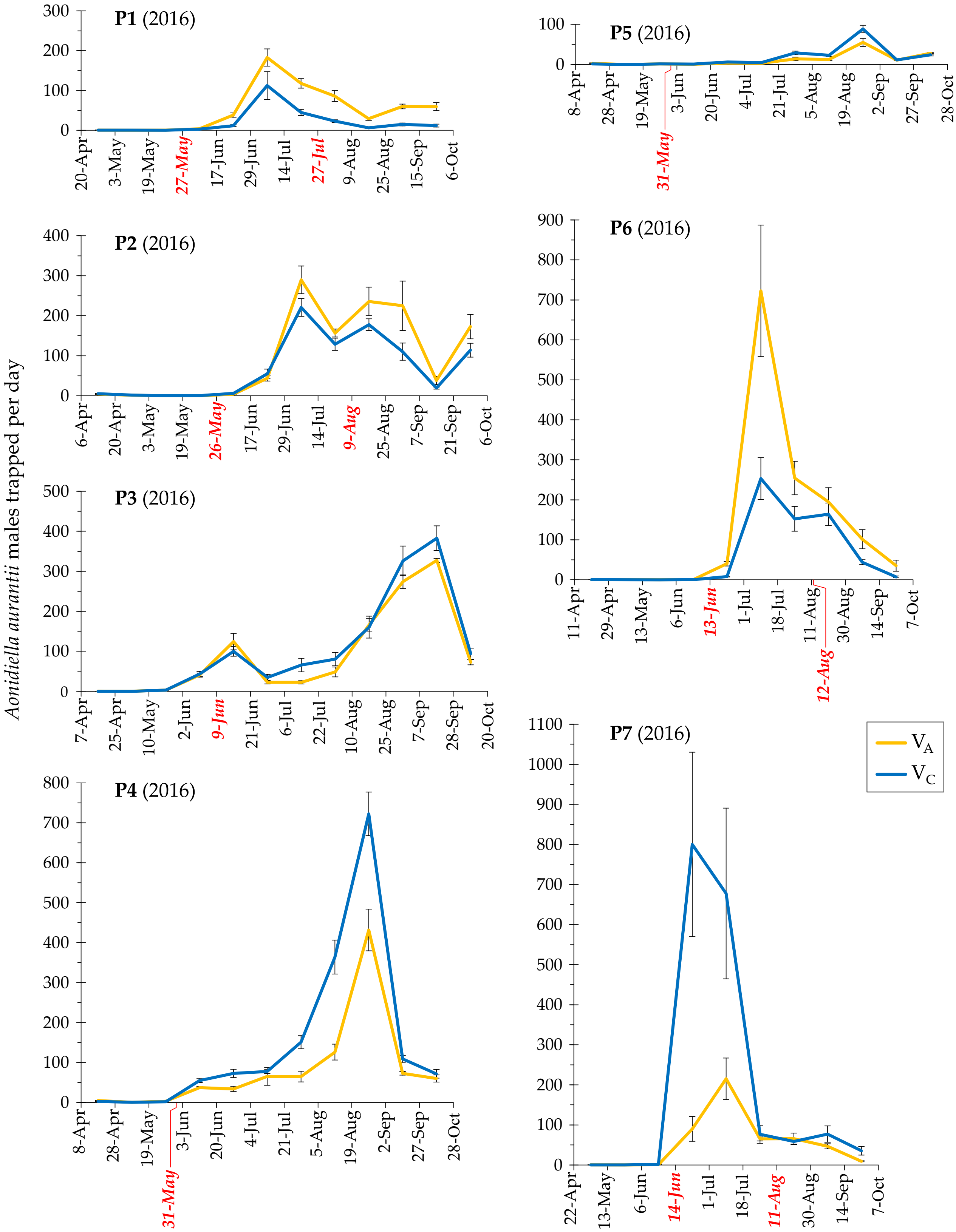

Figure 5. Number of *Aonidiella aurantii* males trapped on sticky traps per day (mean value with standard error bar) for each treatment (VA: adjusted volume, VC: conventional volume) and for the seven plots (P1–P7) between April and October 2016. The x-axis shows the dates the traps were placed/removed. Dates in red indicate spray applications against *A. aurantii*.

