Droplets deposition and harvest-aid efficacy for UAV application in arid cotton areas in Xinjiang, China

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Abstract: With the development of Unmanned Aerial Vehicle (UAV) sprayers, the application of low-volume spraying of harvest-aid and other agrochemicals to cotton using UAVs is becoming a new agronomic trend worldwide. The effect of spray volume and canopy density for UAV spraying is significant but was rarely studied. In this study, five representative spray volumes were explored to examine the effect of spray volume on deposition and harvest-aid efficacy for cotton using a UAV sprayer. To explore the effect of canopy density, similar tests were carried out in a field located nearby with a lower leaf area index (LAI). A conventional trailer boom sprayer was selected for comparison. Different spray volumes had a significant effect on defoliation, but had no significant effect on boll opening and fiber quality. A higher defoliation rate was achieved in the lower LAI field. The total rate of defoliation using the UAV was inferior to the boom sprayer in the high LAI field for lower deposition and defoliation rate in the lower canopy. Considering the deposition, defoliation rate, and working efficiency, a spray volume of 15.0 L/hm^2 with an average droplet size of 150 μm is recommended for UAV application.

Keywords: UAV, droplets deposition, spray volume, canopy density, leaf area index, defoliation, boll opening rate
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1 Introduction

Cotton is an important and economically valued agricultural product worldwide because it provides fiber, feed, foodstuff, oil, and biofuel[1,2], which plays a vital role in daily human life. How to improve the yield and quality of cotton fiber is a matter of great concern. Before the mechanical harvest of cotton, harvest-aid chemical application is critical to improving the cotton yield by increasing the boll opening rate and improving cotton quality, which in turn is achieved by increasing the defoliation rate by decreasing the leaves and trash content in harvested lint[3].

With large-scale cotton cultivation, ground-based sprayers with long boom have always been the main spraying equipment for cotton harvest-aid application[3-6].

However, the use of boom sprayers at this stage can easily damage the plants and causes boll shedding due to this spraying approach is usually slow and has contact with the culture, especially in high planting density and thick canopy at the boll opening stage of cotton. Moreover, the high water consumption of boom sprayers may result in significant water resource wastage, especially in water-scarce areas such as Xinjiang Region. The third issue was the mechanical damage to soils. This heavy-wheeled equipment can compact the soil, resulting in reduced soil aeration and impeded root growth[7]. Spraying with fixed-wing aircraft can be an alternative, but fixed-wing aircraft usually require a dedicated airport and navigation station, which reduced operating convenience and increase operating costs. Besides, low-altitude flight (at around 5 m high) also increases the risk of accidents[8]. An excellent alternative to reduce the risk of fatal accidents is to use unmanned (autonomous or remote-controlled) aircraft, like UAVs.

Worldwide, the rapid development of the agricultural UAV application in recent years and its unique advantages are changing the way agrochemicals application[9]. Based on the prediction of the Association of Unmanned Vehicles Systems International, the legalization of commercial drones could potentially create more than $80 billion in economic impact from 2015 to 2025, and of that share agricultural applications could account for 80%[10]. In China alone, according to the 2019 statistics from the Chinese Ministry of Agriculture, the number of UAV sprayers used in agricultural applications was close to 45 000 with an operating area of 33.5 million hm^2. Among these UAVs, four-rotor UAVs from XAG Company are the most representative, and the spraying area of these UAVs accounts for over a third of all agricultural UAVs in China. Based on the information provided by the XAG company, their UAVs have been used in more than 30 countries, including the USA, Japan, Australia, Korea, and the UK. Given their widespread use and large spraying area, these UAVs have been selected for our study. In comparison to boom sprayers, UAVs spraying is more water- and labor-efficient, less damaging to

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crops, and is associated with a higher working efficiency[11-14].

With the rapid development of agricultural UAVs, an amount of research on the application technology of UAVs has been conducted over the last decades. In terms of spraying equipment optimization, various nozzles including ultra-low volume swirl nozzles[15], centrifugal nozzles[16], and electrostatic nozzles, which are suitable for UAVs had been studied. The spray performance and atomization quality of these nozzles have been systematically evaluated[17], which meets the needs of the current low-volume spraying of UAVs. In terms of spraying parameters optimization, various crops such as rice[18], wheat[19], maize[20], and fruit trees[21,22] under different spraying parameters with UAV application were tested, and deposition rate and variation coefficients of deposition were used as evaluation indicators to analyze the interaction relationship between droplet deposition and crop canopy. The optimized flight height, flight speed, and spray swath were selected[23,24], which improved the pesticide application quality. In terms of field efficacy evaluation, the effect of spray volume and droplet size on different crop diseases and pest control were tested and the results proved the feasibility of UAV spraying[25,26]. Droplets drift is the most challenging and complex issue that caused extensive concern associated with the application technology of UAVs. Studies from paddy rice[27] and pineapple[28] used gasoline-powered single-rotor unmanned helicopters and showed that different UAVs spray under different temperatures and humidity resulting in quite different drift distances. Wang et al[7] compared the drift potential of three different volume median diameters (100 μm, 150 μm, and 200 μm) from a commercial quadcopter equipped with centrifugal nozzles under different wind speeds (0.00-0.38 m/s) and found the deposition at 12 m downwind direction decreased by an order of magnitude compared with the average deposition within the in-swath zone, at 50 m downwind was lower than the detection limits of 0.0002 μL/cm^2. The mass balance method is also a good way to assess deposition and drift. Wang et al.[29] evaluated UAV sprayers' deposition and drift using an artificial vineyard and found air-injector nozzle was an effective technique for promoting deposition distribution and reducing drift. But if a commonly used hollow cone nozzle, over half of the droplets drifted mainly from airborne loss. Although the drift issue is inevitable, the drift distance of the tested UAV model is much less than that of manned aerial applicators[28,29].

Although UAV spraying has been applied to various crops[18-22], studies on cotton defoliation efficacy using UAVs are limited. With the development of UAVs, lower spray height and smaller droplet size enable lower spray volume[8]. Whether the low-volume spraying and small droplets can achieve a satisfying cotton defoliation efficacy is worth to further study. Otherwise, the effect of canopy density or LAI on the penetration of droplets and the cotton defoliation rate in the case of distinct canopies using UAV applications was little-known and also needs further study. The findings of this study are expected to provide reference and data support for UAV harvest-aid chemicals application in Xinjiang Region.

