84. UAV for spraying liquid bait treatments to control *Ceratitis capitata* in citrus is an effective alternative to terrestrial applications

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Abstract

Unmanned aerial vehicles (UAV) are considered well suited to apply liquid bait treatments in bush and tree crops, aimed at attracting and killing the target pest, because they do not need canopy penetration and low volume rates are used. In this work, liquid bait treatments with UAV and the reference terrestrial equipment were compared in terms of canopy spray distribution, ground losses, and efficacy against *Ceratitis capitata* in citrus. Prior to applications, UAV settings were defined to get the large droplets required for these treatments. The results showed that the UAV was a sustainable and effective alternative technique for this application, with even higher efficacy than the terrestrial reference.

Keywords: canopy penetration, drone, large droplets, medfly, Spintor Cebo®

Introduction

Unmanned aerial vehicles (UAV) have a great potential to be used for the application of plant protection products (PPP). However, currently they have limited load capacity, which makes them very inefficient in foliar coverage treatments in bush and tree crops, which may require high spray coverage of the leaves and canopy penetration. Therefore, in these crops they result suitable just for low volume applications, as it is the case of liquid bait treatments. These are aimed at attracting the insects towards droplets deposited on the external part of the canopy, so that the insects ingest the mix lure-PPP and die. The deposits should be large to ensure that the mix remains effective for a long time (Vergoulas and Torné, 2003).

These treatments are used to control fruit flies such as the Mediterranean fruit fly, *Ceratitis capitata*. *C. capitata* is a key pest of citrus in the Mediterranean basin, consistently exceeding economic injury levels each season, which requires chemical and/or biorational control management (Urbaneja *et al.*, 2020). Nowadays, Spintor Cebo® is the reference PPP to control this pest through bait treatments. Chueca *et al.* (2007, 2008) demonstrated that 1 m wide band applications of Spintor Cebo® over the sunny side of the canopy with cumulative area diameter distribution with D25 and D75 of 2 and 4 mm equivalent impact diameter respectively, efficiently controlled *C. capitata*. However, discoloration and presence of the sooty mould appeared on the fruits where droplet deposited. Therefore, currently, it is recommended in the PPP label to be applied producing a solid jet which is deposited on the vegetation as a line towards the areas of the canopy with less fruit presence to avoid those problems. This is normally performed terrestrially with a hydraulic sprayer with a cone nozzle without swirling plate. To maximize the effectiveness and efficiency of UAV-based spraying, it is essential to configure the UAV and its spraying system according to the specific application needs. Studies have shown that key adjustable parameters, such as forward speed, nozzle type, volume rate, and flight height, among others, influence deposition on citrus (Hou *et al.*, 2019, Meng *et al.*, 2022, do Nascimento and da Vitória, 2022) and other orchard trees (Li *et al.*, 2021, 2022, Meng *et al.*, 2020, Ribeiro *et al.*, 2023). In a previous work, the proper settings of the UAV to fulfil the requirements of coarse-impacts liquid bait treatments were determined. The aim of this work is to evaluate the spray distribution and the pest control efficacy of bait treatments applied with UAV in citrus.

Materials and methods

Experimental plot

Field trials were carried out in a commercial 'Navelina' orange orchard located in Valencia (Spain). Trees were planted with 6 by 5 m row and tree spacing. Tree height averaged 3.28 m, canopy height 3.01 m, diameter along the row 3.67 m and diameter across the row 3.74 m. This represented an ellipsoidal canopy volume of 21.62 m^3 on average.

Experimental design

The experimental design consisted of a random block design with three replicates, and the factor of study was the bait application technique, with two levels: UAV and terrestrial hydraulic sprayer. Each experimental unit had around 1 ha.

The response variables were the spray distribution and the efficacy against medfly. The spray distribution was assessed measuring (1) the deposition above and the lateral side of the canopy, (2) the penetration into the canopy, and (3) the ground losses. The efficacy was estimated based on (1) the cumulative population level of medfly at the end of treatments and (2) fruit damage at harvest. Application moment depended on the population level, which was weekly monitored with 6 catch-and-kill traps with lambda-cyhalothrin in each experimental unit: 3 with food lure, to attract females and males, and 3 with sexual female pheromone diffuser, to attract mainly males. The traps were weekly assessed between early September and early December and the number of flies per trap per day was calculated. Once the fruit was susceptible to the pest, that is, when it began to change its colour from green to orange, and the threshold of 0.5 flies per trap and day (MAPA, 2022) was surpassed, applications were performed. A total of six bait applications were made between 5 October and 29 November 2023.

