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Effect of flight operative height and genotypes on conilon coffee spraying using an unmanned aerial vehicle

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ABSTRACT

This study analyzed the effect of operational flight height and conilon coffee genotypes in the deposition and uniformity of destruction in the plant's canopy. The spray were conducted using a unmanned aerial vehicle in a conilon coffee plantation. The experiment was carried out with a randomized block design and treatments arranged in a factorial scheme, with three operational flight heights in relation to the coffee canopy and three genotypes of conilon coffee (*Coffea canephora*). The parameters evaluated were volume median diameter (VMD), density of drops and coverage (%). The interaction between flight height variables and canopy's range was significant for the data on VMD variables, droplet density and coverage. According to the results, spray performance at an average height of 3.0 m is better than at 2.0 and 4.0 m. At 4.0 m, we observed a decrease in these variables, and this can be explained by a possible drift caused by the wind intensity and direction at higher heights. The coverage on the genotype A1 leaves was higher when compared to the other genotypes, although flight operational height was significantly different only in this genotype, 8.1% at 4.0 m, we observed at this height the lowest coverage values.

Key words: Remotely piloted aircraft; spray system; droplet uniformity; Water-sensitive paper; *Coffea canephora*.

1 INTRODUCTION

The expansion of coffee plantations in Brazil and the adoption of a dense planting system to increase productivity in the last decades have caused environmental damages, such as the increase in pests and diseases. Coffee trees are deeply affected by diseases in their vegetative and productive cycle, being fungi and nematodes the main phytopathogenic agents. The main damage is caused by fungal diseases, such as coffee rust, blister spot, anthracnose, koleroga, roseliniosis (*Rosellinia sp.*), rhizoctoniosis, fusariosis and cercosporiosis.

These diseases are strongly correlated with the occurrence of rain and the phenological stages of plants. The application of pesticides is the method most often used to control pests and diseases in coffee trees. However, sometimes the use of machines and equipment is not efficient, as topographic conditions and the way the culture is managed can be limiting factors. Mountain coffee cultivation in Brazil has great productive potential, occupying about 600 thousand ha, the second in size, and covers an area close to the latitude of 0º, in the extreme north of Brazil, to the latitude of 25⁰, in the southern Brazilian region (Batista et al., 2020; Ferreira et al., 2018; Louzada-Pereira et al., 2018; Piato et al., 2020).

In addition to topography, another factor that prevents the use of machines and implements in the control of pests and diseases is the way the culture is conducted. The system called "programmed pruning" of plagiotropic branches increases the coffee tree productivity. However, it causes the arches of the productive branches to bend between the lines, preventing the traffic of machines and implements (Verdin Filho et al., 2014).

In the last decade there has been an increase of scientific research on the use of unmanned aerial vehicles (UAVs) in spraying, especially in China. The most important studies with UAVs have focused on the control of the damage caused by corn borer (Gao et al., 2013; Zheng et al., 2017), protection of crops in general (Pederi; Cheporniuk, 2015), and application in citrus (Tang et al., 2018). Some important parameters on the technology of pesticide application via UAV have been established. Qin et al. (2018) associate the increase in fungicide efficacy on a target that is difficult to access due to UAV spraying. The importance of studying the proper configuration in terms of regulation and calibration of UAVs in the application of pesticides in grape cultures was highlighted by Wang et al. (2021) – the authors observed a work capacity between 2.0 and 4.0 ha h^{-1} for application volumes from 10.0 to 39.,0 L ha^{-1}. Gao et al. (2013) determined the concentration of chlorpyrifos as a function of the UAV flight height, showing the importance of operational parameters on the distribution and uniformity of sprayed drops.

According to Zhang et al. (2017), Tang et al. (2017), Vitória et al. (2018), Wang et al. (2019) and Meng et al. (2020) the architecture of the plant's canopy and the operational flight height significantly influence the droplet spectrum, uniformity and deposition of droplets.

Can UAVs be an alternative for spraying coffee plantations in Brazil? Some studies on the use of UAVs in tree crops indicate their technical feasibility. However, the scarcity and need for more technical information regarding their use in tree cultures has inspired this work. Different coffee genotypes present different canopy architecture, and this factor must be considered, as the uniformity of distribution and deposition of sprayed drops can vary depending on the genotype planted. It is known that, besides the different types of canopy shapes, the spray tip and the operational parameters of UAVs flight can influence the deposition uniformity (Yang et al., 2017; Klauser; Pauschinder, 2021).