2 Materials and methods

2.1 UAV and boom sprayers

The UAV and trailer boom sprayers are illustrated in Figure 1.

The UAV sprayer is a four-rotor electrical-powered aircraft (XAG Company, Guangzhou, China) developed for plant protection services in China (Figure 1a). There are four centrifugal nozzles mounted under each rotor. The nozzles are angled in the vertically downward direction concerning the direction of flying. Under different voltages, the rotation rate of the nozzle was in the range of 0-16 000 r/min, and the droplet size created by the nozzle was varied using the rotation rate. The droplet size and flow rate can be set and adjusted using the handheld ground control unit. According to the recommendations of the manufacturer, a droplet size of 150.0 μm was used for this experiment. The accuracies of the flying height and velocity were controlled in centimeters with the help of real-time kinematic differential positioning technology. The trailer boom sprayer (Figure 1b) was made up of a horizontal boom, a hanging boom, and 16 parallel booms hung vertically under the horizontal boom. Nozzles on the horizontal boom and hanging booms were all spaced by 76 cm, and each hanging boom had three groups of bilateral symmetrical nozzles (Figure 2).

a. UAV sprayer b. Trailer boom sprayer

Figure 1 UAV sprayer (Four-rotor electrical-powered aircraft) and trailer boom sprayer

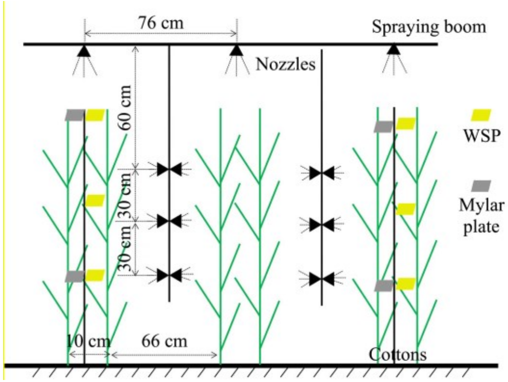


Figure 2 Spraying system of the trailer boom sprayer and the layout of the sampling collectors

The first, second, and third pairs of nozzles on the hanging boom were placed 60 cm, 90 cm, and 120 cm away from the horizontal boom, respectively. The spraying fan on the hanging boom was vertical to the ground. Other parameters of the boom sprayer and the UAV sprayer are listed in Table 1. According to a local service company, the spray volume of the boom sprayer was 450.0 L/hm^2.

Table 1 Technical parameters for the boom sprayer and UAV sprayer

Parameter	Boom sprayer	UAV sprayer
Boom length	12 m	--
Nozzle number	111	4
Nozzle type	Hollow cone nozzle	Centrifugal nozzle
Nozzle spacing	760 mm (Horizontal nozzle spacing)	1050 mm
Nozzle orientation	Downward and horizontal	Downward
Tank capacity	400 L	12 L
Pressure or rotary speed	0.3 MPa	10000 r·min^{-1}
Flow rate	54 L·min^{-1}	0.47-3.16 L·min^{-1}
Spraying width	12 m	3.5 m
Spraying height	0.5 m (Horizontal boom)	2 m

2.2 Experimental design

Two harvest aid application experiments were conducted in the Xinjiang Uygur Autonomous Region, China. The first experiment was conducted in a field with high LAI, and the second experiment was conducted in a field with low LAI during the 2018-2019 crop season on Farm 150 of the Xinjiang Production and Construction Crops (Longitude 86.059491°, latitude 44.948591°) (Figure 3). The two fields are located close by (Figure 3) and cotton was planted on April 27, 2018, and was of the 'Xinluzao 64' variety.

Except for the planting densities, the plant variety, planting date, and management of water and fertilizer were the same for the two fields. The LAI used to characterize the canopy density was measured using a CI-110 Plant Canopy Imager (CID Bio-Science, Inc. USA). Owing to the different planting densities, the LAI of the two fields was different (Table 2). The crop characteristics are listed in Table 2.

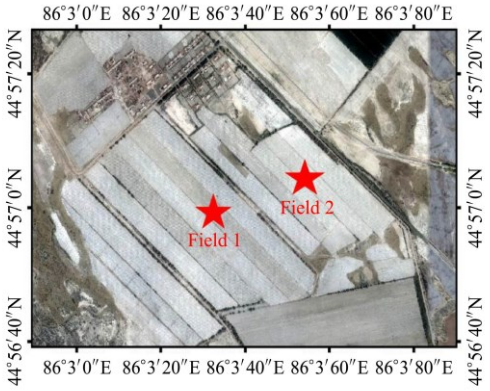


Figure 3 Test location and a brief overview of the studied cotton field

Table 2 Crop characteristics in two fields

Field	Plant height (means±standard error/cm)	Plant density/plant·hm^{-2}	LAI (Means±standard error)	Row spacing/cm	The variety	Test location
Field 1	105.2±1.7	180 000-195 000	1.87 ± 0.31	10+66	Xinluzao 64	Farm 150
Field 2	103.5±2.1	150 000-165 000	1.32 ± 0.16			

Note: The LAI was tested before the harvest aid application on September 5, 2018.

The effect of spray volume, using a UAV sprayer, on the characterization of spray deposition and harvest-aid efficacy, was conducted in the field with high LAI. The UAV sprayer with five different spray volumes (4.5, 7.5, 15.0, 22.5, and 30.0 L/hm^2) was employed for the test. The different spray volumes were achieved by varying the flight speed and flow rate (Table 3).

Table 3 Test arrangement in Field 1 and Field 2

Field	Sprayer	Spray volume /L·hm^{-2}	Working speed /km·h^{-1}	Flow rate /L·min^{-1}
Field 1	UAV Sprayer	4.5	5.0	0.47
		7.5	5.0	0.79
		15.0	5.0	1.58
		22.5	5.0	2.36
		30.0	4.0	2.52
	Boom Sprayer	450.0	6.0	54.0
	Blank	0.0	--	--
Field 2	UAV	15.0	5.0	1.58
	Boom Sprayer	450.0	6.0	54.0
	Blank	0.0	--	--

Based on the experience of the service company, a spray volume greater than 30.0 L/hm^2 was not tested owing to the excessive spray volume, which resulted in excessively lower working efficiency and higher economic cost. A spray volume lower than 4.5 L/hm^2 was also not tested owing to the hot and dry conditions of the Xinjiang region, which are associated with high evaporation conditions.

