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Effects of Dosage and Spraying Volume on Cotton Defoliants Efficacy: A Case Study Based on Application of Unmanned Aerial Vehicles

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Abstract: Plant protection unmanned aerial vehicles (UAVs) consist of light and small UAVs with pesticide spraying equipment. The advantage of UAVs is using low-volume spray technology to replace the traditional large-volume mass locomotive spray technology. Defoliant spraying is a key link in the mechanized cotton harvest, as sufficient and uniform spraying can improve the defoliation quality and decrease the cotton trash content. However, cotton is planted at high density in Xinjiang, with leaves in two adjacent rows seriously overlapped, making the lower leaves poorly sprayed. Thus, the defoliation effect is poor, and the cotton quality is degraded. To improve the effect of defoliation and reduce the losses caused by boom sprayer rolling, the effect of defoliant dosage on defoliation, boll opening, absorption and decontamination in cotton leaves and the effect of spraying volume on absorption and decontamination in cotton leaves sprayed by UAVs are studied. The pooled results indicate that plant protection UAVs could be used for cotton defoliants spraying with a twice defoliant spraying strategy, and the defoliant dosage has no significant effect on seed cotton yield and fiber quality in Xinjiang. The residue of thidiazuron in cotton leaves reaches the maximum at four days after spraying, the residue of diuron in cotton leaves reaches the maximum at one day after second spraying. The thidiazuron and diuron residues are increased with spraying volume at rang of 17.6–29.0 L/ha. When the spraying volume is less than 17.6 L/ha, the residue of thidiazuron and diuron is reduced. The research results could provide a reference for further optimization of the spraying parameters of cotton defoliant by plant protection UAVs.

Keywords: cotton defoliant; dosage and spraying volume; absorption and decontamination; unmanned aerial vehicle

1. Introduction

Cotton (*Gossypium hirsutum* L.) is an important commercial crop worldwide, and serves as a significant source of fiber, feed, foodstuff, oil and biofuel [1,2]. Cotton is the pillar industry of

Xinjiang Uygur Autonomous Region, China, which is of great significance to the economic and social development of Xinjiang [3]. Defoliation or leaf abscission is induced in cotton as a natural physiological process, which is usually inadequate or not timely enough for a complete mechanical harvest of cotton. Therefore, defoliation before harvest is often induced by managing the plants so that senescence, abscission (separation) layer development and leaf drop are encouraged [4–7]. Advantages associated with defoliant application prior to cotton harvest include: increased harvester efficiency, reduction in the leaves and trash content in harvested lint, and quicker drying of dew. Defoliant spraying is a key link in the mechanized cotton harvest, as sufficient and uniform spraying could improve the defoliation quality and decrease the cotton trash content, and it is significant to solve defects of cotton quality [8,9]. Mechanization, modernization and standardized production are the basic paths of sustainable development of the Xinjiang cotton industry [10]. Most cotton pesticide operations are carried out using large-volume ground machinery in Xinjiang, which results in rolling the cotton plant, hitting the bolls, pulling the cotton branch, hitting the opened balls off, water and pesticide wastage, and reduces the yield and quality of cotton. It is a bottleneck and technical issue that restricts the cotton quality and efficiency of Xinjiang. Herbicidal defoliant diuron and hormonal defoliant thidiazuron are widely used in Xinjiang. Thidiazuron increases the concentration of ethylene relative to auxin in leaf petioles and results in the activation of the leaf abscission layer [11–13]. Diuron accelerates the scorch of cotton leaves, improves defoliation under low temperature conditions [14]. However, these types of defoliants induce drastic leaf abscission which inhibits timely transport of nutrients from leaves to cotton bolls. Also, these defoliants do not directly influence boll ripening and must be applied in combination with ethephon, a boll opener, to provide satisfactory defoliation and boll opening [15,16].