Spray equipment and operational conditions

The UAV was a quadcopter of 8-litre tank capacity (AGRAS T10, DJI, Shenzhen, P.R. China), which worked at a flight speed of 6.67 m s^{-1} and at a pressure of 0.1 MPa, flying 1.5–2 m above the citrus canopies. Two air-induced flat fan nozzles (TeeJet AI 110 04, TeeJet Technologies, Glendale Heights, IL, USA) were located under the rotors of the UAV. The nozzles' jets were oriented perpendicular to the advance, and the spraying was carried out in all rows. The spray volume applied was 7.58 l/ha. The terrestrial sprayer was a PTO-driven conventional axial fan air blast sprayer (mod. Citrus, Mañez y Lozano, Alginet, Spain) set up with a single nozzle (Hardi 1553, nozzle size 10, without diffuser, Hardi International, Nørre Alslev, Denmark) and without air, producing a jet directed towards the middle part of the canopy (at a height of 1.6 m). The forward speed was 5 km h^{-1} and the pressure was 110 kPa. The south-east side of all rows of trees was sprayed. The spray volume applied was 10 l/ha. With the two sprayers, the PPP used was Spintor Cebo (spinosad 0.024%, w/v) at a dose of 1 l/ha.

Evaluation of the spray distribution

The spray distribution on the canopy (above and on the lateral side of the canopy, and the penetration) and the losses to the ground, were estimated with artificial collectors. In all cases, water-sensitive papers (76×26 mm, Syngenta, Basel, Switzerland) were used, except in the case of the lateral side deposition with the terrestrial sprayer, where filter papers (420×520 mm, Scharlab, Barcelona, Spain) were used to ensure catching the jet (Figure 1). The very dark colour of the PPP enabled its visualization on the collector. Collectors were digitated and images were analysed with the custom-made software based on Food Color Inspector (personal communication, IVIA, available upon request at cubero_ser@gva.es) to obtain the impacts' size (mm), and the coverage (%).

The spray distribution was evaluated in the first four applications on one tree in the centre of one experimental unit of each spray technique.

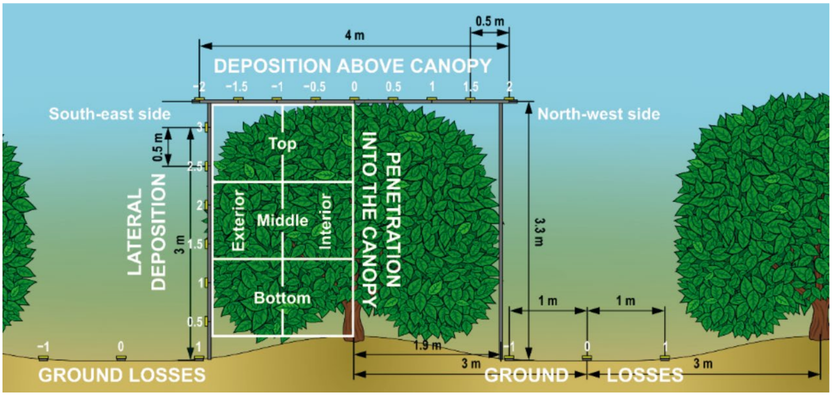

Figure 1. Side view across the row showing the position of the water-sensitive papers.

Evaluation of the efficacy of the treatments

First, considering the weekly number of flies per trap and day, the accumulated value of the trappings after the first bait application was calculated.

On the other hand, the percentage of fruit with oviposition holes of *C. capitata* at harvest was calculated. For this, 10 fruits of 30 random trees per experimental unit were assessed, 5 fruits from each side of the row.

Data analysis

The percentage of coverage in the different areas and the size of the impacts were analysed descriptively.

The effect of the bait application technique on the cumulative number of flies per trap and day after the first application was analysed by means of a linear mixed model (LMM), including the application technique, the type of trap and their interaction as fixed effects, and the location of each replicate of each application technique as a random effect.

The study of the percentage of damaged fruits was done by means of a one-way analysis of variance (ANOVA). In all cases, it was verified that the assumptions of homoscedasticity (through the Levene test) and normality (checked by normal probability plot of the residuals) were fulfilled. The confidence level considered was 95%.

Results

Spray distribution

The results showed that the UAV deposited the droplets mainly above the canopy where there is no fruit presence, reaching almost the whole width of the canopy (Figure 2), with an average coverage of 1.59% and with cumulative area distribution with D25 and D75 of 1.73 and 5 mm equivalent impact diameter respectively (Figure 3). As expected, the lateral coverage was very low (Figure 2). It is to note that the fourth application with UAV showed a displacement of the deposits towards an edge of the canopy (Figure 2), which could be due to the lack of a high-precision positioning system when the UAV was employed.