To explore the effect of canopy density on spray deposition and harvest-aid efficacy, a spray volume of 15.0 L/hm^2, using a UAV sprayer, was tested in the field with low LAI. A conventional trailer boom sprayer with a spray volume of 450.0 L/hm^2 was set up as a reference, and a blank control was arranged for comparison in two fields. The blank control was used to verify the effect of the chemicals on defoliation as compared to the natural defoliation of the plants. The spray parameters of the two sprayers used in the experiment are listed in Table 1.

A rectangular area of 1200 m^2 (12 m×100 m) was reused to test the characterization of the spray deposition in the two fields on September 5, 2018. Note that the cotton canopy should be undamaged when sampling, so as not to affect subsequent sampling. Before application, a spray mixture containing water and a fluorescent tracer of Rhodamine-B (Surround WP, Engelhard Corp., Iselin, NJ, USA, 60 g/hm^2) was added to the tank for each treatment.

For the harvest-aid efficacy test, treatments in each field were set up in completely randomized blocks with three replications. Each replication was arranged in an area of 1500 m^2 (30 m×50 m).

2.3 Characterization of spray deposition

The effect of spray volume on deposition was conducted in the field with high LAI. To explore the effect of canopy density on spray deposition, the UAV sprayer with a spray volume of 15.0 L/hm^2 was tested in the field with low LAI. A boom sprayer with a spray volume of 450.0 L/hm^2 was used as a reference in two fields.

2.3.1 Layout of the sampling collectors

Before application, a total of 3 groups containing 24 sample sites were set up perpendicular to the spray direction (Figure 4). Each group included eight equally spaced sample sites across the center of the flight line (Figure 4).

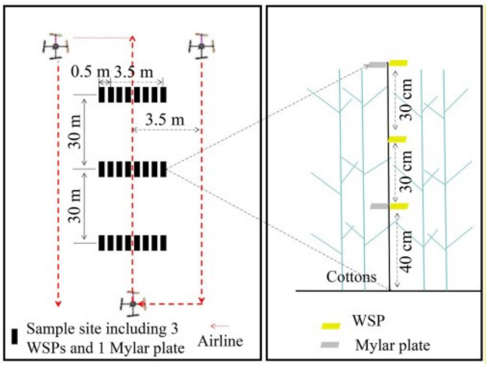


Figure 4 Layout of the sampling collectors

To avoid cross-contamination, each group was located at an interval of 30 m. Each sample site was located 0.5 m apart and spanned a total of 3.5 m within the same group. Artificial samplers, including 3 WSPs and two mylar plates, were fixed horizontally on the plastic rod through double-headed clamps at each sample site (Figure 5). Two mylar plates positioned on the top and bottom of the canopy were placed 100 cm and 40 cm above the ground, respectively. The heights of the 3 WSPs were adjusted to assist their positioning in regions equivalent to the upper, middle, and bottom of the cotton, which were located 100, 70, and 40 cm above the ground, respectively (Figure 5).

Figure 5 Placement of samples at each sampling site within the cotton canopy

After application, each mylar plate and WSP were collected separately in zip-lock bags along with a label describing the details of information pertaining to the treatment of the sample site. 72 WSPs and 48 mylar samples for each treatment were collected.

2.3.2 Deposition on the mylar cards

The mylar plates (50 mm×80 mm) were used to assess the amount of spray deposition and were analyzed in the laboratory using an F-380 spectrofluorophotometer (Guangdong Sci. & Tech. Development Co., Ltd, Tianjin, China). Each mylar plate was washed using 20 mL of distilled water in a zip-lock bag. After sufficiently agitating the sample, part of the effluent was poured into a cuvette. The cuvette containing the effluent was tested using the spectrofluorophotometer with an excitation wavelength of 550 nm and an emission of 575 nm. The spray deposition on the mylar plates was calculated by comparing with similarly determined dye concentrations and area of the mylar plates.

2.3.3 The number of deposits and the spray coverage rate

WSPs (25 mm×30 mm) were used to assess the number of deposits and coverage rates. A scanner with a resolution of 600 dpi in the laboratory was used to scan the WSPs. An imagery software, DropletScan (USDA, USA)[30], was used to analyze the coverage rate and the number of deposits on the scanned images.

2.3.4 Meteorological parameters

Meteorological data during the deposition experiment were collected using a Kestrel 5500 digital meteorograph (Loftopia, LLC, USA), which recorded air temperatures ranging from 32.9°C-36.0°C, relative humidity between 32.9%-36.0%, and wind velocities between 1.4-2.1 m/s during the test periods. The wind angle deviation corresponding to the angle of the wind relative to the sampling line was in the range of (52±11)°.

2.4 Study of harvest-aid efficacy

The effect of spray volume on harvest-aid efficacy was also conducted in the field with high LAI. To explore the effect of canopy density on harvest-aid efficacy, the UAV sprayer with a spray volume of 15.0 L/hm^2 was tested in the field with low LAI. In each field, the boom sprayer with a spray volume of 450.0 L/hm^2 and a blank control were used for comparison.

2.4.1 Defoliant and Reagents

Based on the local situation, the harvest aid chemicals were applied twice to each field, once on September 5, 2018, and again seven days later (Table 4). A second application is required for rank cotton with dense foliage because the initial coverage rate may not be sufficient for the bottom leaves of the plants. Harvest aid chemicals in the first application were a combination of 540 g/L Thidiazuron-Diuron suspension concentrate at 180 g a.i./hm^2 (Jiangsu Institute of Ecomones Co., Ltd., China), 40% Ethephon Aqueous Solution at 450 g a.i./hm^2 (Anyang Quanfeng Biological Technology Co., Ltd., Anyang, China) and 280 g/L Alkyl-ethyl-sulfonate spray adjuvants at 720 g a.i./hm^2 (Jiangsu Institute of Ecomones Co., Ltd., China). The only difference between the second application and the first application was that the amount of Ethephon was increased to 1050 g a.i./hm^2 (Table 4). The chemicals and application times were determined based on standard methods used in the area.