3.2.2. Number of *A. aurantii* per Fruit

The mean number of *A. aurantii* scales per fruit at harvest, considering the plots as repetitions, was similar in trees treated with the adjusted or conventional volume in both depths of the canopy and in both years (Kruskal-Wallis test, 2016: outside: $p = 0.38$, inside: $p = 1$; 2017: outside: $p = 0.74$, inside: $p = 0.32$) (Figure 6).

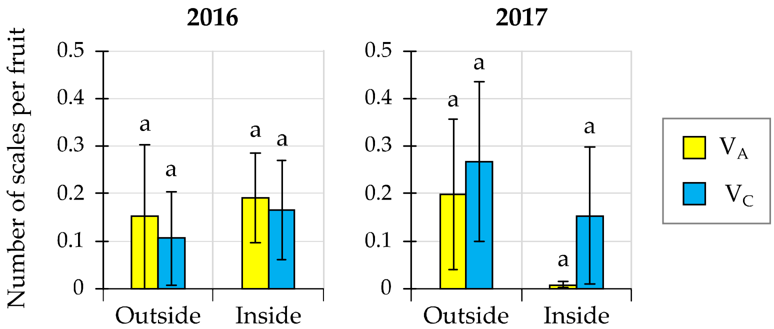

Figure 6. Number of *Aonidiella aurantii* scales per fruit (mean value with standard error bar) at two depths of the canopy (outside, inside), for both treatments (V_A: adjusted volume, V_C: conventional volume) and two years (2016 and 2017) considering the plots (P1–P7) as repetitions. Different letters above the bars indicate significant differences (Kruskal-Wallis test, $p < 0.05$).

In all orchards and in both years, the mean number of scales per fruit for both spray volumes was very low (Figure 7).

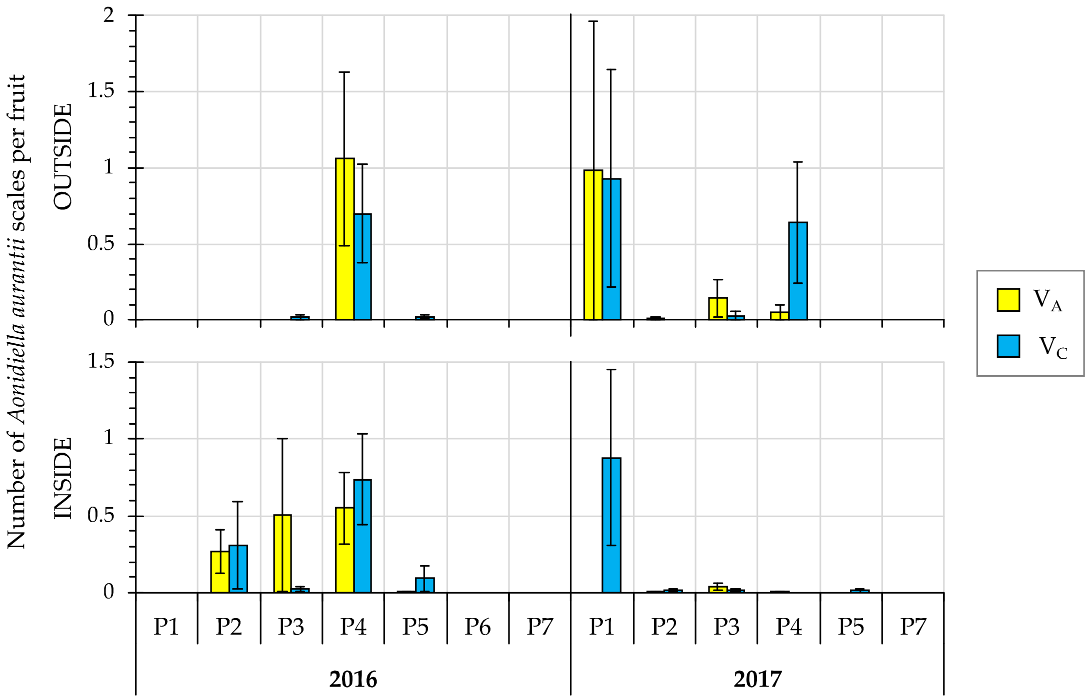

Figure 7. Number of *Aonidiella aurantii* scales per fruit (mean value with standard error bar) at two depths of the canopy (outside, inside), in function of the treatment (V_A: adjusted volume, V_C: conventional volume), for each plot (P1–P7) and year (2016 and 2017).