In contrast, and as presumed, no drops were recorded above the canopy for the terrestrial sprayer, because it produced a continuous solid line 3.19 cm wide at 1.6 m height from the ground (Figure 4). This represented a coverage of 1.07% on the vertical leaf wall. Ground losses were very low in both cases.

Penetration into the canopy was low with both application methods (Table 1). With the UAV the highest coverage was obtained in the top canopy zone. Whereas with the terrestrial sprayer, the highest coverage was obtained in the external part of the middle height, which could be due to splashing when the spray jet hit the outermost leaves.

Efficacy of the application against C. capitata

Considering the average values of fly trappings of the 3 sexual and the 3 food traps of each experimental unit, it could be seen that population level was reduced below the treatment threshold after the first two applications with both sprayers. However, three weeks later, the number of *C. capitata* per trap and day with the terrestrial sprayer increased and was higher than with the UAV. (Figure 5).

Regarding the efficacy, the interaction between application technique and type of trap resulted statistically significant for the cumulative number of *C. capitata* per trap and day (*F*=6.62, df=1, 28,

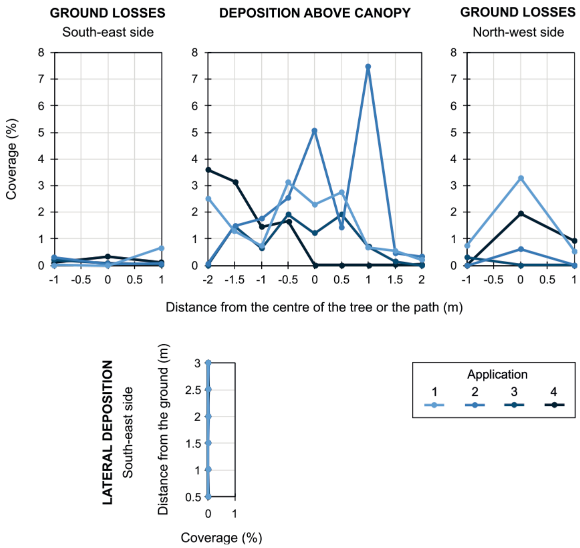

Figure 2. Coverage (%) above and on the lateral side of the canopy, and ground losses from the 4 applications with the UAV.

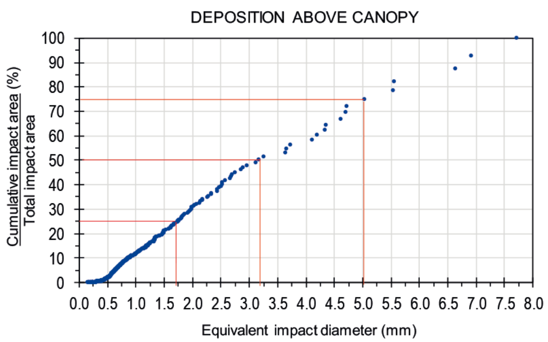

Figure 3. Distribution of the fraction of accumulated area of the impacts divided by the total area of the impacts versus the equivalent impact diameter (mm) considering the impacts deposited above the canopy with the UAV.

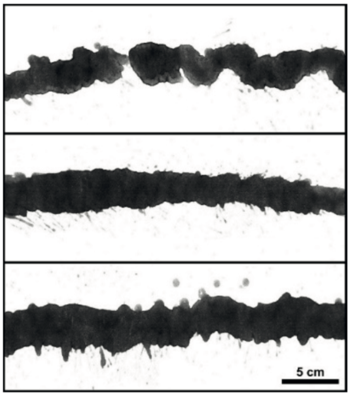

Figure 4. Deposits achieved on filter papers on the lateral side of the canopy with the terrestrial sprayer.

Table 1. Penetration into the canopy (% coverage (average value with standard error in parentheses)).

Spray technique	Height	Exterior		Interior	
		Upperside	Underside	Upperside	Underside
UAV	Top	0.15 (0.11)	0.12 (0.12)	1.16 (0.32)	0.01 (0.01)
	Middle	0.03 (0.02)	0 (0)	0.02 (0.02)	0 (0)
	Bottom	0.35 (0.35)	0 (0)	0 (0)	<0.01 (<0.01)
Terrestrial sprayer	Top	<0.01 (<0.01)	<0.01 (<0.01)	0.01 (0)	<0.01 (<0.01)
	Middle	0.33 (0.25)	0 (0)	0.01 (0)	0 (0)
	Bottom	0.04 (0.04)	<0.01 (<0.01)	0.01 (0.01)	<0.01 (<0.01)