Table 4 Harvest-aid chemicals usage and application date

Application date	Harvest-aid chemicals (product name)	Applied rate	Spray equipment
September 5, 2018 (First application)	540 g/L Thidiazuron·Diuron SC+40% Ethephon AS +280 g/L Alkyl-ethyl-sulfonate spray adjuvants	180 g a.i. hm^{-2}+450 g a.i. hm^{-2} +720 g a.i. hm^{-2}	UAV and Boom Sprayer
September 13, 2018 (Second application)	540 g/L Thidiazuron·diuron SC+40% Ethephon AS +280 g/L Alkyl-ethyl-sulfonate spray adjuvants	180 g a.i. hm^{-2}+1050 g a.i. hm^{-2} +720 g a.i. hm^{-2}	

Note: SC, Suspension Concentrate; AS, Aqueous Solution; a.i., active ingredient

2.4.2 Cotton defoliation and boll opening after application

Before chemical application, a five-point sampling method was applied to investigate the number of leaves and opening bolls. At each point, ten plants were randomly tagged with red ropes. To avoid drift pollution, these plants were only assessed in the center of the test field, about 5 m from the edge. The positions of the tagged cotton were also marked in the upper, middle, and lower parts. Similar to the deposition test, the upper, middle, and lower sections were set at 100 cm, 70 cm, and 40 cm above the ground, respectively. The numbers of leaves, opening bolls, and total bolls in the three different positions were investigated. After the first application, the number of leaves, opening bolls, and total bolls were counted four times at 4, 7, 11, and 13 days after treatment (DAT) for the same tagged plants. The defoliation percentage was calculated using Equation (1). The Boll opening percentage was calculated using Equation (2).

$$D_P=(L_b-L_a)/L_b\times100\% \tag{1}$$

$$B_O=O_b/T_b\times100\% \tag{2}$$

where, D_P is the defoliation percentage, %; L_b is the number of leaves before treatment; L_a is the number of leaves after treatment; B_O is the boll opening percentage; O_b is open bolls; T_b is the total number of bolls.

2.4.3 Fiber quality determination

At 15 DAT, the cotton samples from different parts of the plant in the field with high LAI were taken to the laboratory for fiber quality analysis. One subsample weighing 200 g was extracted from each replication to test the fiber quality. The testing was conducted at the Supervision Inspection and Test Center of Cotton Quality, at the Ministry of Agriculture in Henan province, China. The test variables included fiber length, uniformity, micronaire, strength, maturity ratio, and elongation.

2.4.4 Meteorological parameters

The temperature and rainfall 22 d after the defoliation application in September 2018 are shown in Figure 6. The daily maximum temperature varied widely, and the average and minimum temperatures showed a steady decrease. Before September 24, the minimum temperature was in the range of 7.1°C-17.3°C, and the average temperature was in the range of 16.2°C-25.3°C. The machine picked the cotton before the temperature decreased on September 22.

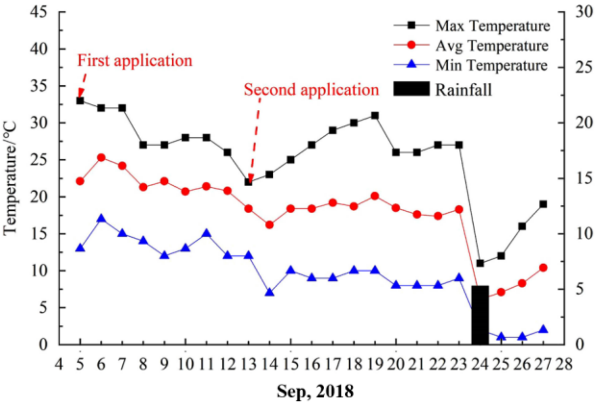


Figure 6 Temperature and rainfall within 22 d after the defoliation application in September 2018

2.5 Statistical analysis

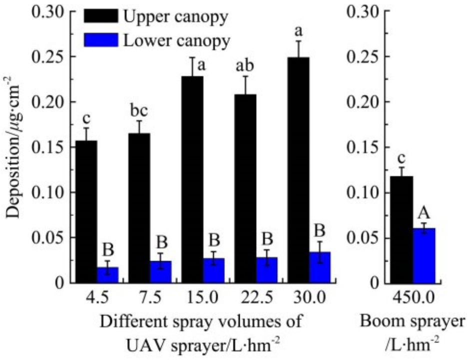
Statistical analyses of deposition, defoliation rate, boll opening, and fiber quality were performed using the SPSS generalized linear model procedure (SPSS v22.0, SPSS Inc, Chicago, IL, USA). Before analysis, the data were transformed to stabilize wide variances and satisfy assumptions of normality. The data expressed as a percentage (defoliation, boll opening, uniformity, and elongation of the cotton fiber) was required to be arcsine-transformed to match the requirements of the normal, rather than binomial, distribution. The other data was required to be log (x+1) transformed for the sake of normality. The transformed data were proved to be normally distributed according to the Kolmogorov-Smirnov test and had equal variances based on Levene's test. With the normalized data, a factorial analysis of variance (ANOVA) was used to ascertain the effect of spray volume on the deposition, cotton defoliation rate, boll opening, and fiber quality. Two-sample t-tests were used to distinguish significant differences caused by canopy density. Duncan's new multiple test was used to analyze significant differences between the multifactor treatments, and the significance level was set at α = 0.05.

3 Results

3.1 Effects of spray volume on spray deposition and harvest-aid efficacy

3.1.1 Deposition on the mylar cards

The spray volume, of the UAV sprayer, significantly ($p < 0.01$) affected the deposition on the mylar cards (Figure 7). The average deposition on the upper canopy achieved by the UAV sprayer at 15.0 L/hm^2 and 30.0 L/hm^2 was significantly higher than at spray volumes of 4.5 L/hm^2 and 7.5 L/hm^2. The minimum deposition on the upper canopy of 0.16 μg/cm^2 was recorded at 4.5 L/hm^2, which was 63.2% of the maximum deposition at 30.0 L/hm^2. Compared with the UAV sprayer, the boom sprayer had a lower deposition on the upper canopy. However, on the lower canopy, the deposition was significantly higher than in the case of the UAV sprayer. This was mainly caused due to the different spraying systems of the two sprayers. For the boom sprayer, the hanging spray booms extend inside the canopy, leading to a higher proportion of deposition in the lower canopy than in the case of the UAV sprayer. For the UAV sprayer, the droplets were sprayed from a height of 2 m without the hanging boom extending within the canopy, and thus the deposition mainly occurred on the upper canopy. The cotton canopy profoundly influenced the deposition on the lower canopy.