Qiu et al. (2013) developed a model of the relationship between droplet deposition distribution two factors, flight height and velocity of an unmanned aerial vehicle. Some factors can interfere with the quality of the pesticide application using UAV, eg height and flight speed, size and droplet generating elements, application rate and spray solution properties (Cunha et al., 2021). The effects of UAV operational parameters on droplet distribution were evaluated for perennial culture. The Flight velocity, flight height and nozzle flow rate significantly affect droplet distribution (Meng et al., 2020).

Based on the hypothesis that the uniformity of distribution and deposition of droplets in spraying by UAVs is influenced by the genotype and operating parameters, our study aims to analyze the effect of the operational flight height and genotypes of conilon coffee in relation to deposition and destruction uniformity in the plant's canopy.

2 MATERIAL AND METHODS

The experiment was carried out at the Experimental Farm of the North University Center of Espírito Santo, at the Federal University of Espírito Santo, Brazil, latitude 18 º40' 25"S, longitude 40º 51' 23" W. The climate of the region is hot and humid, type Aw, with dry season in autumn-winter and rainy season in spring-summer, according to the Köppen classification.

The cultivation was installed and handled in clay loam with sandy texture. The age of the coffee plantation at the time of the experiment was 18 months, being composed of genotypes of medium cycle – genotype 143, Cultivar EN̶MCAPA in useful lines, and the pollinating genotypes: "Bamburral" and "A1", Cultivar TRIBUTUM (Giles et al., 2018) "LB1" and "P1" in the other lines, in the 3.0 m spacing between lines and 1.0 m between plants in the line. The average height of the plants at the time of the experiment was 1.60 m. Table 1 lists the main biometric and foliar characteristics of the genotypes (Dubberstein et al., 2020; Partelli et al., 2022) evaluated.

The unmanned aerial vehicle (UAV) used was model JT-5 (Joyance) with a capacity of 5 L in the tank (Figure 1), adapted and regulated for spraying on the coffee crop and with a new generation of SUPERX2 RTK flight control system with more accurate GNSS RTK positioning module and spray system to make UAV plant protection more precise, smarter, and more efficient.

Table 1: Average biometric and leaf-related characteristics the of genotypes of Coffea canephora cv. Conilon A1, LB1 and P1.

Characteristic	Genotypes used in the estimates		
	A1	LB1	P1
NNP	14.67	17.33	15.00
DBP	3.89	3.86	3.75
OBL	70.33	72.83	71.50
NNO	17.66	19.66	19.00
Hgt	154	140	156
Diam	160	153	171
LA	67.4	60.2	63.6

NNP: number of nodes in plagiotropic branches; DBP: distance between nodes of plagiotropic branches (cm); OBL: orthotropic branch length (cm); NNO: number of nodes in orthotropic branches; Hgt: plant height (cm); Diam: canopy diameter (cm); LA: Leaf area (cm²).

Figure 1: Multirotor unmanned aerial vehicle used in the spraying experiment.

In addition to the storage tank, the UAV is equipped with a water pump, piping circuit for liquid circulation, empty conical spray nozzles, electronic control valves and other components. The four spray nozzles are distributed equidistant and perpendicular to the aircraft's axis, with a spacing of 0.75 m. The application rate of 10 L ha^{-1} was used for all treatments. The main specifications are listed in Table 2.

The experiment was carried out according to a randomized block design and treatments distributed in a 3 × 3 factorial scheme, with three flight operational heights in relation to the coffee canopy (2.0, 3.0 and 4.0 m) and three genotypes of conilon coffee (A1, LB1 and P1), four replicates per treatment. Table 3 shows the operational parameter of nine treatment tests like T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8 and T_9.

Table 2: UAV Joyance JT-5 specifications.

Number of rotors	6
Flying speed	0 to 12 m s^{-1}
Operating speed	0 to 8 m s^{-1}
Tank capacity	5 L
Autonomy	10 to 25 minutes
Spray	Full cone
Number of tips	4
Tip distribution	Below 4 rotors in sequence

Table 3: Experimental treatments.

