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Abstract: The influences of the canopy height and the spray volume on the droplet distribution in the upper and bottom of the cotton canopy were discussed in this study. XAG P30 plant protection Unmanned Aerial Vehicle (UAV) was used as a spray tool and water sensitive paper was used as the droplet test card. The spray volumes by the UAV include 18.0 L/ha, 22.5 L/ha, and 30.0 L/ha. The average planting heights of cotton in the test areas are 0.5 m, 0.7 m, and 1.1 m, respectively. The results show that the droplets are more well-distributed in the upper part of the canopy rather than the lower part. The spray volume has a significant effect on the droplet distribution in the canopy. The coverage, deposition, and droplet density will gradually increase with the increase of the application volume. The droplet distribution in the 1.1 m canopy area is poor, but it can be improved by increasing the spray volume.

Keywords: unmanned aerial vehicle, droplet distribution, spray volume, canopy height
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1 Introduction

UAVs (Unmanned Aerial Vehicle) as a technical tool for pesticide applications have developed rapidly in East Asia, especially China. In China, due to the terrain conditions, not all plots are suitable for ground machinery to enter, but flexible drones have wide application possibilities[1,2]. According to statistics from the agricultural department, China's plant protection drones sprayed over 200 million mu in 2019[3]. On the one hand, the rapid development of plant protection drones is market demand. The flexibility of drones can be applied to more farmland scenarios. On the other hand, the precision operation of the drone can keep the operator away from the pesticide tank, reducing the risk of human environmental exposure[1]. The rapid development of agricultural drones gave birth to the profession of UAV pilots, who provide spraying services. As an operator, the pilot's experience and pesticide application skills directly affect the distribution of pesticide droplets and the control effect of pests.

The spraying applications of drone known in the literature include low crops such as wheat, rice, corn, cotton, etc., as well as fruit trees such as citrus, apple trees, sugar, and betel nut trees[4-8]. However, the spray effect of drones has not been verified in all crops or application scenarios. Existing studies have shown that plant protection drones have certain efficiency and effectiveness advantages for the prevention of crop diseases and insects[4,7,9-11]. Compared with ground spray machinery, UAV spraying has poor penetration in the crop canopy. The droplet density at the bottom of the canopy is only 30% of the upper canopy[4,11]. For diseases and insect pests that occur on the top of crops, such as wheat head blight, wheat aphids, etc., UAV spraying still has a great control effect. But for insect pests living at the bottom of the canopy, such as rice planthoppers, smaller droplets must be used to obtain sufficient droplet deposition density. Of course, this also increases the risk of droplet drift. Different from the insecticides and fungicides, the spraying of cotton defoliants needs to cover every part of the canopy evenly. It is difficult to achieve a uniform defoliation effect in farmland after UAV spraying, which is mainly manifested in the inconsistent defoliation rate between the upper and lower cotton canopy.

Cotton chemical assisted defoliation facilitates the mechanized harvest of cotton[12]. Spraying chemicals accelerate the shedding of cotton leaves, helps reduce the mixing of leaves in cotton during harvest, and improves the cotton quality. Existing studies believe that the defoliation of cotton is directly related to the distribution of the droplets on the cotton canopy, and the distribution of the droplets is affected by the operating parameters of the drone and the cotton canopy structure. There have been many studies on the influence of plant protection drone operating parameters on the droplet deposition effect. Chen et al.[13] and Wang et al.[14] reported that drone flight speed and height have a significant effect on the deposition between crop canopies. Qin et al.[15] explored the effects of drone flying height and speed on spray penetration and deposition uniformity of rice canopy. Zhang et al. studied the effects of flight height, flight speed, and spray volume on the density, uniformity and penetration of droplets. The result was

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that the optimal spraying parameters were 15 L/ha of spray volume, 3 m of flight height, and 4 m/s of flight velocity could be used as a reference parameter of the drone when applied in sugarcane crop[5]. Wang's research[16] shows that a larger application volume can achieve good droplet coverage and pest control effects in UAV spraying. In addition, the research on the influence of the canopy structure on the distribution of droplets currently focuses on the influence of the canopy structure of fruit trees on the ground spray machinery[17]. Few studies are based on the impact of plant protection drone application volume and crop canopy structure.