Furthermore, in all orchards and in both years, the percentage of cull fruit with more than three *A. aurantii* scales per fruit was in general similar for both spray volumes (Figure 8).

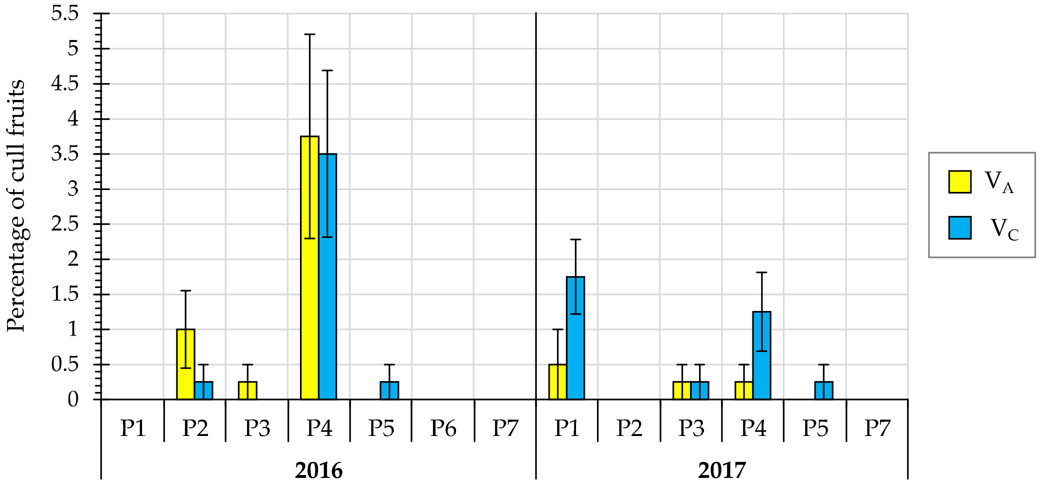

Figure 8. Cull fruit (%) with more than three *Aonidiella aurantii* scales per fruit (mean value with standard error bar), in function of the treatment (V_A: adjusted volume, V_C: conventional volume), for each plot (P1–P7) and year (2016 and 2017).

3.3. Economic and Environmental Advantages with CitrusVol

The time savings of tank refill for each spray application for 1, 10 and 100 hectares are shown in Table 4. Application time decreased when the volume was adjusted with CitrusVol and these differences were higher when the treated surface increased. For an area of 1 ha, the range of time saving per PPP application using CitrusVol in the plots tested was between 0 and 1.17 h, and on average 0.34 h. Meanwhile, for an area of 10 ha, the use of CitrusVol would save between 0.42 and 9.77 h, and on average 3.12 h, and for an area of 100 ha, the use of CitrusVol would save between 5.42 and 97.36 h, and on average 31.25 h (Table 4).

Table 4. Tank refill time for each equipment and orchard, and time savings of tank refill with CitrusVol for each spray application for 1, 10 and 100 hectares.