Treatments	Genotypes	Operational heights (m)
T_1	A1	2.0
T_2	A1	3.0
T_3	A1	4.0
T_4	LB1	2.0
T_5	LB1	3.0
T_6	LB1	4.0
T_7	P1	2.0
T_8	P1	3.0
T_9	P1	4.0

The UAV performed overflows covering 60.0 m over a line of coffee plants and at the end of this route it returned to the next line. For every three lines covered, the central line was considered useful for assessment at each of the flight heights. In the useful lines, six uniform plants were drawn from each of the genotypes, which served as experimental plots to determine the spectrum and droplet deposition Figure 2.

Water-sensitive paper labels with dimensions of 76 × 26 mm were used to characterize the spectrum of sprayed drops. These were stapled to the leaves of the third node of the plagiotropic branches in a way that they remained facing upwards. In the first half of flight operational height of the plants, about 0.40 m from the ground, four labels were stapled, two in the direction of the line and two in the direction of the lines. The same fixation procedure was carried out in the second half of flight operational height, about 1.20 m high, totaling eight labels per experimental unit Figure 3.

The quantification and characterization of the impacts on each water-sensitive paper label were performed immediately after the application of each treatment and by drying the labels with a wireless DropScope system, composed of application programs and a digital wireless microscope with image sensor with more than 2500 dpi. This allowed the researchers to estimate partially overlapping drops of approximately 35 µm. The following parameters were evaluated: mean volume diameter (VMD, µm), droplet density (droplets cm^{-2}) and coverage (%).

To estimate the deposition of the sprayed syrup, rhodamine B (tetra-ethyl-rhodamine) was added to the spray tank, a fluorescent dye used as a marker for measuring spray deposits (800 mg ha^{-1}). After the application of each treatment, leaves from the third node were removed from the plagiotropic branches in positions close to those that were attached to water-sensitive paper labels, totaling eight leaves per treatment, four in each half of the plant's canopy height. The samples were properly identified, packed in plastic bags and stored in a polystyrene box. A 50 mL sample of each application was collected, allowing the calibration curves used in a fluorimeter, in which the rhodamine concentrations were determined.

The leaves were washed with 25 mL of a solution of distilled water and alkaline detergent (1% v/v), allowing the extraction of tracer dye from the leaves. The mass balance generated by the deposits of the tracer on the samples in relation to the initial concentration was used to estimate the deposition on leaves. A portable digital fluorometer with a minimum detection of 0.02 ppb (parts per billion) of rhodamine was used. The leaf area was subsequently measured with a Li-Cor L1-3100 leaf area meter.

From the reading of the fluorimeter, the data of calibration curves and leaf area, amount of spray deposit per unit area were calculated in µL cm^{-2} Equation 1.

$$\beta_{deposit} = \frac{\left(\rho_{sample} - \rho_{white}\right) \times F_{calibrate} \times V_{deposit}}{\rho_{spray} \times A_{leaf}} \quad (1)$$

Where: $\beta_{deposit}$ is the spray deposit on the leaves, µL cm^{-2}; ρ_{sample} is the reading of the sample fluorimeter; ρ_{white} is the fluorimeter reading of the "white" test; $F_{calibrate}$ is *p* calibration factor, µg L^{-1}; $V_{deposit}$ is the dilution liquid volume, L; ρ_{pray} is the sprayed concentration, g L^{-1}; A_{leaf} is the coffee leaf area.

The experiment took place in September 2020, and the climatic conditions were monitored and recorded by a meteorological station (Sigma Sensors®, model EMI-RX-500) during the applications Table 3. Besides being monitored at the time of applications, the climatic conditions were monitored in the days and hours preceding them to standardize these conditions, considering as appropriate ranges the temperatures not exceeding 30° C, relative humidity between 55 and 80%, and speed 0.5 and 2.5 m s^{-1}.

VMD data, droplet density, coverage and droplet deposition were tested. To verify the homogeneity and normality of the residues, the researchers applied the Levene and Shapiro-Wilk tests. Data transformation was performed when necessary and for the variance analysis, to identify the difference between treatments, the Tukey's test was applied. All tests were performed with the Statistical Analysis System Software (SAS 9.1), considering a level of significance of 5%.