Note: Bars with the same label in the same canopy do not differ statistically (p< 0.05).

Figure 7 Spray deposition (mean±standard error) on the mylar plates under different spray volumes

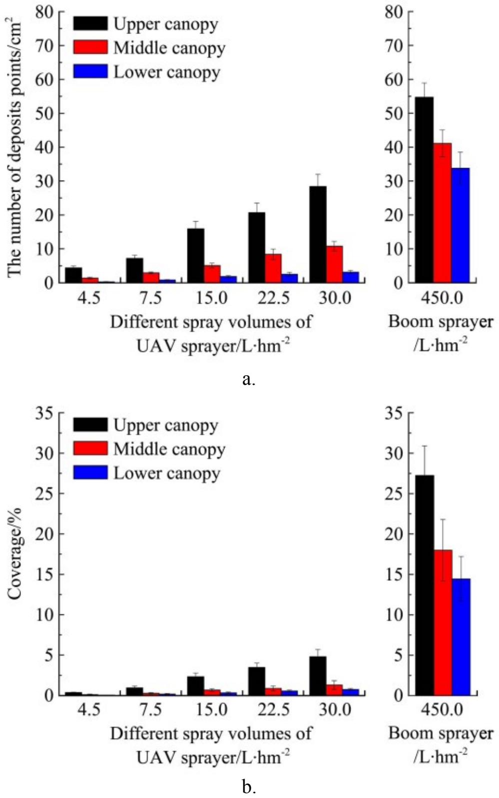
3.1.2 The number of deposits and coverage rate on the WSP

The coverage rate depends on droplet size, the number of deposits, and the extent of the coverage of the WSP40. In this experiment, the changing rules of the coverage were consistent with the number of deposits and presented a positively linear relation to the spray volume (R^2>0.95) (Figure 8). When the spray volume was set at 4.5 L/hm^2, 7.5 L/hm^2, 15.0 L/hm^2, 22.5 L/hm^2, and 30.0 L/hm^2, using the UAV sprayer, the number of spray deposits per area on the upper canopy and lower canopy were 4.4, 7.2, 15.9, 20.7, 28.4, and 0.3, 0.8, 1.8, 2.5, 3.1 points/cm^2, respectively (Figure 8a). However, the spray volume of the boom sprayer was more substantial, leading to a significantly higher number of deposits and coverage rate.

Shielded by the cotton leaves and branches, the number of deposits and coverage rate significantly decreased from the top canopy to the bottom (Figure 8). Compared with the upper canopy, the coverage rate of boom sprayer in the middle and bottom were reduced by 34.0% and 47.0%, respectively (Figure 8b). For the UAV sprayer, the coverage rate in the middle and bottom canopy decreased by 70.2%-74.7% and 82.0%-86.0% than the upper canopy, respectively (Figure 8b). Compared to the boom sprayer, the UAV sprayer had poor droplet penetration.

3.1.3 Cotton defoliation

The defoliation rate of different spray volumes produced by the UAV sprayer in the field with high LAI is indicated in Figure 9. The total defoliation of the blank control was 20.0% at 13 DAT, which was significantly lower than the chemical application. A significant difference (p<0.01) in the defoliation rate was also observed between the different spray volumes of the UAV sprayer at 13 DAT (Figure 9). The lowest achieved cotton defoliation rate was 64.1% at a spray volume of 4.5 L/hm^2, which was significantly lower than other measurements. When the spray volume was higher than 7.5 L/hm^2, the spray volume showed no significant effect on the defoliation rate. The total defoliation rate of the boom sprayer was 85.6%, which was significantly higher than the UAV sprayer, except for the spray volume of 15.0 L/hm^2.



a.

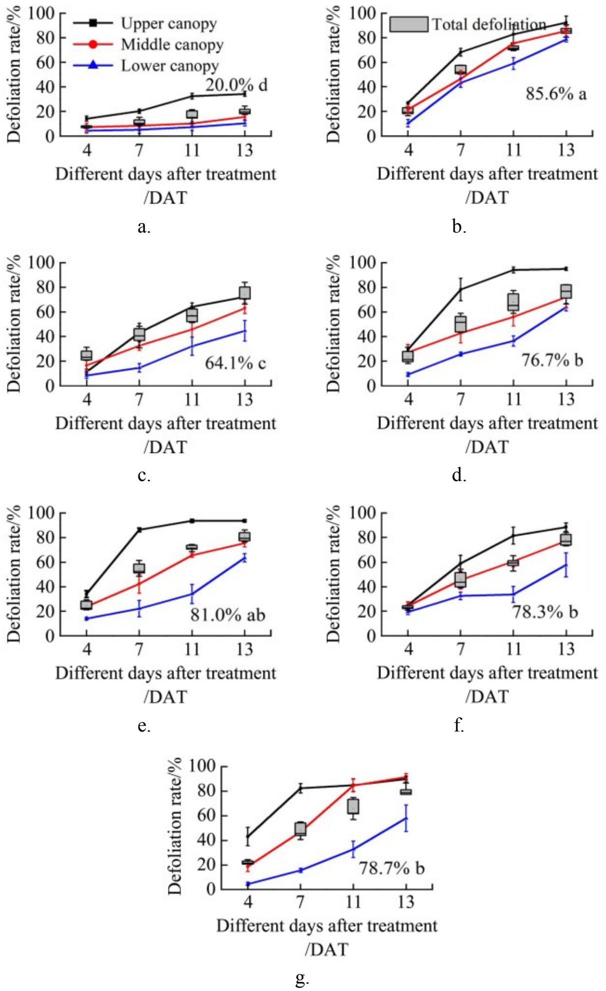
b.

Figure 8 The number of deposits (mean±standard error, a) and coverage rate (mean±standard error, b) of the UAV sprayer and boom sprayer on the upper, middle, and lower canopies at different spray volumes

The defoliation rate in different parts of the cotton canopy differed. This phenomenon was observed in both the UAV sprayer and the boom sprayer but was more pronounced for the UAV sprayer. The greatest defoliation rate occurred in the upper canopy, followed by the middle canopy, and the lowest for the lower canopy. This was because the deposition decreased from the top canopy to the bottom. Additionally, juvenile leaves are mostly found at the top of the canopy and are more sensitive to harvest aid chemicals. When the spray volume varied from 7.5 to 30.0 L/hm^2, the defoliation rate, using the UAV sprayer, in the upper, middle, and lower canopies were in the range of 88.5%-94.9%, 72.1%-91.5%, and 57.7%-63.9%, respectively. In the upper and middle canopy, the defoliation of the boom sprayer was 92.3% and 85.5%, which was similar to that of the UAV sprayer. However, in the lower canopy, the defoliation rate of the boom sprayer was 78.6%, which was superior to that of the UAV sprayer.