Plant protection unmanned aerial vehicles (UAVs) are light and small UAVs with pesticide spraying equipment. UAVs achieve precision pesticide spraying using the global positioning system (GPS) and geographic information system (GIS) [17,18]. The advantage of UAVs is using low-volume spray technology replaced the traditional large-volume mass locomotive spray technology. [19]. UAVs accomplish spray precision docking by GPS and real-time kinematic (RTK) automatic navigation technology, which increases the quality of aviation plant protection operations significantly [20]. Compared to conventional agricultural aircraft, UAVs do not require a special airport and have additional advantages, such as good mobility [21,22]. UAVs are also more adaptable for spraying at low altitudes due to geographical restrictions [23,24]. Meanwhile, UAVs could effectively improve pesticide efficacy, reduce pesticide amounts, and rational use of pesticide [25,26]. The problem of the development of plant protection UAVs is the combination and relationship between aircraft and agricultural plant protection in China [27,28]. Plant protection is accompanied by the reduction in agricultural disease, insects, weed control and prevention, while low-altitude aviation is emerging as a breakthrough in aviation technology. The initial combination of aviation and plant protection has resulted in low-altitude aviation plant protection. UAVs have a very important value in the development of precision agriculture, fulfilling an urgent need in the development of modern agriculture in China. Currently, leaves of the cotton canopy overlap, making it inconvenient for crop spraying using a conventional land spraying machine. Due to the harsh walking conditions in cotton fields, operating a land-spraying machine is very difficult and requires high labor intensity. Large-volume spraying not only leads to pesticide waste but also seriously endangers the environment and the operators [29]. The development of aviation plant protection technology would drive the development of new pesticide industries and the aviation application equipment industries in line with the needs of national strategic development which has broad market prospects and bring about huge economic, social and ecological benefits [30].

Boom sprayers are widely used for large farm crops due to their high working efficiency and favorable spraying effect. However, there are still some problems in cotton defoliant spraying in Xinjiang. Cotton is planted in a high density in Xinjiang, the row space is 10 cm and 66 cm, causing leaves in two adjacent rows to be seriously overlapped, which results in reducing the yield and quality of cotton [9]. Zhao et al. [31,32] and An [33] reported control of cotton aphids, Qin et al. reported control of plant hoppers by UAVs, which showed good results and could effectively decrease insect population trends [34]. However, there are few reports on the spraying defoliants by UAVs. Herein, the authors report this study's results concerning the effect of defoliant dosage on defoliation, boll opening, absorption and decontamination in cotton leaves and the effect of spraying volume on absorption and decontamination in cotton leaves sprayed by plant protection UAVs, to obtain the optimized parameters for the working of UAVs, and provide references and bases for further improving the cotton defoliant spraying technique.

2. Materials and Methods

2.1. Experimental Material

2.1.1. The UAV Sprayers and Equipment

The aviation platforms were the JT-30 UAV (UAV 1, Figures 1 and 2, Xinjiang Jiangtian Aviation Science and Technology Co., Ltd., Xinjing, China) and the 3WQF120-12 UAV (UAV 2, Figure 1, Anyang Quanfeng Aviation Plant Protection Technology Co., Ltd., Anyang, China), which were equipped with a spraying unit. The main parameters of the UAV 1 and UAV 2 are presented in Table 1. The UAVs both used GPS and RTK navigation technology, with the accuracy of the flying height and flying velocity controlled within 0.1 m and 0.1 m/s, respectively. The spraying platforms consisted of a medical kit with a capacity of 30 L (UAV 1) and 12 L (UAV 2), a miniature straightway pump, pipeline, spraying nozzle, and electronic control valve. UAV 1 with six spraying nozzles (hollow conical nozzle) were symmetrically arranged on both sides of the UAV at the same interval (700 mm), and the installing angle of the 4 spraying nozzles was a vertically downward spraying direction and using 2 spraying nozzles with a 60° angle in a horizontal direction. UAV 2 with three spraying nozzles (LU120-02) were symmetrically arranged on both sides of the UAV and in the precise middle at the same interval (625 mm), and the installing angle of the spraying nozzles was a vertically downward spraying direction. Using a working pressure of 0.3 MPa (UAV 1) and 0.3 MPa (UAV 2), the measured flow rate of a single spraying nozzle was 250 mL/min (UAV 1) and 400 mL/min (UAV 2).

Figure 1. Spraying defoliant by unmanned aerial vehicle (UAV) (UAV 1 and UAV 2).