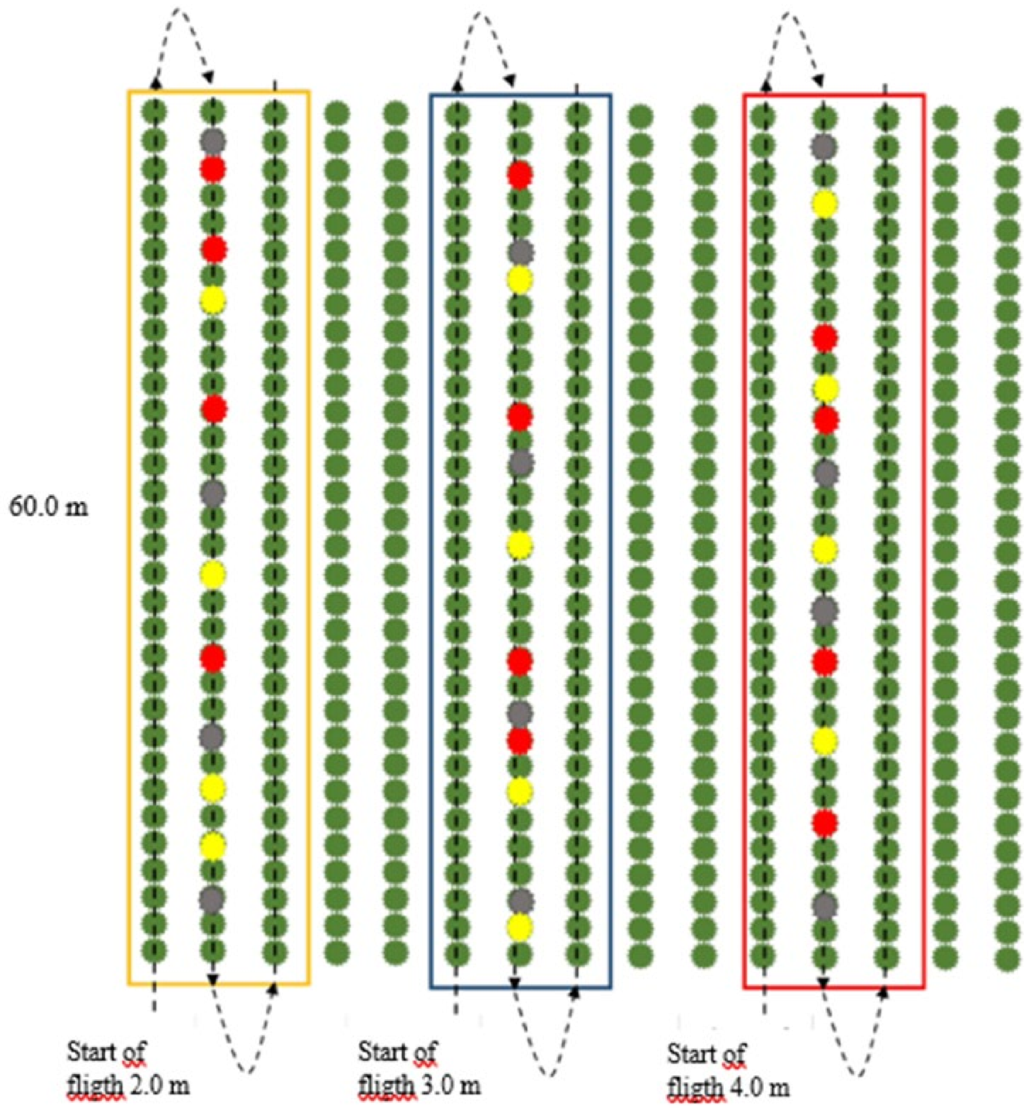

Figure 2: Representation of the experimental design.