The purpose of this study is to evaluate the influence of the canopy height and the spray volume on the droplet distribution on the upper and bottom of the cotton canopy. XAG P30 plant protection drone was as a spray tool and water sensitive paper was as the droplet test card. The amount of liquid sprayed by the drone includes 18 L/ha, 22.5 L/ha, and 30 L/ha. The average planting height of cotton in the test area is 0.5 m, 0.7 m, and 1.1 m respectively. The parameters of droplet evaluation include droplet deposition, density, and coverage.

2 Materials and methods

2.1 Field plots

The test was carried out in Changji City, Xinjiang (87°18′22″E, 44°7′21″N) in September 2019. The test sites consisted of 3 continuous cotton planting plots with different growths, each with an area of approximately 1800 m^2. From June to August, multiple canopy height were obtained from different water and fertilizer treatments. The cotton plants (Xinluzao 57) were sown on 23rd April 2019, and the planting density was 180000/ha. The trials were on September 8th.

2.2 Instruments and devices

XAG P30 plant protection UAV (Figure 1, XAG Co., Ltd, Guangzhou, China) was used in this experiment. As shown in Figure 1, the UAV can automatically plan routes in the flight area and fly autonomously when spraying. The drone automatically adjusts the flying height through the radar device to maintain the distance from the crop canopy. The XAG P30 UAV is powered by a 48V power supply and has 4 rotors, 4 centrifugal nozzles, and 4 peristaltic pumps. The motor of the peristaltic pump and the nozzle can be independently adjusted to achieve different flow rates and atomized particle sizes. Before the drone takes off, set the flight route and operating parameters (amount of spray liquid, droplet size Dv50, flight height, flight speed, etc.) through the handheld ground station. During the operation, the flow rate will change with the flight speed to ensure the consistency of the amount of liquid applied per unit area. The technical parameters of UAV showed in Table 1.

Figure 1 XAG P30 plant protection UAV

Table 1 XAG P30 plant protection UAV technical parameters

Classification	Parameters
Size/m	1.945×1.945×0.44
Max working efficiency/ha·h^{-1}	5.3
Terrain following accuracy/m	≤0.1
Positioning mode	GNSS RTK
Operation method	Mobile control
Spraying system	Rotary atomization
Number of nozzles	4
Load capacity/L	15
Spraying width/m	3.5
Night work	Yes

2.3 Experimental design

According to the numerical range in the reference and the actual operation, the application liquid volume is 18 L/ha, 22.5 L/ha, and 30 L/ha. The droplet size D_V50 is 200 μm when the rotational speeds of the centrifugal nozzle at 5700 rpm. The flight height is 2 m above the canopy surface. As shown in Table 2, three spraying operations were carried out in three planting areas on September 8th.

Table 2 UAV spraying treatment

Test	Spray volume/L·ha^{-1}	Average canopy height/m
1	18	0.5
2	22.5	0.5
3	30	0.5
4	18	0.7
5	22.5	0.7
6	30	0.7
7	18	1.1
8	22.5	1.1
9	30	1.1

In each test area, 3 collection belts are arranged perpendicular to the flight route, and each collection belt has 4 test points, for a total of 12 test points (Figure 3). Four sampling points with 1 m interval are deployed in the test area. Each test point is fixed with a test rod and a test clamp, and the water-sensitive paper is fixed on the test clamp. Two artificial samplers are used in each sampling point (Figure 2), where one artificial sampler is attached in the upper layer according to the canopy height (0.5 m, 0.7 m, 1.1 m), and the other is placed in the bottom layer (0.3 m above the ground). After each spray operation, collect water-sensitive paper into an envelope and seal it for storage. WSP was scanned in grayscale at 600 DPI to produce a digital image in the lab. Images were analyzed using DepositScan™ software (U.S. Department of Agriculture, Agricultural Research Service, Wooster, OH) to calculate droplet information. In this study, the coverage, droplet density, and droplet deposition were used to evaluate the spray effect.