Thidiazuron and diuron were analyzed with an Agilent 1200 HPLC equipped with a reversed-phase column (Agilent XDB-C18 4.6 × 150 mm, 5 µm, Agilent, Santa Clara, CA, USA) at 25 °C. The mobile phase was methanol/water (65/35, v/v) at a flow rate of 0.8 mL/min. The injection volume was 20 µL and electronic balance, BSA224S-CW, was from Sartorius, Göttingen, Germany. High speed centrifuge, LDZS-2, was from Beijing Jingli centrifuge Co. Ltd., Beijing, China. Swirl meter, MS3 D S25, IKA, came from Staufen im Breisgau, Germany. Ultrasonic cleaner, KQ-500 DB, was from Kunshan Ultrasonic Instruments Co. Ltd., Kunshan, Jiangsu, China and the Rotary Evaporators, RV10 D, were from IKA, Staufen im Breisgau, Germany.

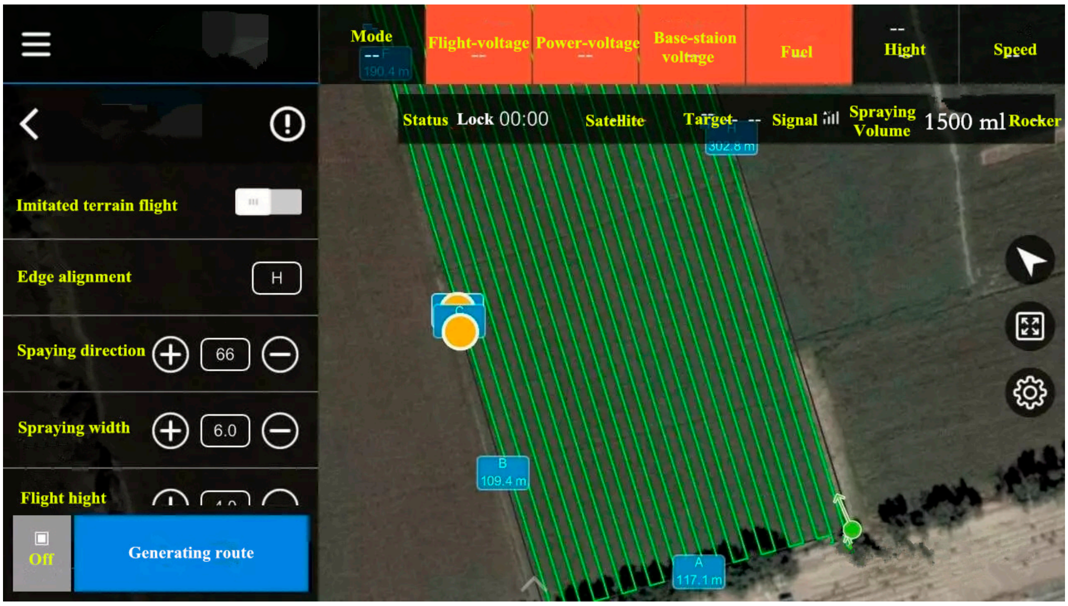

Figure 2. Flight control platform of UAV 1.

Table 1. Characteristic parameters of UAV 1 and UAV 2

Parameter	UAV 1	UAV 2
Rotor (cm)	Six rotor (Diameter, 76.5)	Single rotor (Diameter, 2410)
Motor	Electric-Powered	Kerosine-powered
Nozzle type	Hollow conical nozzle	LU120-01/LU120-02/LU120-02/LU120-04
Nozzle numbers	6	3
Pressure (MPa)	0.3	0.3
Spraying angle (°)	4 for 0 (vertically down), 2 for 60 (horizontal direction)	0 (vertically down)
Spraying width (m)	6	4
Spraying height (the height to the canopy of the cotton, m)	2	2
Flying altitude (the height to the ground) (m)	2.7	2.7
Spray rod length (m)	3.5	1.25
Flow rate (one nozzle) (mL/min)	680	300/560/770/930
Driving speed (m/s)	5	4
Tank capacity (L)	30	12
Working efficiency (ha)	50–60	20–25
Net weight (kg)	24	30
No-load operation (min)	35	≥45