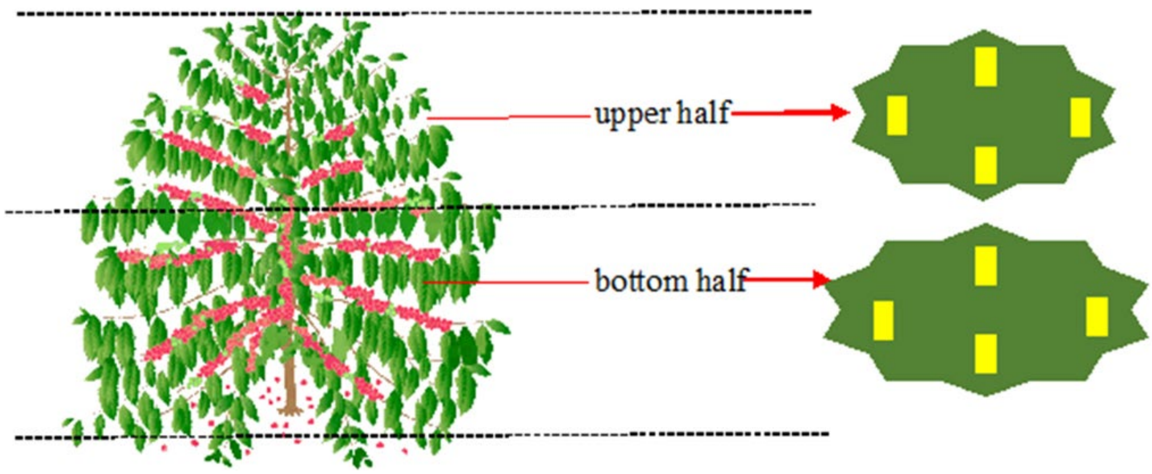

Figure 3: Scheme of the positioning of water-sensitiv.

3 RESULTS

The canopy height range of the coffee plant did not have significant interaction when analyzed together with the operational flight height and the coffee genotype; therefore, only the last two were analyzed. Table 4 shows the effects of flight heights, genotype and their interactions for the variable's droplet density and coverage. The three variables studied showed coefficient of variation (CV) from moderate to high, a fact that can be explained by the different operational conditions imposed by the treatments.

The coverage on the leaves of the genotype A1 was higher when compared to other genotypes. Although only in this genotype flight operational height was significantly different, 8.1% at flight operational height of 2.0 m, we observed the lowest values for roof. The P1 genotype had the lowest coverage values, 6.9, 7.0 and 6.7% at heights 1.0, 1.5 and 2.0 m, respectively. As with the droplet density, the coverage is also influenced by the target area (in this case, the leaf).

Although higher for the LB1 genotype and flight height 3.0 m, VMD values were not significantly different for the variables analyzed. The highest value was 337.1 µm, and the lowest, 314.3 µm, for heights of 3.0 and 4.0 m, respectively. The climatic conditions considered ideal at the time of applications influenced this homogeneity; in addition, VMD is not influenced by the leaf area size of the three coffee genotypes (Figure 4).

The interaction between flight height variables and canopy's range was significant for data on variables droplet density and coverage Table 5. The CVs of the Analysis of Variance varied from 21.22 to 30.25%, indicating possible influence of the operational conditions imposed, but which did not render the statistical analyzes unfeasible.

The highest VMD value occurred in the upper range of the canopy regardless of height, 2.0 m away from the canopy; the highest VMD value was observed at 420.2 µm. When analyzed in the lower range, the highest value is 334. µm at 3.0 m. The closer to the target, the greater the diameter of the deposited drops, and the greater the distance, the lower the VMD values Figure 5.

The deposition of spray droplets as a function of operational flight height and canopy height range for each genotype is shown in Figure 6.

4 DISCUSSION

The interaction between flight height and genotype variables was significant for the data on drop density variable, with the highest value (69.2 drops cm^{-1}) for the A1 genotype at the flight height of 2.0 m, and the lowest value (49.8 cm^{-1}) drops for the P1 genotype at a height of 3.0 m. Regardless of the flight height, the highest values of droplet density occurred in genotype A1, and the lowest in P1. The leaf area size has a direct influence on this variable, as smaller leaf areas concentrate a greater number of drops. The A1 genotype presented leaf area 10% smaller than the LB1 genotype, and 8% smaller than P1 (Giles at al., 2018).

Table 4: Effect of the operational height of application and the conilon coffee genotype on coverage and density of drops.

		Flight operational height (m)		
	Genotype	2.0	3.0	4.0
Density (drops cm^{-2})	A1	69.2 aA	68.1 aA	68.1 aA
	LB1	57.7 bB	66.1 aA	54.2 bB
	P1	51.7 bA	49.8 bA	54.0 bA
	CV = 31.39%	$W = 0.7532^{ns}$	$F_L = 1.824^{ns}$	$DW = 1.511^{ns}$
	$F_{height} = 1.532^{ns}$	$F_{genotype} = 5.107^{*}$	$F_{interaction} = 2.258^{*}$	
Coverage (%)	A1	9.0 aA	9.5 aA	8.1 aB
	LB1	7.3 bA	7.0 bA	6.9 bA
	P1	6.9 bA	7.0 bA	6.7 bA
	CV = 30.06%	$W = 0.684^{ns}$	$F_L = 0.987^{ns}$	$DW = 1.611^{ns}$
	$F_{height} = 1.205^{ns}$	$F_{genotype} = 7.602^{*}$	$F_{interaction} = 1.212^{*}$	