2.4 Weather conditions

The environmental parameters were collected by the Kestrel weather station (Model NK-5500, Nielsen-Kellerman Co., Boothwyn, PA, 209 USA) with a collection frequency of 2 s, and include temperature, humidity, wind direction, wind speed, etc. The natural wind was the transverse wind perpendicular to the route. During the whole test, the mean temperature is 25.2±0.8°C, mean humidity is 36.8±2.6%, and mean wind speed is 2.3±0.3 m/s.

2.5 Data analysis

In this research, Statistical Product and Service Solutions (SPSS v. 25.0, SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Data were compared across all factor combinations and for each experiment separately using Multi-way ANOVA. Duncan's multiple range test was used for multiple comparisons.

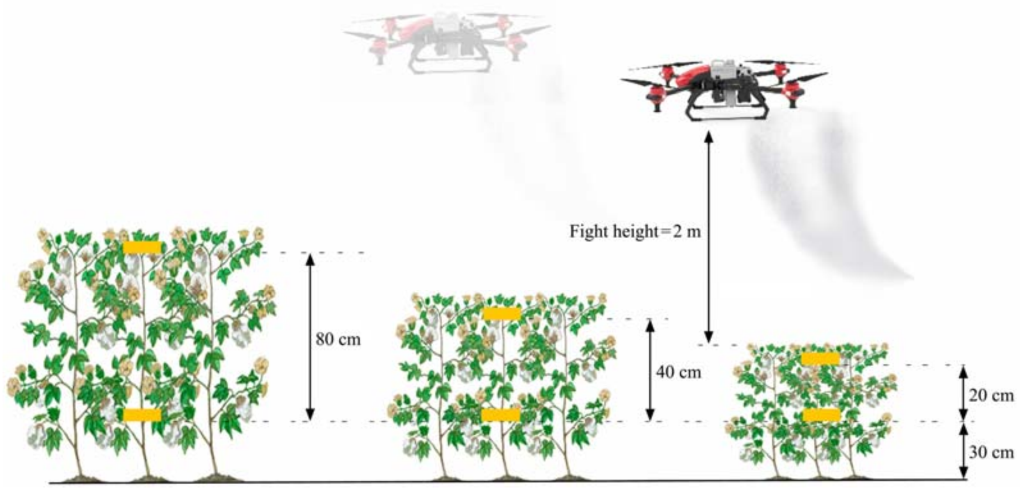


Figure 2 Flight information and the layout of WSP cards in multiple height cotton canopy

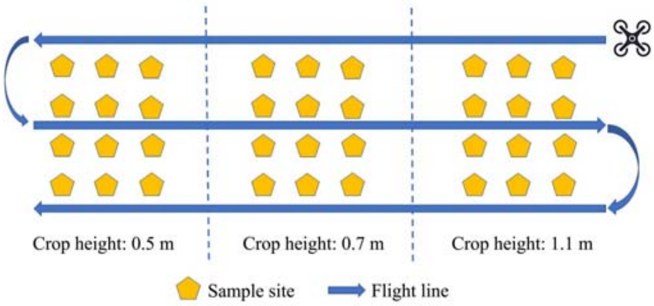


Figure 3 Experimental layout of each plot, in relation to the UAV sprayer

3 Results

3.1 Droplet distribution in upper layer

This part is the result of droplet distribution on the upper layer of the cotton canopy. The main indicators include droplet deposition, deposition density, and droplet coverage. The effects of the spray volume and the canopy height on the droplet distribution are discussed separately.