2.1.2. Defoliant and Reagents

80% thidiazuron wettable powder was produced by Jiangsu Repont Pesticide Factory Co., Ltd., Changzhou, China. 37% thidiazuron + 17% diuron suspension concentrate, came from Jiangsu Institute of Ecomones Co., Ltd., Nanjing, China. 40% ethephon aqueous solution produced by Jiangsu Anpon Electrochemical Co., Ltd., Huaian, China were used. Thidiazuron standard (97%) and diuron standard (97%), from J&K Scientific Ltd., Beijing, China were used. Methanol (HPLC), came from Sigma-Aldrich, St. Louis, MO, USA. Primary secondary amine (PSA) sorbent, was produced by Welch Technology (Shanghai) Limited Co., Ltd., Shanghai, China.

2.2. *General Situation of Experimental Field*

The effect of defoliant dosage on defoliation, boll opening, absorption and decontamination in cotton leaves experiment was carried out in Beiquan town of Xinjiang Production and

Construction Crops, Shihezi, (E 85°28′32″, N 44°39′54″), Xinjiang Uygur Autonomous Region, China, during September 2017. The experimental field had middle level fertilizer and planted cotton for many years. Cotton (Xinluzao 64) was planted on 24 April 2017, using a mechanical cotton-picking planting model, with wide film planting 6 lines (10 cm + 66 cm), 195,000 cotton /ha, and drip irrigation under plastic film. The effect of spraying volume on the dynamics of defoliant absorption and decontamination in cotton leaves experiment was carried out in Farm 150 of Xinjiang Production and Construction Crops (E 86°03′28″, N 44°56′42″), Shihezi, Xinjiang Uygur Autonomous Region, China, during September 2017. The experimental field had middle level fertilizer planted cotton for many years. Cotton (Xinluzao 64) was planted on 21 April 2017, using a mechanical cotton-picking planting model, a wide film planting 6 lines (10 cm + 66 cm), 180,000 cotton /ha, drip irrigation under plastic film. The heights, growing ways and leaf area index were uniform within each farm. The difference of the two farms was the density, which was affected by the soil fertility and planting density.

2.3. Experimental Treatment

2.3.1. Effect of Defoliant Dosage on Defoliation Effect Sprayed by UAV 1

The experiment consisted of 4 treatments (Table 2). Cotton defoliant spraying was carried out on 7 September 2017 and 15 September 2017.

Table 2. Defoliant treatment for defoliant dosage.

Treatment	**Spraying Volume (L/ha)**	**Dosage (g/ha)**					
		7 September 2017			**15 September 2017**		
		80% Thidiazuron	**Adjuvant**	**40% Ethephon**	**37% thidiazuron + 17% diuron**	**Adjuvant**	**40% Ethephon**
1	22.5	150	150	300	180	720	900
2	22.5	300	300	600	180	720	900
3	22.5	450	450	900	180	720	900
4	22.5	0	0	0	0	0	0

2.3.2. Effect of Spraying Volume on Defoliation Effect Sprayed by UAV 2

The experiment consisted of 4 treatments (Tables 3 and 4). Cotton defoliant spraying was carried out on 5 September 2017 and 13 September 2017. The weather during the experimental period is in Table S1.

Table 3. Defoliant treatment for spraying volume.

Treatment	**Spraying Volume (L/ha)**	**Nozzle Type**	**Speed (m/s)**	**Area (m^2)**
5	9.3	LU120-01	4	3200
6	17.6	LU120-02	4	3200
7	24.2	LU120-03	4	2400
8	29.0	LU120-04	3.5	2400

Table 4. Defoliant treatment for spraying volume.

Treatment	**Spraying Volume (L/ha)**	**Dosage (g/ha)**					
		5 September 2017			**13 September 2017**		
		37% thidiazuron + 17% diuron	**Adjuvant**	**40% Ethephon**	**37% thidiazuron + 17% diuron**	**Adjuvant**	**40% Ethephon**
5	9.3	180	720	450	180	720	1050
6	17.6	180	720	450	180	720	1050
7	24.2	180	720	450	180	720	1050
8	29.0	180	720	450	180	720	1050

2.4. Defoliation and Boll Opening

Prior to treatment application, 30 plants were randomly tagged to count the number of leaves on each plant. The number of leaves was counted again 4, 8, 12 and 15 day after spraying on the same tagged plants. Defoliation rate was calculated by Equation (1).

$$\text{Defoliation rate (\%)} = ((N_a - N_b)/N_a) \times 100\% \quad (1)$$

where N_a = Number of leaves before treatment, N_b = Number of leaves after treatment.