Means followed by distinct letters, small letters in the columns, and capital letters in the lines differ from each other by the Tukey's test, at the 0.05 significance level; CV: coefficient of variation; W, F_L, DW and F: Statistics of the Shapiro-Wilk test for normality of residues, Levene for homogeneity of variances, Durbin-Watson for independence of residues and F test; ^{ns} Normally distributed residues, homogeneous variances, independent residues and acceptance of the H_0 hypothesis, all with a level of significance of 0.05; * Residues not normally distributed, non-homogeneous variances, non-independent residues and rejection of the H_0 hypothesis, all with a level of significance of 0.05.

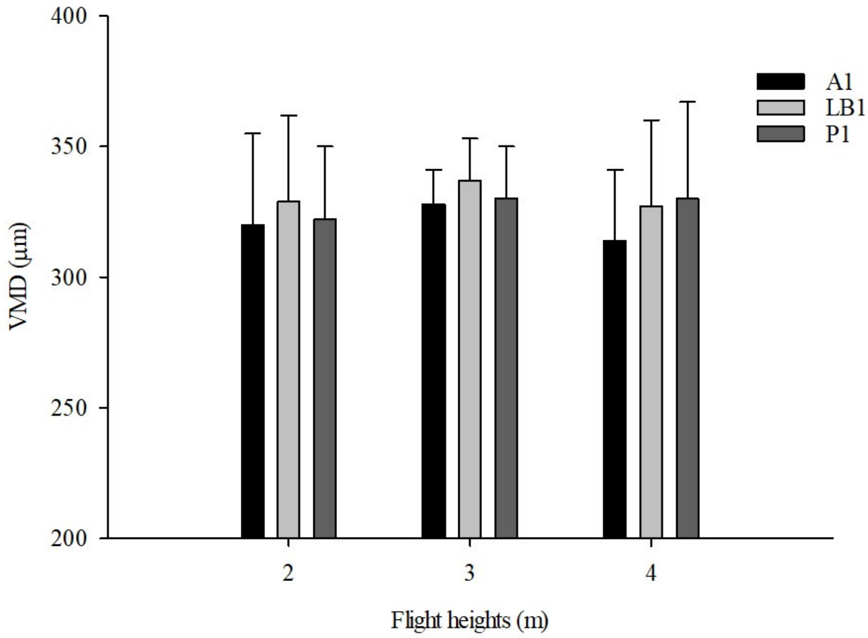

Figure 4: Effects of flight heights and genotype and their interactions for the variables VMD.

Table 5: Effect of the operational application height and the canopy layer of conilon coffee on coverage and density of droplets.

		Canopy sash	
	Flight height (m)	Bottom	Higher
Density (drops cm^{-2})	2.0	40.8 bB	49.5 bA
	3.0	57.7 aA	61.3 aA
	4.0	42.5 bB	52.2 bA
CV = 28.13%	$W = 0.997^{ns}$	$F_L = 1.482^{ns}$	$DW = 1.113^{ns}$
$F_{height} = 7.209$*	$F_{layer} = 1.721^{ns}$	$F_{interaction} = 5.997$*	
Coverage (%)	2.0	6.2 bB	9.2 aA
	3.0	8.7 aA	9.3 aA
	4.0	8.3 aA	8.8 aA
CV = 21.22%	$W = 0.7377^{ns}$	$F_L = 1.994^{ns}$	$DW = 1.543^{ns}$
$F_{height} = 1.235$*	$F_{layer} = 6.422$*	$F_{interaction} = 0.892^{*}$	

Means followed by distinct letters, small letters in the columns, and capital letters in the lines, differ from each other by the Tukey's test, at the 0.05 significance; CV: coefficient of variation; W, F_L, DW and F: Statistics of the Shapiro-Wilk test for normality of residues, Levene for homogeneity of variances, Durbin-Watson for independence of residues and F-test; ^{ns} Normally distributed residues, homogeneous variances, independent residues and acceptance of the H_0 hypothesis, all with a significance level of 0.05; * Residues not normally distributed, non-homogeneous variances, non-independent residues and rejection of the H_0 hypothesis, all with a significance level of 0.05.