Plot	Application Date	Water Volume (L/ha)		Sprayer Tank Capacity (L)	Tank Refill Time [1] (h)	Number of Tanks/ha		Time Savings of Tank Refill (h/ha)	Number of Tanks/10 ha		Time Savings of Tank Refill (h/10 ha)	Number of Tanks/100 ha		Time Savings of Tank Refill (h/100 ha)
		V_C	V_A			V_C	V_A		V_C	V_A		V_C	V_A	
P1	27 May 2016	4905	3255	1500	0.27	4	3	0.27	33	22	2.96	327	217	29.58
	27 July 2016	4905	3255			4	3	0.27	33	22	2.96	327	217	29.58
	7 June 2017	4899	3487			4	3	0.27	33	24	2.42	327	233	25.28
	8 September 2017	4899	3153			4	3	0.27	33	22	2.96	327	211	31.20
P2	26 May 2016	4204	2800	1500	0.30	3	2	0.30	29	19	2.98	281	187	28.02
	9 August 2016	4204	2800			3	2	0.30	29	19	2.98	281	187	28.02
	22 August 2017	4199	2070			3	2	0.30	28	14	4.17	280	138	42.33
P3	9 June 2016	3264	2294	2000	0.34	2	2	0.00	17	12	1.68	164	115	16.51
	23 June 2017	3395	1461			2	1	0.34	17	8	3.03	170	74	32.34
P4	31 May 2016	7311	3011	2000	0.35	4	2	0.70	37	16	7.33	366	151	75.06
	26 June 2017	4262	2998	1000	0.25	5	3	0.50	43	30	3.25	427	300	31.74
P5	31 May 2016	6702	1737	2000	0.39	4	1	1.17	34	9	9.77	336	87	97.36
	27 June 2017	3674	1811	1000	0.29	4	2	0.58	37	19	5.25	368	182	54.27
P6	13 June 2016	3201	2535	3000	0.46	2	1	0.46	11	9	0.93	107	85	10.19
	12 August 2016	3318	2628			2	1	0.46	12	9	1.39	111	88	10.65
P7	14 June 2016	3468	3065	3000	0.42	2	2	0.00	12	11	0.42	116	103	5.42
	11 August 2016	3595	3177			2	2	0.00	12	11	0.42	120	106	5.84
	30 June 2017	3932	3290			2	2	0.00	14	11	1.25	132	110	9.17

[1] Including filling time and equipment transit time to and from the water sources. V_C: conventional volume; V_A: adjusted volume.

The cost savings per spray application due to, in the one hand, the reduction of PPP application service, and on the other hand, the reduction of fuel consumption, and also the CO_2 emissions reduction are shown in Table 5. Regarding the cost savings of PPP application service using CitrusVol in the plots tested, for an area of 1 ha, the range was between 0 and 30.46€, and on average 8.44€; for an area of 10 ha, the use of CitrusVol would save between 11.01 and 253.82€, and on average 75.91€; and for an area of 100 ha, the use of CitrusVol would save between 143.11 and 2582.02€, and on average 760.05€. Regarding the savings of fuel consumption and its cost, for an area of 1 ha, the range was between 0 and 9.69 L (2.69 L on average) that suppose a cost of 0 and 7.96€, and on average 2.21€; for an area of 10 ha, the use of CitrusVol would save between 3.50 and 80.76 L (24.15 L on average) that suppose a cost of 2.88 and 66.30€, and on average 19.83€; and for an area of 100 ha, the use of CitrusVol would save between 45.53 and 804.37 L (241.83 L on average) that suppose a cost of 37.38 and 660.39€, and on average 198.55€. Finally, regarding the reduction of CO_2 emissions, for an area of 1 ha, the range was between 0 and 25.29 kg CO_2, and on average 7.01 kg CO_2; for an area of 10 ha, the use of CitrusVol would reduce the emission of between 9.14 and 210.78 kg CO_2, and on average 63.04 kg CO_2; and for an area of 100 ha, the use of CitrusVol would reduce between 118.85 and 2099.41 kg CO_2 emitted to the environment, and on average 631.18 kg CO_2 (Table 5).

Furthermore, it has to be taken into account that the percentage of reduction of cost of PPP and of reduction of direct emissions of PPP to the environment are the same reduction percentage of water volume, that is, between 11.62% and 74.08%, with an average of 35.02%, because PPPs are mixed based on concentration.

Table 5. Economic and environmental advantages per each orchard with CitrusVol for each spray application for 1, 10 and 100 hectares.