Boll opening rates were determined on the same tagged 30 plants. Bolls on each plant were examined and recorded as either opened or closed and the boll opening rate was calculated by Equation (2).

$$\text{Boll opening rate (\%)} = (N_c/N_d) \times 100\% \quad (2)$$

where N_c = Number of opened bolls, N_d = Number of Total bolls.

2.5. Cotton Leaves Processing

2.5.1. Cotton Leaves Extraction and Purification

The cotton leaves (upper, middle and lower layer) were collected before spraying and 1, 4, 7, 8 and 12 days (1, 5, 7, 8 and 15 days for spraying volume experiment) after spraying. There are eight fruit branches per cotton, the upper, middle and lower layers are three, three, and two fruit branches, respectively (Figure 3). A method had been developed to determine defoliant residues in cotton leaves using QuEChERS-pretreatment method and HPLC. Sample preparation and purification were performed as follows: 4.0 g of cotton leaves were accurately weighed, frozen in liquid nitrogen and grinded into powder. The powder was transferred to a 50 mL centrifuge tube. Afterwards, 25 mL of acetonitrile was added to the centrifuge tube, and the mixture was ultrasonically extracted for 20 min. Subsequently, NaCl (3 g) was added to the solution, which was vortexed for 1 min and centrifuged at 3800 rpm for 5 min. Next, 1 mL of supernatant was transferred into a 2 mL centrifuge tube with 50 mg of PSA, vortexed for 1 min and centrifuged at 10,000 rpm for 3 min. The supernatant was filtered through a 0.22 μm organic membrane filter for HPLC. Blank samples were used for validation studies and matrix-matched standard calibration. An untreated group was set up as control group, and all samples were stored in a −20 °C freezer.

2.5.2. Standard Curve and Added Recovery

The thidiazuron and diuron standard (50 mg, respectively) were dissolved in 50 mL methanol and diluted to 100 mL together, obtaining 500 mg/L thidiazuron and diuron mixed mother liquid, then diluted to 2, 4, 6, 8 and 10 mg/L, respectively, resulting in a series of mixed standard solutions. The standard solution was determined by HPLC. The standard curve was obtained by drawing the area as an ordinate and drawing the concentration of the thidiazuron and diuron standard solution as abscissa. The standard curve equation of thidiazuron and diuron were $y = 29.845x - 23.63$, $R^2 = 0.9964$ and $y = 114.33x - 82.01$, $R^2 = 0.995$, respectively. The peak area and concentration of thidiazuron and diuron exhibited a good linear relationship (2–10 mg/L).

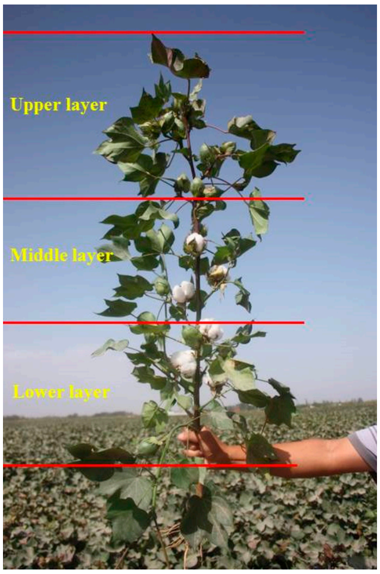

Figure 3. Layout of sampling collectors on the cotton.

Samples for recovery studies were spiked with the corresponding volume of the working solution and incubated for 30 min before extraction. Cotton leaves were treated with 0.05, 0.5 and 5 mg/kg (thidiazuron) and 0.05 and 0.5 (diuron) standard working solution, and thidiazuron and diuron recoveries were determined using an established method. Each additional level was repeated three times whilst setting a blank control (Tables 5 and 6). The average recoveries of 0.05, 0.50 and 1.0 mg/kg thidiazuron from cotton leaves were 81.47%, 83.11% and 93.71%, respectively. The average recoveries of 0.05 and 0.50 mg/kg diuron from cotton leaves were 117.28% and 100.75%, respectively. These values met the requirements for residue analysis.