According to the results of droplet density and coverage, spray performance at an average height of 3.0 m is better than at 2.0 and 4.0 m. At flight operational height of 4.0, the researchers observed a decrease in these variables, and this factor may be explained by a possible drift caused by the wind intensity and direction at higher heights. The movement of the leaves of the canopy that occurs due to the air generated by the rotors favors the penetration of drops the closer to the canopy the greater the chance of runoff on the leaves and soil loss, and the greater flight operational height from a lower flight the movement of the leaves decreasing the penetration, at this point the influence of the air vortex was observed in the direction of the sprayed drops towards areas below the plant's canopy. Similar results were found by Guo et al. (2019) in a study that characterized the size of droplets influenced by the air flow generated by the multirotor UAV vortex.

In general, VMD increases inversely with the flight height in the upper range, however, in the lower range the highest observed value of 334,9 μm occurred at the highest height. These observations are explained by two aspects, the proximity of operational height to the canopy and the influence of air movement on leaf agitation and penetration of drops in the canopy. Chen et al. (2020) explain that this effect of droplet size is essential for spraying efficiency, and in the case of UAV spraying is important to optimize the droplet size parameters and a better distribution of droplet deposition.

The droplet density was higher in the upper range of the canopy regardless of the operational flight height – the highest value was observed at 3.0 m, 61.3 drops cm^{-2}. Similar behavior was observed in the lower range, where 57.7 drops cm^{-2} were observed. In this situation, there was no significant difference between the drop density values. Regarding flight heights at 2.0 and 4.0 m, there was a significant difference between flight height ranges, corroborating that 3.0 m provides greater uniformity in relation to droplet density.

The highest coverage value was found in the range above 3.0 m of the operational flight height, 9.3%. This does not differ statistically from the value of 8.7% found in the lower range. The lowest value of coverage was obtained in the range below 2.0 m, that is, the proximity to the canopy prevents the coverage to be more uniform in the plant's canopy, in the opposite direction, the measure that increases the flight height, the greater the chances of homogeneity of coverage in the studied ranges. Obviously, by increasing the flight height beyond the values tested, there is a possibility of unevenness due to the increased chance of drift.

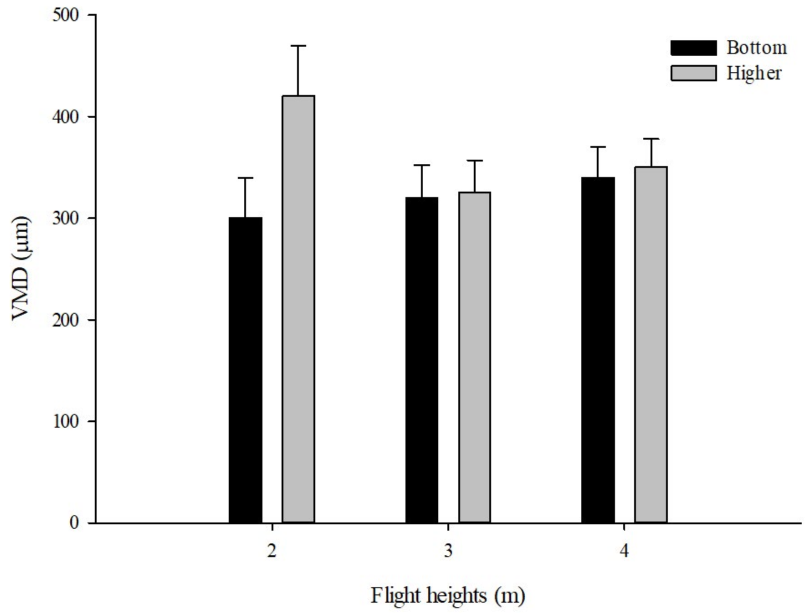

Figure 5: Effect of the operational application height and the canopy layer of conilon coffee on VMD.