Plot	Application Date	Cost Savings of PPP Application Service [1] (€/ha)	Cost Savings of Fuel Consumption (€/ha)	CO_2 Emission Reduction of Diesel B (kg CO_2/ha)	Cost Savings of PPP Application Service [1] (€/10 ha)	Cost Savings of Fuel Consumption (€/10 ha)	CO_2 Emission Reduction of Diesel B (kg CO_2/10 ha)	Cost Savings of PPP Application Service [1] (€/100 ha)	Cost Savings of Fuel Consumption (€/100 ha)	CO_2 Emission Reduction of Diesel B (kg CO_2/100 ha)
P1	27 May 2016	6.12	1.60	5.09	67.37	17.60	55.95	673.70	175.99	559.48
	27 July 2016	6.12	1.60	5.09	67.37	17.60	55.95	673.70	175.99	559.48
	7 June 2017	6.12	1.60	5.09	55.12	14.40	45.78	575.71	150.39	478.10
	8 September 2017	6.12	1.60	5.09	67.37	17.60	55.95	710.45	185.59	590.00
P2	26 May 2016	7.09	1.85	5.89	70.88	18.52	58.86	666.29	174.05	553.32
	9 August 2016	7.09	1.85	5.89	70.88	18.52	58.86	666.29	174.05	553.32
	22 August 2017	7.09	1.85	5.89	99.23	25.92	82.41	1006.52	262.93	835.87
P3	9 June 2016	0.00	0.00	0.00	41.84	10.93	34.75	410.06	107.12	340.53
	23 June 2017	8.37	2.19	6.95	75.32	19.67	62.55	803.38	209.86	667.17
P4	31 May 2016	17.54	4.58	14.57	184.19	48.12	152.96	1885.79	492.62	1566.06
	26 June 2017	11.00	2.87	9.13	71.47	18.67	59.35	698.20	182.39	579.83
P5	31 May 2016	30.46	7.96	25.29	253.82	66.30	210.78	2528.02	660.39	2099.41
	27 June 2017	13.76	3.59	11.43	123.83	32.35	102.83	1279.54	334.25	1062.60

P6	13 June 2016	12.53	3.27	10.40	25.06	6.55	20.81	275.63	72.00	228.90
	12 August 2016	12.53	3.27	10.40	37.59	9.82	31.21	288.16	75.27	239.30
P7	14 June 2016	0.00	0.00	0.00	11.01	2.88	9.14	143.11	37.38	118.85
	11 August 2016	0.00	0.00	0.00	11.01	2.88	9.14	154.12	40.26	127.99
	30 June 2017	0.00	0.00	0.00	33.03	8.63	27.43	242.18	63.27	201.12

[1] Not including the PPP reduction cost. PPP: plant protection product.

4. Discussion

The use of CitrusVol reduced the spray volume used to control *A. aurantii* by between 11.62% and 74.08% with an average of 35.02%. This reduction of volume implied a reduction in the coverage in some parts of the tree canopy mainly in the top but it was enough to control the number of *A. aurantii* scales per fruit at harvest outside and inside the canopy. These results are in line with previous studies where the reduction of spray volume up to optimal volume, did not decrease the effectiveness of the application against *A. aurantii* [20–23,49] and other citrus pests such as citrus mealybug *Planococcus citri* Risso [20], citricola scale *Coccus pseudomagnoliarum* (Kuwana) [24], Asian citrus psyllid *Diaphorina citri* Kuwayama and citrus leafminer *Phyllocnistis citrella* Stainton [25], and citrus rust mite *Phyllocoptruta oleivora* (Ashmead) [26,27]. The mean number of scales per fruit was very low in most of the cases, in spite of the number of males trapped per day, which showed maximum values between 100 and 800. These values, in Spanish conditions, indicate that the density of *A. aurantii* population was not low. Therefore, the low number of scales per fruit at harvest was likely due to the high efficacy of both conventional and adjusted volume.