Table 5. Recovery of thidiazuron in cotton leaves.

Added Concentration (mg/kg)	Added Recovery (%)			Average Added Recovery (%)	RSD (%)
	1	2	3		
0.05	77.06	82.94	84.41	81.47	2.1
0.5	83.19	82.37	83.78	83.11	5.8
1.0	98.22	91.72	91.20	93.71	7.1

Table 6. Recovery of diuron in cotton leaves.

Added Concentration (mg/kg)	Added Recovery (%)			Average Added Recovery (%)	RSD (%)
	1	2	3		
0.05	117.23	116.49	118.11	117.28	2.6
0.5	94.90	103.86	103.50	100.75	6.9

2.6. Yield Characters and Fiber Quality

The cotton yield was measured after all the cotton bolls opened where 100 cotton bolls from the canopies (upper, middle and lower layer) were randomly tagged and collected in each experimental area to determine the cotton yield characteristic and fiber quality.

2.7. Data Statistics and Processing

Defoliation, boll opening, uniformity and elongation of the cotton fiber which were expressed in percentage, were transformed to arcsin$\sqrt{X/100}$; others were log (x + 1) transformed prior to analysis to stabilize wide variances and meet normal assumptions. After transformation, the data was analyzed for normality using the Kolmogorov-Smirnov test and for equal variance across the treatments and replicates using Levene's test. Data was compared across different application rate using analysis of variance (ANOVA) (SPSS v21.0, SPSS Inc, an IBM Company, Chicago, IL, USA). Duncan's new multiple test was used for multiple comparisons and the significance level was p = 0.05. In the factorial design for both experiments, the averages were compared by using *t*-test at 5% probability.

3. Results and Discussion

3.1. Effect of Defoliant Dosage on Defoliation Efficacy

3.1.1. Defoliation Efficacy

Efficacy of defoliation was affected strongly by overall defoliant dosage. Analysis of variance in relation to cotton parameters among defoliation efficacy and defoliant dosage is presented in Figure 4. The leaf abscission began to form at four days after spraying, and the dose had a great effect on the defoliation effect; the defoliation rate of upper layer leaves was more than 20% in three dosages. The defoliation rate was 34% by the dosage of 450 g/ha, which was significantly higher than that of two low dose treatments. The defoliation rate then rose gradually, through eight days of spraying the defoliation rate of upper layer leaves was more than 45% of three dosages, and displayed a concentrated effect. Defoliation rates were 45.49%, 52.16% and 61.06% for 150, 300 and 450 g/ha, respectively. Interestingly, the middle and lower leaves of the cotton canopy with 150 and 450 g/ha showed good defoliation effect, and 300 g/ha showed moderate defoliation effect. The results indicated the defoliation effect was influenced by defoliant quantity, and the amount of defoliants could be reduced in Xinjiang. To further improve the defoliation effect, spraying treatments were carried out again on 15 September 2017, when the temperature had dropped. Therefore, the 37% thidiazuron + 17% diuron was chosen. Following a second spraying, within four d (twelve d after the first spraying), the upper, middle and lower layer leaves of defoliation rate had been significantly improved, with the upper layer defoliation rate nearly 90%, the middle layer more than 63% and the lower layer more than 42%. Seven days after the second spraying (fifteen days after the first spraying), the upper layer defoliation rate was more than 90% and the total defoliation rate was more than 80%, which reached the requirements for machine picked cotton harvesting.

These findings suggest that the 80% thidiazuron dosage of the first spraying had a significant effect on the upper and middle layer leaves, and the defoliation effect was proportional to the dosage in good temperatures (the minimum temperature is higher than 12 °C). When the temperature began to drop, the compounded formulations of 37% thidiazuron + 17% diuron was used, which further strengthened the effect of defoliation. Therefore, the defoliation rate reached more than 80% after being sprayed twice, which met the requirements for machine picked cotton harvesting. Generally, it was feasible to achieve better defoliation by reducing the defoliant dosage of the first spraying.