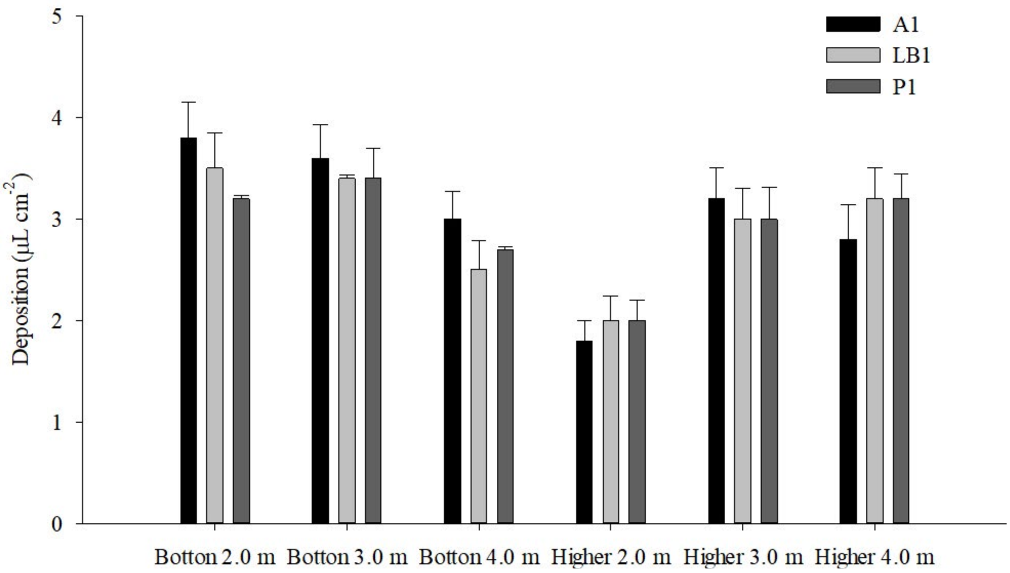

Figure 6: Effect of operational height and height range of the plant on deposition.

There was a significant difference in the deposition of the sprayed syrup when comparing the upper and lower canopy halves of the coffee plant, regardless of the genotype and operational flight height. The greater leaf mass in the lower half of the coffee plants made it difficult for the drops to penetrate and compromised the deposition. However, it is not possible to state that using UAVs for phytosanitary control is unfeasible, given that future studies should analyze the effectiveness of pesticides applied by UAV combined with efficiency translated by the characterization of droplets size and deposition. The results agree with those observed by Zhang, Lian and Zhang (2017), Tang et al. (2017), and Meng et al. (2020).

Analyzing the variables VMD, droplets density, coverage and deposition of droplets observed that the comparative efficiency of the flight at 3.0 m was better than those between 2.0 to 4.0 m. Even with the differences in the leaf mass of canopy's upper and lower half, we can infer that the air flow generated by the rotors helps in the penetration of droplets. The closer the plant's canopy, the worse the spraying efficiency – under these conditions the air flow intensity impairs drops deposition on the upper half, which may even influence their flow, which occurred at 2.0 m. Increasing the flight height to 4.0 m, we have a greater drift, and even considering that this variable was not analyzed in this study, it was possible to observe the wind influence as the flight height increased. In a spray experiment using citrus UAV, Xue et al. (2014) and Tang et al. (2016) also reported this effect. More recently, Kharima et al. (2019), Chen et al. (2020), Meng et al. (2020) and Ahmad et al. (2020) observed the same effect.

The variables analyzed here can be influenced by the shape of the coffee plant's canopy – the leaf mass in the lower half is greater than in the upper part. The consistency of our results is corroborated by others that have focused on medium or tall perennial crops, notably Chen et al. (2017), Tang et al. (2018), Richardson et al. (2019) and Meng et al. (2020), who reported the influence of the canopy shape on the deposition and on the characterization of the droplet spectrum. However, these authors used different UAV models, a fact that can contribute to have small differences in the analysis of spraying efficiency using UAVs.

5 CONCLUSIONS

The operational flight height of 3.0 m in relation to the top of the coffee plant's canopy showed the best results for droplet density and coverage;

The coverage on the genotype A1 leaves was higher when compared to other genotypes, although only in this genotype the height was significantly different;

Observed that with this value the lowest values for coverage were obtained. The deposition values were higher in the upper half of the coffee plants when compared to the lower half, regardless of the genotype.

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7 AUTHORS' CONTRIBUTIONS

ELV: Methodology, Software Data curation, Writing- Original draft preparation and Supervision. RFO: Conceptualization, Visualization, Investigation. DHC and LFOR: Visualization, Software, Writing- Reviewing and Editing.

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