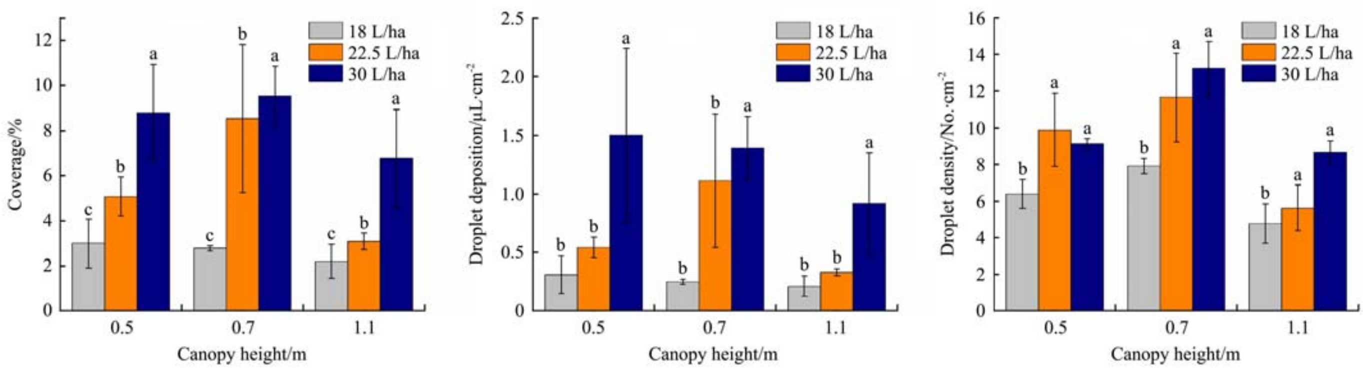
3.1.1 Effect of spray volume

As shown in Table 3, the droplet deposition distribution in the upper layer of the cotton canopy is significantly affected by the spray volume. For the droplet coverage (P<0.001), there is a significant difference between the 30 L/ha treatment (T3, T6, T9) and the 18 L/ha (T1, T4, T7) treatment. When the volume was 30 L/ha, the maximum droplet coverage was achieved in the T3, T6, and T9 treatments. The droplet coverage is 8.79% at T3, 9.51% at T6, and 6.77% at T9. Regarding the droplet deposition (P<0.001) and the droplet density (P<0.001), the results of treatment with different spray volume also showed significant differences. When the spray volume is 30 L/ha, the droplet deposition is 1.50 μL/cm² (T3), 1.39 μL/cm^2 (T6), and 0.92 μL/cm^2 (T9), which is much higher than that of 18 L/ha treatment 0.31 μL/cm^2 (T1), 0.25 μL/cm^2 (T4), and 0.21 μL/cm^2 (T7). Increasing the spray volume can also increase the density of droplets. When the spray volume is 30 L/ha, the droplet density is from 8.66 to 13.23/cm^2, while the result of 18 L/ha treatment is 4.77 to 7.91/cm^2.

Table 3 Model results for the analysis of the effects of different factors in upper layer

Factor	Df (Factor, error)	Spray coverage		Droplet deposition		Droplet density	
		F-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
Canopy height	2,18	4.8	0.02*	2.2	0.1	17.7	<0.001***
Spray volume	2,18	17.9	<0.001***	12.0	<0.001***	13.9	<0.001***
Canopy height *Spray volume	4,18	1.2	0.3	0.9	0.5	1.5	0.3

Note: [a] Significant at the P<0.05 level, ** significant at the P <0.01 level, *** significant at the P<0.001 level.
[b] (2, 18), where 2 corresponds to the factor degree of freedom and18 refers to the error degree of freedom.