The efficacy of an application depends on how the PPP is distributed on the tree, rather than on the amount of water volume applied itself [24]. It is acknowledged that the spray volume play an important role on the distribution of the spray on the canopy but increasing the spray volume does not always imply better results in terms of efficacy. Once the efficacy limit is reached, increasing spray volumes and coverage is meaningless. Therefore, the most important is to get a minimum coverage in the area of the canopy where the target pest is located, increasing the efficiency of the applications. In the case of *A. aurantii* applications must reach the inner part of the tree, and the minimum coverage to be achieved depends on the PPP and the pest stage, and in general terms, it should be between 20–40% [21]. In this study, the reduction of the spray volume did not greatly affected the distribution, because it was observed that, regardless the spray volume used (conventional or adjusted), a satisfactory spray distribution was achieved, and in both cases it followed the common pattern got with air blast sprayers in citrus: less coverage on the top and inside the canopy and on the underside of leaves, which is the surface least exposed to the application [50–52]. The reduction of spray volume only produced differences in the top of the canopy, but it is important to highlight that in all cases the minimum coverage necessary to control the pest was achieved, which will support the results obtained in the efficacy evaluations.

The male flight monitoring, although it is used to monitor the number of generations of *A. aurantii* per year, was not useful to determine potential differences between treatments in our study. No clear trend was observed in 2016 and, therefore, this method was not used in the following year.

In Spain, as in other countries of the southern European Union regulatory zone (including Bulgaria, Cyprus, France, Greece, Italy, Malta and Portugal), the dose expression in PPP instructions labels for three-dimensional crops such as citrus, is mainly expressed as concentration (%, rate/hL) and/or as the maximum dose of product per hectare in each application [53,54]. Consequently, a reduction of the spray water volume results in a reduction of applied dose of pesticide per unit area because concentration is constant. Therefore, the use of concentration, as dose expression, together with the CitrusVol tool allows for increasing effectiveness of the PPP use in citrus.

Moreover, the cut down on spray volume rate is likely to reduce drift, leaching and run-off, and therefore to reduce PPP losses to the environment (atmosphere, soil and groundwater) [37,55]. As it has been shown, CitrusVol would allow an average reduction of 35% of PPP emissions to the environment. Moreover, the reduction on tractor use time due to the use of CitrusVol may decrease CO_2 emissions in 7.01 kg CO_2/application for 1 ha, 63.04 kg CO_2/application for 10 ha and 631.18 kg CO_2/application for 100 ha on average.

Together with the environmental advantages of CitrusVol, its use also represents economical advantages, because it likely reduces the use of PPP and fuel, and the working hours, due to the lowering of tank refills [37]. Time savings per spray application against *A. aurantii* may reach 0.34 h/application for 1 ha, 3.12 h/application for 10 ha and 31.25 h/application for 100 ha on average, which would imply that the cost of the PPP application service is reduced by 8.44€/application for 1 ha, 75.91€/application for 10 ha and 760.05€/application for 100 ha on average. Time savings would imply also a reduction in fuel cost, which could be reduced by 2.21€/application for 1 ha, 19.83€/application for 10 ha and 198.55€/application for 100 ha. The percentage of reduction of cost of PPP would be 35% on average. Since the cost of PPP applications, including PPP cost, PPP application service and fuel consumption, account for 10% of the production costs in mandarin crops in the Valencian Community (Spain) [56], farmers would increase the profitability of their farms using CitrusVol.

In conclusion, as it was demonstrated in real citrus production conditions, CitrusVol is a useful tool supporting the growers to adjust the spray volume rate for PPP applications against *A. aurantii* in citrus. Such adjustment allows for significant reduction of PPP use, saving on time, labour and fuel, as well as decreasing CO_2 emission during the crop protection practices.

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Appendix A

Table A1. Active ingredients of the plant protection products (PPPs) used in the spray applications against *Aonidiella aurantii*.