3.1.4 Cotton boll opening

The cotton boll opening for different spray volumes produced by the UAV sprayer in the field with high LAI is indicated in Figure 10. The boll opening rate before the application of the sprayer was in the range of 7.7%-12.8%. Compared with the blank control, the application of harvest aid chemicals can significantly improve the boll opening rate (Figure 10). The rate of boll opening increased with the duration of the experiment after application, and significant differences produced by different spray volumes, using the UAV sprayer, began to show at 4 DAT. The highest boll opening rate at 4 DAT was achieved for the spray volume of 22.5 L/hm^2, which was 31.2%. The changing trends at 7 DAT and 11 DAT were similar to that at 4 DAT. At 13 DAT, the boll opening rate, using the UAV sprayer, was in the range of 74.3%-85.9%, which did not significantly (p=0.078) differ from the boom sprayer which recorded a rate of 84.0% (Figure 10). Combined with the results of deposition, the lack of significant difference between spray volumes and sprayers may be attributed to the excessive application of Ethephon.



a.

b.

c.

d.

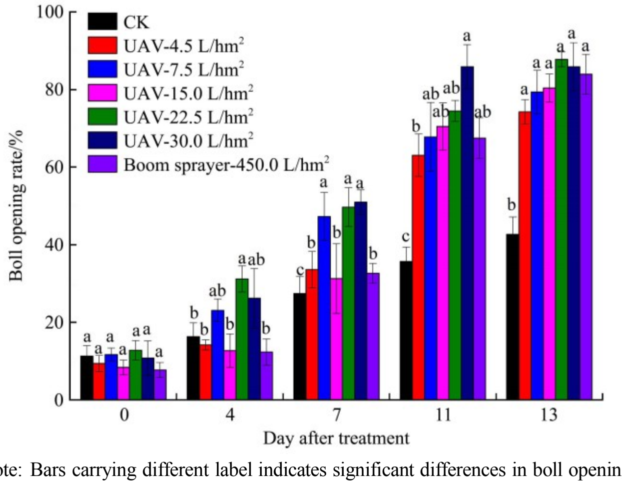
e.

f.

g.

a: Blank control; b: Boom sprayer with a spray volume of 450.0 L/hm^2; c, d, e, f, g: UAV sprayer with spray volumes of 4.5, 7.5, 15.0, 22.5, 30.0 L/hm^2, respectively. The percentage numbers are the defoliation rate at 13 DAT. The same label of the different spray volumes at the 13 DAT does not differ statistically (p<0.05).

Figure 9 Different canopies and total defoliation rates (mean±standard error) of the UAV sprayer and boom sprayer at 4, 7, 11, and 13 DAT under different spray volumes in the field with high LAI



Note: Bars carrying different label indicates significant differences in boll opening rate on the same DAT at p<0.05 level by Duncan's new multiple range test.

Figure 10 Boll opening rate (mean±standard error) before application and at 4, 7, 11, and 13 DAT under different spray volumes of the UAV sprayer and boom sprayer in the field with high LAI

3.1.5 Cotton fiber quality

The spray volume of the harvest aids had no significant effect on cotton fiber quality, as shown in Table 5. The test results of fiber length, uniformity, micronaire, fiber strength, maturity, and elongation were in the range of 23.1-24.0 mm, 82.4%-85.6%, 4.76-5.39, 27.4-27.6 cN/tex, 0.84-0.85, and 6.6%-6.7%, respectively. The test results show that the high concentration of chemicals sprayed by the UAV did not affect the fiber quality of the cotton.

Table 5 Effects of spray volumes using the UAV sprayer and boom sprayer on the fiber quality of the cotton. Data followed by the same letters do not differ statistically

Equipment	UAV sprayer					Boom sprayer
Spray volume/L·hm^{-2}	4.5	7.5	15.0	22.5	30.0	450.0
Length/mm	24.3^{a}	23.7^{a}	23.5^{a}	24.0^{a}	23.8^{a}	23.1^{a}
Uniformity/%	81.7^{ab}	85.6^{a}	83.8^{a}	84.3^{a}	84.1^{a}	82.4^{a}
Micronaire	5.1^{a}	5.4^{a}	4.9^{a}	5.4^{a}	5.3^{a}	4.76^{a}
Strength (cN/tex)	27.5^{a}	27.4^{a}	27.4^{a}	27.4^{a}	27.4^{a}	27.6^{a}
Maturity ratio	0.83^{a}	0.85^{a}	0.84^{a}	0.85^{a}	0.85^{a}	0.84^{a}
Elongation/%	6.6^{a}	6.6^{a}	6.6^{a}	6.7^{a}	6.7^{a}	6.7^{a}

Note: $p<0.05$; Duncan's test

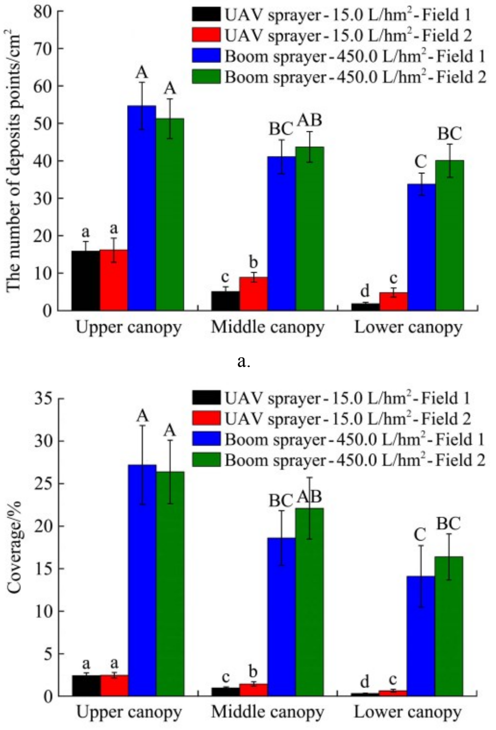
3.2 Effects of canopy density on spray deposition and harvest-aid efficacy