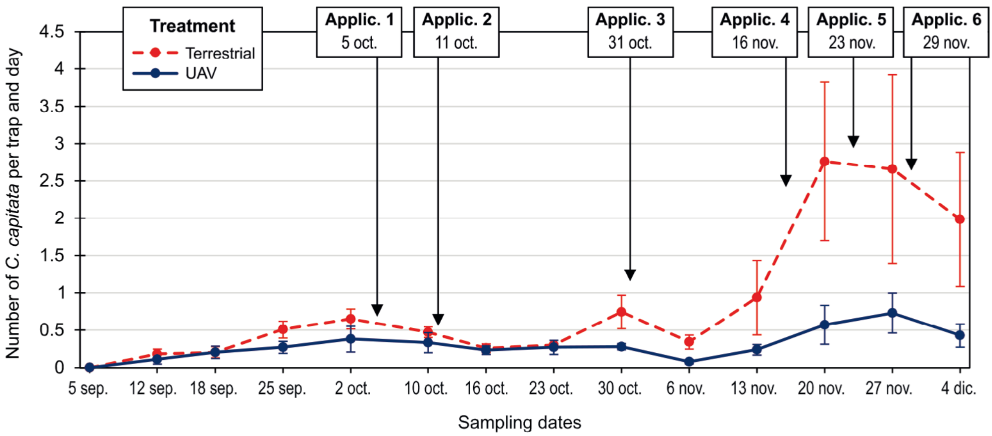

Figure 5. Number of *C. capitata* per trap and day with each application technique (mean with standard error bars). (The dates of spray applications are indicated).

p=0.0156). In the sexual traps, the terrestrial sprayer showed significantly higher values of cumulated flies than the UAV (p=0.0215). Meanwhile, in the food traps there were not significant differences between treatments (p=0.4153) (Figure 6).
The percentage of damaged fruit prior to harvest was not significantly different between application techniques: 3.44% with the UAV, and 3.89% with the terrestrial sprayer (F=0.17, df=1, 5, p=0.6981).

Conclusions

The applications performed with the UAV fulfilled the requirements for bait treatments, the impact sizes were considered big enough to attract the target pest, and droplets remain on the external part of the canopy in order to attract the pest with very low penetration into the vegetation. With the UAV, the droplets mainly were deposited above the canopy, covering all the width of the canopy that represents 100% of the top horizontal leaf wall. It is much higher than the canopy covered by the terrestrial sprayer producing a jet that represents 1.07% of the vertical leaf wall. As a result, the presence of medfly on citrus orchards treated with UAVs was lower than on those treated with terrestrial sprayers, and this could be due to the larger coverage area of vegetation treated with PPP droplets with the UAV, which increases the likelihood of medflies coming into contact with the droplets. Regarding the percentage of damaged fruits by medfly, no differences were found between treatments.
Therefore, it can be concluded that the UAV achieved, if not superior, at least the same level of control efficacy for *C. capitata* as the terrestrial sprayer. This result together with the reduction of the application time due to the increased forward speed and the decrease of pesticide exposure of operators and environment makes this spray technique a sustainable and effective alternative for bait applications against *C. capitata* in citrus to the terrestrial ones.
Nevertheless, using a highly precise positioning system, like RTK (real-time kinematic) antennas that provide centimetric precision is very important. This is especially challenging in tree orchards, such as citrus, where the crop is grown in rows and the spray must be deposited over the vegetation and ground losses should be minimised. In extensive crops, where the whole area must be sprayed, it is also important, to prevent over-spraying some areas and/or under-spraying others. This has been demonstrated in this study, where this type of system was not available, and in some cases

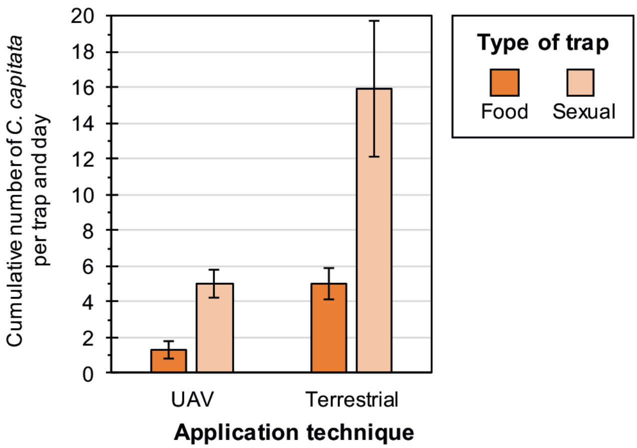

Figure 6. Cumulative number of *C. capitata* per trap and day of the nine post-application samplings (mean with standard error bars) depending on the application technique and type of trap.

the UAV did not fly over the row, and droplets ended on the ground, reducing the effectiveness of the application.

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