Plot	Application Date	Commercial PPP	Active Ingredient
P1	27 May 2016	Dursban 48 Promex	Chlorpyrifos Pyriproxyfen
	27 July 2016	Movento 150 O-Teq	Spirotetramat
	7 June 2017	Dursban 48	Chlorpyrifos
	8 September 2017	Reldan E	Chlorpyrifos-methyl
P2	26 May 2016	Dursban 48 Promex	Chlorpyrifos Pyriproxyfen
	9 August 2016	Movento 150 O-Teq	Spirotetramat
	22 August 2017	Movento 150 O-Teq	Spirotetramat
P3	9 June 2016	Movento 150 O-Teq	Spirotetramat
	23 June 2017	Movento 150 O-Teq	Spirotetramat
P4	31 May 2016	Movento Gold	Spirotetramat
	26 June 2017	Movento Gold	Spirotetramat
P5	31 May 2016	Clorifos 48 EC Atominal 10 EC	Chlorpyrifos Pyriproxyfen
	27 June 2017	Movento Gold	Spirotetramat
P6	13 June 2016	Dursban 48 Juvinal 10 EC	Chlorpyrifos Pyriproxyfen
	12 August 2016	Movento 150 O-Teq	Spirotetramat
P7	14 June 2016	Dursban 48 Juvinal 10 EC	Chlorpyrifos Pyriproxyfen
	11 August 2016	Movento 150 O-Teq	Spirotetramat
	30 June 2017	Movento 150 O-Teq	Spirotetramat