3.2.1 The number of deposits and coverage rate on the WSP

The comparison of two fields on the number of deposits and coverage rate is shown in Figure 11a and Figure 11b, respectively. Influenced by a lower canopy density for the field with low LAI, the number of deposits (Figure 11a) and the coverage rate (Figure 11b) of the same sprayer in the same canopy were higher than for the field with high LAI. For the UAV sprayer, the number of deposits in the middle and lower canopy of the field with low LAI was improved by 74.5% and 160.9% than for the field with high LAI, respectively. For the boom sprayer, the number of deposits in the middle and lower canopy was improved by 6.3% and 18.7%, respectively. Similar results were obtained for the coverage rate. Compared with the boom sprayer, the thicker canopy had a greater effect on the droplets' penetration in the middle and lower canopy when using the UAV sprayer.

3.2.2 Cotton defoliation

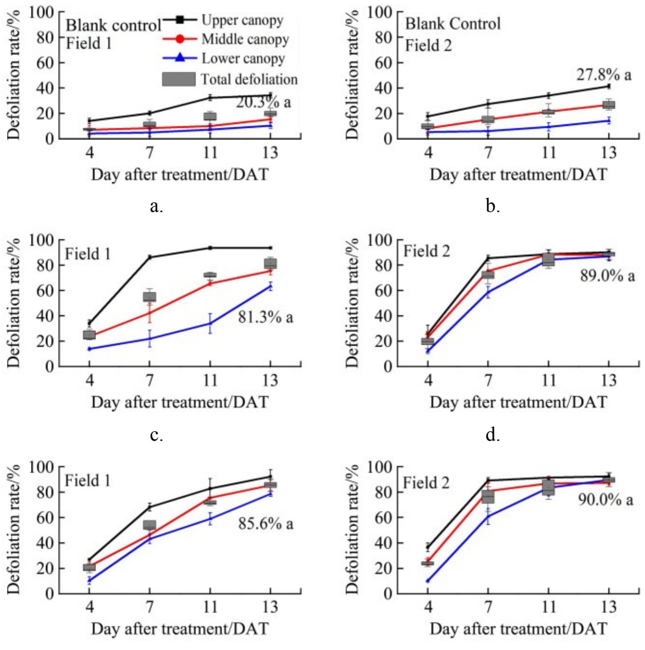
The total defoliation in the field with high LAI and the field with low LAI did not show significant differences for both the UAV and boom sprayer at 13 DAT (Figure 12). For the UAV sprayer, although the total defoliation rates in the two fields were not significantly different, the defoliation rates in the upper, middle, and lower were slightly different. In the field with low LAI, the defoliation rate in the upper canopy was 93.6%, which was slightly higher than the field with a high LAI of 90.3%, which is confusing. The defoliation rate in the middle and lower canopy was 88.1% and 88.7%, respectively, which were significantly higher than in the field with high LAI of 75.4% and 63.4%, respectively. This phenomenon is comprehendible. Due to the different LAI, the number of deposits and coverage in the middle and lower canopy in the field with low LAI were significantly higher than the field with high LAI, which leads to different cotton defoliation values. For boom sprayers, the difference in LAI did not result in a significant difference in the number of deposits, coverage, and defoliation. Similar to the defoliation results in the field with high LAI, the total defoliation rate using the UAV sprayer and the boom sprayer in the field with low LAI was not significantly different from one another.



a.

b.

Figure 11 Comparison of the two fields with different LAI on the number of deposits (mean±standard error, a) and coverage rate (mean±standard error, b) by UAV sprayer and boom sprayer. Bars with the same label under the same sprayer do not differ statistically ($p<0.05$)



a.

b.

c.

d.

e.

f.

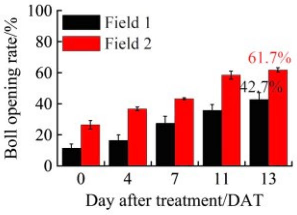
Note: Bars with the same label under the same sprayer do not differ statistically ($p<0.05$) by *t*-test. a, b: Blank control in Field 1 and Field 2; c, d: UAV sprayer application in Field 1 and Field 2; e, f: Boom sprayer application in Field 1 and Field 2.

Figure 12 Comparison of the two fields on defoliation rates (mean±standard error) at 4, 7, 11, 13 DAT

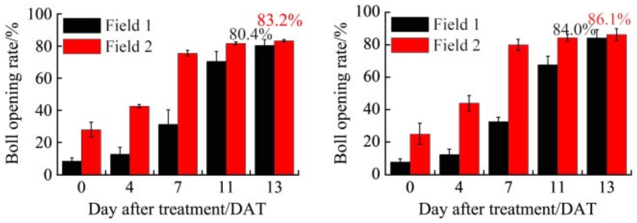
3.2.3 Cotton boll opening

For the blank control, the boll opening rate in the field with low LA before application and at different DAT was higher than for the field with high LAI (Figure 13). With the chemical application, the boll opening rates for the two fields were improved.

At 13 DAT, there was no significant difference between the two fields regardless of the sprayer. Although the deposition in the lower canopy was quite different in the two fields, it did not cause variations in the boll opening rate. Similar to the inference in Section 3.1.4, the excessive application of Ethephon may mask the effect of different depositions.



a. blank control



b. UAV sprayer application with a spray volume of 15.0 L/hm^2

c. Boom sprayer application with a spray volume of 450.0 L/hm^2

Figure 13 Comparison of the two fields for boll opening rates (mean±standard error) at 4, 7, 11, 13 DAT

4 Discussion

The results demonstrate that the spray volume, using the UAV sprayer, had a significant effect on harvest-aid efficacy by affecting deposition, the number of deposits, coverage rate, and canopy penetration. The changing trend of the deposition caused by the spray volume was consistent with the defoliation rate. When a specific spray volume (15.0 L/hm^2) was reached, the deposition and the defoliation rate did not change with the spray volume. However, the number of deposits and coverage rates presented a positively linear relation to the spray volume. The number of deposits and coverage increased with the spray volume but did not have a significant influence on defoliation and boll opening. Defoliants are often divided into two categories, herbicides or hormones[31].