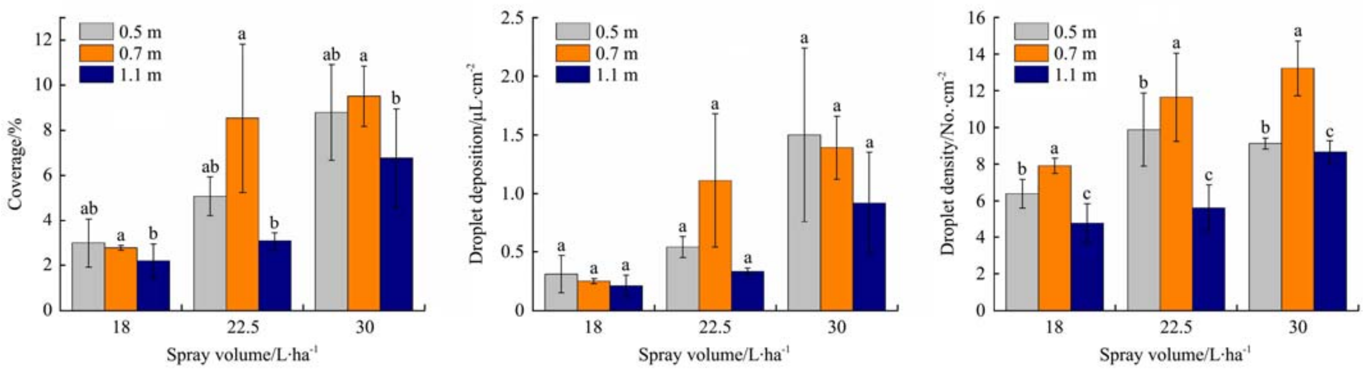


a. Coverage under the spray volumes b. Droplet deposition under the spray volumes c. Droplet density under the spray volumes

Figure 4 The results of droplet distribution among spray volumes on upper layer
(The column chart from left to right is T1, T2, T3; T4, T5, T6; and T7, T8, T9)

3.1.2 Effect of canopy height

The results of droplet coverage (P=0.022) and deposition density (P<0.001) are significantly different in several canopy heights. There is no significant difference in the coverage results between the cotton canopy is 0.5 m and 0.7 m. As shown in Figure 5, when the average height of the canopy is 0.7 m, the coverage on the upper canopy is 2.78% (T4), 8.54% (T5), and 9.51% (T6). While the coverage rates are 2.20% (T7), 3.08% (T8), and 6.77% (T9) when canopy height is 1.1 m. The coverage of 1.1 m area is much lower than 0.7 m area. Compared with 0.5m and 1.1 m, the result of droplet density achieves a maximum value when the canopy height is 0.7 m. And he density of droplets is 7.91/cm^2 (T4), 11.65/cm^2 (T5), and 13.23/cm^2 (T6) respectively. There is no significant difference in the average result of droplet deposition in different canopy regions.



a. Coverage under the canopy heights b. Droplet deposition under the canopy heights c. Droplet density under the canopy heights

Figure 5 The results of droplet distribution among canopy heights on upper layer
(The column chart from left to right is T1, T4, T7; T2, T5, T8; and T3, T6, T9)

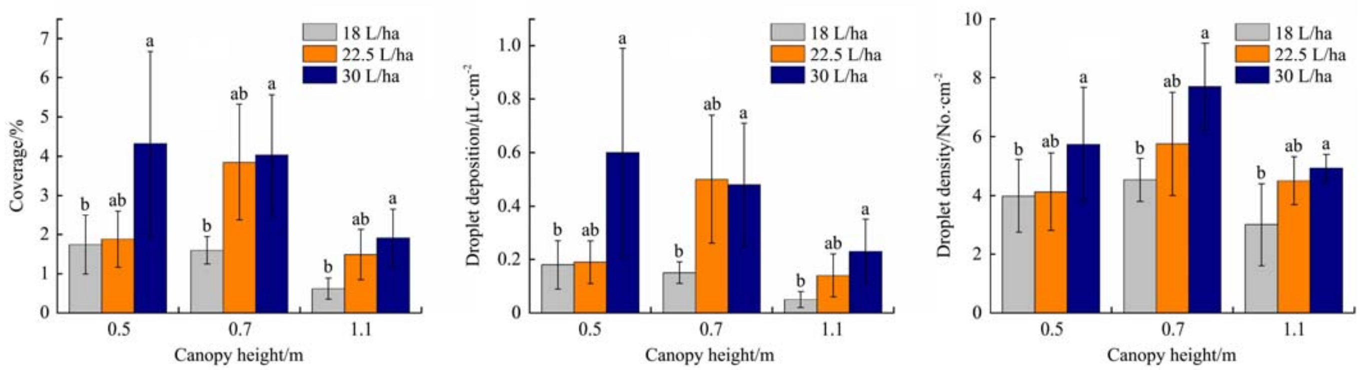
3.2 Droplet distribution in bottom layer