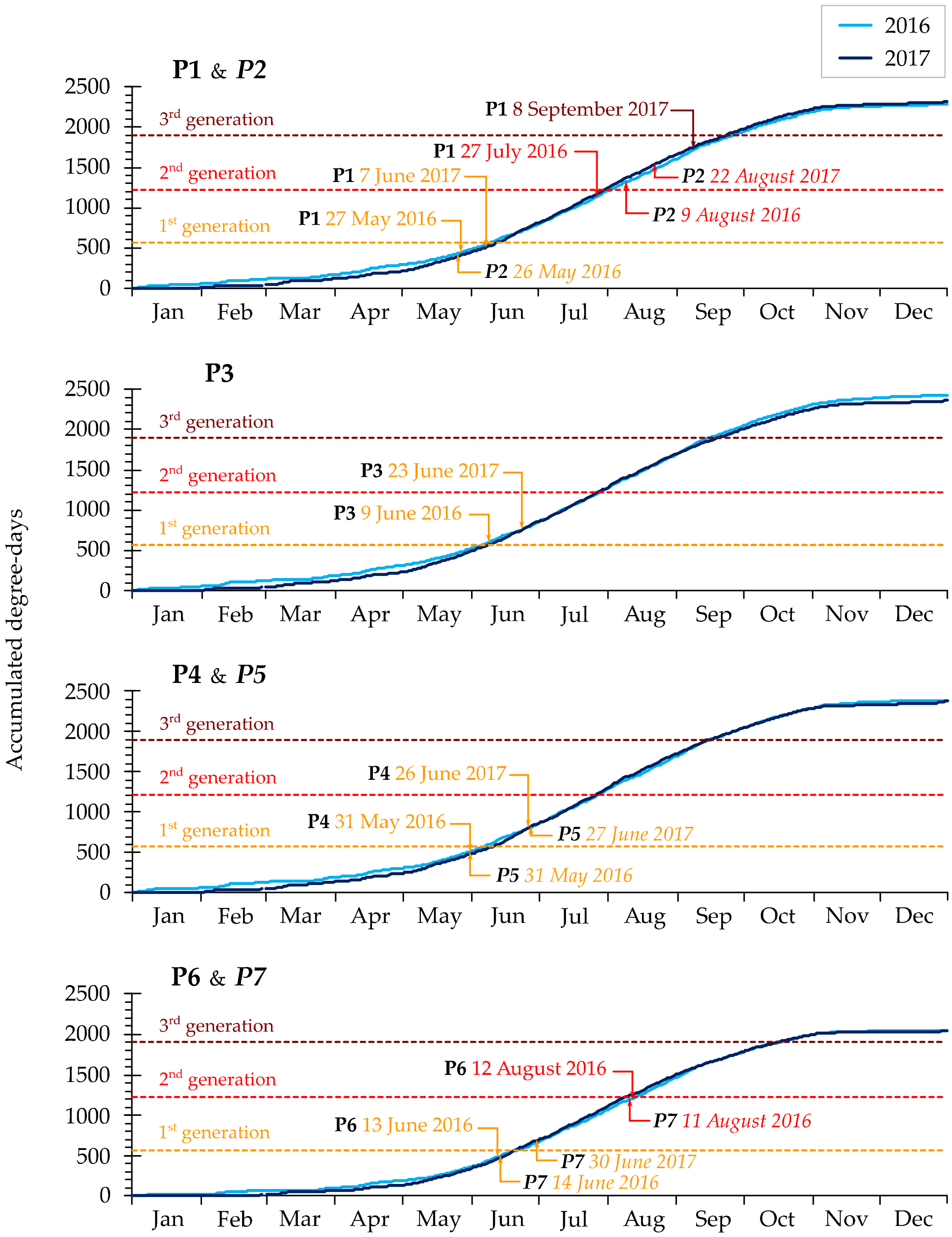

Figure A1. Accumulated degree-days (ADD) in the seven plots (P1–P7) during 2016 and 2017. The application dates are indicated for each plot and each year. The treatment threshold for the first generation is indicated in orange (at 570 ADD), in red for the second generation (1220 ADD) and in maroon for the third (1900 ADD). Lower development threshold temperature for *Aonidiella aurantii* = 11.7 °C. The temperature data were obtained from the weather stations of the Spanish SIAR ("Servicio de Información Agroclimática para el Regadío", Agroclimatic Information Service for Irrigation) network [57].

Table A2. Meteorological conditions [1] during the spray applications and coverage evaluations: temperature, relative humidity, solar irradiance, wind speed, wind direction and precipitation [2].

Plot	Coverage Evaluation	PPP Application	Date	Temperature (°C)		Relative Humidity (%)		Solar Irradiance (W/m²)		Wind Speed (m/s)		Wind Direction	
				V_C	V_A	V_C	V_A	V_C	V_A	V_C	V_A	V_C	V_A
P1	●	●	27 May 2016	23	24	57	59	731	893	1.11	2.50	SE-S	E
		●	27 July 2016	25	27	63	67	337	474	0.56	1.39	NW-N-NE	N
	●	●	7 June 2017	23	21	62	81	590	208	1.67	0.28	NE	NW-SE
		●	8 September 2017	24	22	79	89	265	89	0.56	0.56	N-E	NW-W-SE
P2	●	●	26 May 2016	22	22	66	68	811	609	1.94	1.94	E	E
		●	9 August 2016	31	28	26	31	690	499	1.39	1.11	SE	SE
	●	●	22 August 2017	28	24	52	64	546	310	1.11	0.28	SE	W
P3	●	●	9 June 2016	26	26	58	58	902	721	1.94	1.67	E-SE	E
	●	●	23 June 2017	29	27	50	50	712	353	1.39	0.28	SE	SE-E
P4	●	●	31 May 2016	24	24	58	41	696	966	1.39	2.22	NE-E	E
	●	●	26 June 2017	24	30	77	54	241	846	0.28	1.67	SE-E	E-NE-N
P5	●	●	31 May 2016	23	24	42	41	748	910	1.67	1.67	E	E
		●	27 June 2017	30	30	50	55	604	395	0.56	1.39	SE-E	E-NE
	●		19 September 2017	25	19	51	88	694	209	1.39	0.56	E-NE	SE-E
P6	●	●	13 June 2016	33	32	27	29	909	828	1.39	1.11	S-SE	W-SW
		●	12 August 2016	23	22	72	79	323	236	0.56	0.56	SW	W-S
P7	●	●	14 June 2016	28	27	45	41	916	724	2.22	1.39	SE-E	S-SE
		●	11 August 2016	22	25	69	54	451	770	0.83	1.11	SW-S	S-SE
		●	30 June 2017	26	21	22	32	863	484	2.22	0.83	W	SW-NW
	●		4 August 2017	27	29	55	40	295	438	0.56	1.11	SE-N-SW	E-SE-S

[1] The meteorological conditions were taken from the weather stations of the Spanish SIAR ("Servicio de Información Agroclimática para el Regadío", Agroclimatic Information Service for Irrigation) network [57]. [2] The precipitation was 0 mm in all cases, except in the application of 26 June 2017 in plot P4 for V_A treatment, where it was 0.02 mm. V_C: conventional volume; V_A: adjusted volume; PPP: plant protection product.

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