During chemical spraying, the spray volume plays an essential role in droplet deposition and field efficacy because it has a significant effect on leaf run-off, coverage, droplet numbers, and chemical concentration per unit leaf area[25]. From our study, the spray volume of 15.0 L/hm^2 was acceptable for the test involving the UAV, and a lower spray volume leads to an unsatisfactory defoliation rate. Traditionally, harvest aid application has primarily been provided by boom sprayers with the spray volume in the range of 93-280 L/hm^2 (10-30 gallons per acre)[3-6] or using manned aerial vehicles with a spray volume in the range of 47-93 L/hm^2 (5-10 gallons per acre)[6,32,33]. Siebert et al.[34] studied the optimum combination of nozzle type and spray volume (47, 94, and 140 L/hm^2) to maximize harvest-aid efficacy. The study concluded that the harvest-aid application should employ a hollow cone or flat fan nozzles for a spray volume of at least 94 L/hm^2 using a boom sprayer. Using the recommendations provided by the 2019 Mid-South cotton defoliation guide for the United States (2019)[6], the spray volume should not be lower than 46.7 L/hm^2 (5 gallons per acre) for aerial and 140.1 L/hm^2 (15 gallons per acre) for ground cotton defoliation applications when the amount of water was used as a carrier. Compared with previous studies[31,34], the spray volume of 15.0 L/hm^2 is a very low recommended value. When the spray volume was set at 15.0 L/hm^2, the coverage sprayed by the UAV was recorded as 2.30%, 0.67%, and 0.33% on the upper, middle, and lower canopy of the cotton, respectively.

According to our analysis, two reasons lead to satisfactory defoliation and boll opening results. Although most harvest aid chemicals do not translocate or move far within the cotton[31], the droplets deposited on the leaves can translocate to the petiole, and a certain amount of deposition can cause abscission and can help achieve good defoliation[34]. Besides, the size of the droplets in the test case was 150 μm, which is smaller than conventional sprayers. The smaller droplets benefit chemical penetration and are absorbed by the leaves, which may be another reason for the comparable defoliation for the lower coverage.

When the spray volume is set at 4.5 L/hm^2 and 7.5 L/hm^2, the deposition was significantly lower than in other cases. Based on the high temperature, dry testing environment, and deposition results, the losses are largely attributed to the droplet's evaporation, which has a more significant effect on lower spray volumes. Besides, too low a spray volume makes it harder to spread a relatively small dosage of chemicals over a relatively large area and a relatively large number of leaves in different canopies. The optimal spray volume for producers must have high efficiency and be effective and economical[35]. If the spray volume was set at a lower rate than recommended, a producer will risk higher foreign matter and a lower defoliation rate, which would also have a direct impact on lint quality and economic benefit[36].

From the deposition results on the lower canopy, the UAV sprayer exhibited inferior penetration than the boom sprayer. This result was similar to that arrived at by other studies[5,14]. This phenomenon was more pronounced in the field with high LAI. Although the downwash from the UAV sprayer can improve droplet penetrability[37], the thick cotton canopy also prevents the penetration of droplets into the lower canopy, which leads to poor defoliation of the lower canopy.

Besides the spray volume, the canopy structure, including the amount of foliage, also has a significant effect on the distribution of spray deposits within canopies and harvest-aid efficacy. The leaf area index (LAI) is defined as the one-sided green leaf area per unit ground surface area[38], which reflects the amount of foliage linked to the trajectory of droplets passing through the canopy. With an increased LAI, droplets were more easily captured, which leads to a lower proportion in the lower canopy[39]. However, UAV sprayers have unique characteristics, including rotor wings, which are significantly different from conventional sprayers and may have a distinct influence on droplet penetration[40]. The total defoliation of the two fields was not significantly different for both the UAV and the boom sprayer. However, for the UAV sprayer, although the total defoliation rates in the two fields were of no significant difference, the defoliation rates in the upper, middle, and lower sections were slightly different. The defoliation rates in the middle and lower canopy in the field with low LAI were significantly higher than in the field with high LAI. According to the deposition results, the difference in LAI between the two fields must be the crucial reason for this behavior. Although the LAI is also used in precision farming for controlling the spray volume[41], the increase in the spray volume did not affect the defoliation rate in the field with high LAI. Positively, the canopy density also affects the cotton yield, but the conclusion was inconsistent[42-45]. Nevertheless, improving the cotton yield, the defoliation rate, and the lint quality through reasonably dense planting need thorough consideration.

Machine harvesting is a once-over operation that occurs when all the leaves are desiccated, and the boll opening rate reaches 85%[36]. However, the total defoliation rate in our experiment was lower than 90%. The main factor limiting the improvement of the defoliation rate could be attributed to the weather conditions. Harvest aids, such as Thidiazuron, Diuron, Ethephon, and Cyclanilide, have optimal activity when the maximum daily temperatures hover above 27°C and the minimum daily temperatures are above 10°C[4]. However, the experiments were conducted in the northern region of Xinjiang, where cotton has a relatively short growth period and the temperature drops early in September. To further avoid the influence of cold weather on defoliation, the first application was carried out earlier and the boll opening rate was lower (only 7.7%-12.8%, Figure 10). Although a boll opening rate of 40%-60% would be a better period for application[43,44], the weather conditions in northern Xinjiang did not allow for this and might have further contributed to the poor defoliant results.

5 Conclusions

In this study, the effect of spray volume and canopy density on cotton harvest-aid in two fields was studied. In the field with high LAI, the total defoliation using the UAV sprayer was inferior to that obtained by the boom sprayer. The inferior total defoliation rate was mainly caused by the lower deposition and defoliation rate in the lower canopy, thus requiring improvement. Considering the deposition, harvest aid efficacy, and working efficiency, a spray volume of 15.0 L/hm^2 would be recommended to farmers using UAV sprayers for harvest aid application with cotton. The total defoliation rate using the UAV sprayer was calculated as 81.0% when the spray volume was set at 15.0 L/hm^2, which achieved the maximum working efficiency and lowest economic cost under the condition of satisfying the requirement of mechanical picking. There was no significant difference in the boll opening rate and fiber quality among the different spray volumes using the UAV sprayer.

The canopy density had a significant effect on deposition and defoliation. In the field with low LAI, the droplets easily penetrated the lower canopy resulting in a higher defoliation rate.

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