3.2.1 Effect of spray volume

The spray volume has a significant effect on the droplet distribution in the lower layer. When the spray volume is 30 L/ha, the droplet coverage, deposition and droplet density are better than other spray volume treatments. As shown in Figure 6, when the application volume is 30 L/ha, the droplet coverage was 4.32% (T3), 4.03% (T6), and 1.91% (T9), respectively. When the spray volume is 18 L/ha, the droplet coverage is 1.74% (T1), 1.59% (T4), and 0.62% (T7). The droplet deposition (P=0.03) and the deposition density (P=0.03) have similar results, and the deposition distribution data when the spray volume is 30 L/ha is much higher than the 18 L/ha spray treatment.

Table 4 Model results for the analysis of the effects of different factors in bottom layer

Factor	Df (Factor, error)	Spray coverage		Droplet deposition		Droplet density	
		F-value	P-value	F-value	P-value	F-value	P-value
Canopy height	2, 18	3.9	0.04*	2.7	0.1	3.2	0.07
Spray volume	2, 18	4.9	0.02*	4.2	0.03*	4.5	0.03*
Canopy height *Spray volume	4, 18	0.8	0.6	0.9	0.5	0.3	0.9

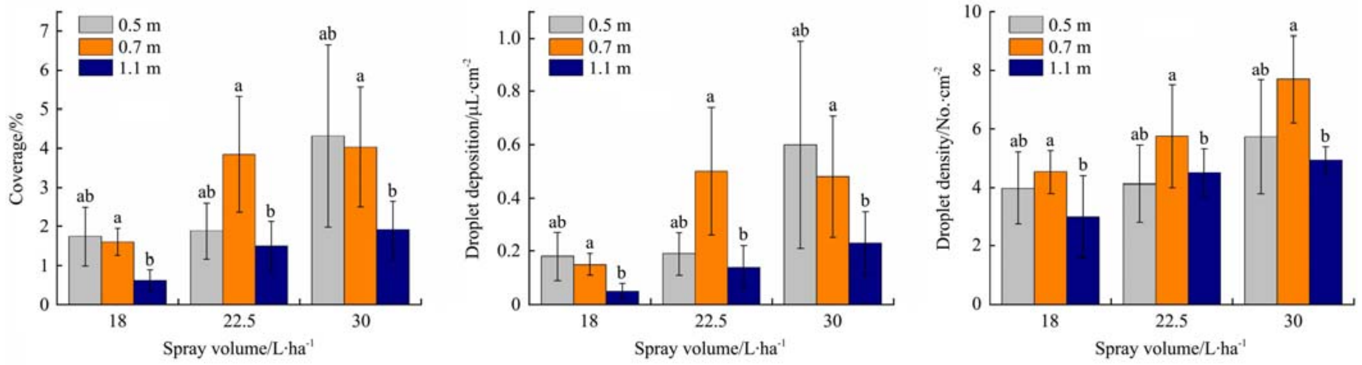


a. Coverage under the spray volumes b. Droplet deposition under the spray volumes c. Droplet density under the spray volumes

Figure 6 The results of droplet distribution among spray volumes on bottom layer
(The column chart from left to right is T1, T2, T3; T4, T5, T6; and T7, T8, T9)

3.2.2 Effect of canopy height

The droplet coverage at the bottom of the canopy (P=0.04) is affected by the canopy structure. As shown in Figure 7, the droplet coverage were 1.59% (T4), 3.84% (T5), and 4.03% (T6) in the cotton area with an average height of 0.7 m. There is no significant difference between this data and the result of 0.5 m area, but it is better than the result of droplet coverage in 1.1 m area. Although the P value of the significance test of the deposition amount (P=0.1) and the droplet density (P=0.07) is greater than 0.05, after Duncan's post-test, the deposition distribution in the 0.7 m area is still better than the 1.1 m area. The average droplet deposition is 0.32 μL/cm^2 at 0.5 m, 0.38 μL/cm^2 at 0.7 m, and 0.14 μL/cm^2 at 1.1 m. The average droplet density is 4.61/cm^2 at 0.5 m, 5.99/cm^2 at 0.7 m, and 4.13/cm^2 at 1.1 m.



a. Coverage under the canopy heights b. Droplet deposition under the canopy heights c. Droplet density under the canopy heights

Figure 7 The results of droplet distribution among canopy heights on bottom layer
(The column chart from left to right is T1, T4, T7; T2, T5, T8; and T3, T6, T9)

3.3 Discussion

The above results indicate that the spray volume has a significant effect on the droplet distribution in the canopy. Regardless of the upper layer or the lower layer, the droplet deposition, including coverage, deposition, and droplet density, etc., will gradually increase with the increase of the spray volume. These results are similar to the conclusions of previous studies[16,18]. The increase of spray volume means the change in the spray flow per unit area, which is extremely important for improving the droplet distribution in the lower layer of the cotton canopy. But in actual application, it is difficult to guarantee the spray volume.

Limited by battery life, the load capacity of agricultural drones is mostly in the range of 10-20 L[1,2,13,14]. The most prominent contradiction is the limited load capacity and the operational efficiency requirements in market applications. In the spraying applications, the applicator not only cares about the spraying effect, but also pays more attention to work efficiency and economic benefits. In the case of limited load, in order to improve work efficiency, the applicator may reduce the required application volume, such as choosing 18 L/ha instead of 30 L/ha. For cotton with low density or low canopy height, a certain degree of spraying effect may be obtained, but for cotton areas with high canopy density, the deposition and distribution of droplets on the cotton canopy is minimal. Therefore, it is necessary to ensure the amount of spraying volume through the popularization of spraying technology and legal improvement.

In this study, the canopy height is used to describe the difference between the three cotton areas. Canopy height is only one of the quantifiable values. In fact, the difference in height represents different cotton canopy biomass. From the data analysis results, in the upper canopy, the droplet deposition distribution in the area with an average height of 0.7 m is better, while the droplet deposition distribution in the 1.1 m canopy area is poor. The droplet distribution of the lower layer in the area with an average height of 0.7 m and 0.5 m is better than that in the area of 1.1 m. However, with the increase of sprayed volume, the droplet distribution in the 1.1 m canopy area, especially in the lower layer of the cotton canopy, has been greatly improved.

Some theories believe that the UAV has a rotor wind field, which can disturb the canopy through the airflow[19]. This may cause more droplets to penetrate the crop canopy and reach the bottom area of the crop. In this study, the results of droplet distribution on the upper and lower canopy are significantly different. The droplets are more distributed in the upper part of the canopy rather than the lower part. The droplet deposition on the upper part is 200%-400% of the bottom. The dense crop leaves are a natural barrier for the movement of droplets. The upper leaves intercept more droplets, and only a small part of the droplets can reach the lower part of the crop canopy[20,21]. For the cotton defoliation process, the lower part of the canopy needs to be covered with more droplets to ensure a consistent defoliation effect. This study believes that increasing the liquid volume can improve the distribution of droplets in the canopy, especially the lower layer. In addition, how to choose the appropriate spray volume for different droplet canopy structures is a problem that should be considered.

4 Conclusions

Several drone spraying tests were carried out in cotton canopy areas of different heights. The application liquid volume is 18 L/ha, 22.5 L/ha, and 30 L/ha. The average canopy height is 0.5 m, 0.7 m, and 1.1 m. XAG P30 plant protection UAV was used in this experiment. The effects of the spray volume and the canopy height on the droplet distribution on the upper and bottom of the cotton canopy are discussed separately. The results show that the droplets are more distributed in the upper part of the canopy rather than the lower part. The spray volume has a significant effect on the droplet distribution in the canopy. The coverage, deposition, and droplet density will gradually increase with the increase of the application volume. The droplet distribution in the 1.1m canopy area is poor, but it can be improved by increasing the spray volume.

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