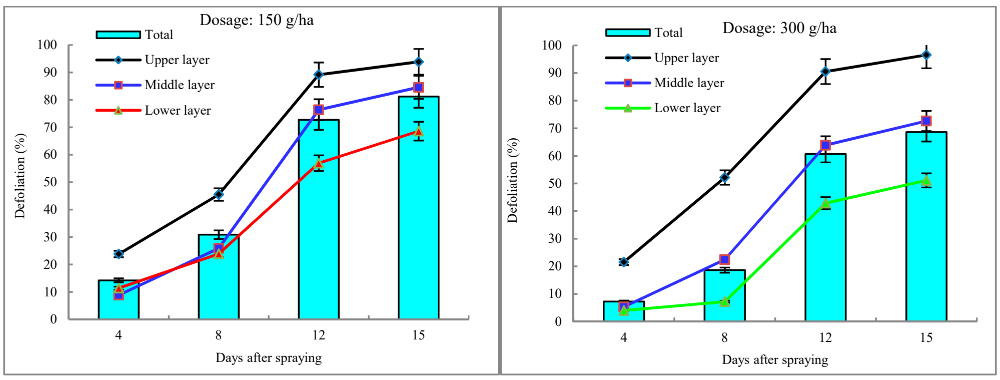

Figure 4. *Cont.*

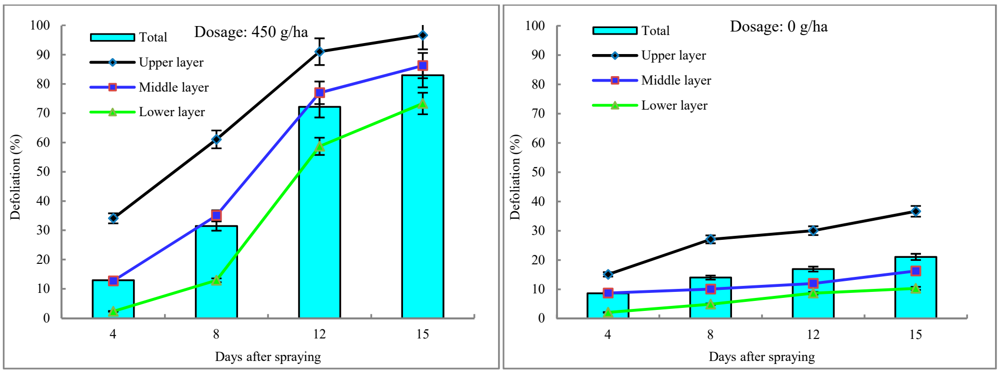

Figure 4. Defoliant dosage effect on defoliation efficacy by UAV 1.

3.1.2. Boll Opening

As illustrated in Figure 5, the cotton bolls opening effect increased significantly after spraying by UAV 1. Eight days after spraying, the boll opening rate increased by 21.87%, 20.43% and 24.04% for 300, 600 and 900 g/ha ethephon, respectively. The boll opening rate was slightly higher with the high-dose ethephon treatment, but not significantly different. However, the large-dose ethephon caused the cotton leaves to wither without falling, improving the impurity content in the cotton. The boll opening rate was significantly improved, increasing to 82.59%, 90.00% and 88.84%, respectively, within four days after the second spraying (twelve days after first spraying). The boll opening rate was more than 85% within seven days (fifteen days after the first spraying) after the second spraying, reaching the requirements for machine picked cotton harvesting. The thick canopy and weather condition have a greater impact on defoliation and boll opening [35]. Defoliants like thidiazuron/diuron and ethephon/cyclanilide have optimal activity when maximum and minimum daily temperatures are above 27 °C degrees and above 10 °C, respectively [6]. However, in the northern areas of Xinjiang, where the cotton has a relatively short growth period and the temperature cool down soon in September. Plant protection UAVs could be used for cotton defoliant spraying with a two-time defoliant spraying strategy, the first spray composed of 80% thidiazuron, the second spray being the compounded formulations 37% thidiazuron + 17% diuron, which could guarantee the defoliation and boll opening effectively.

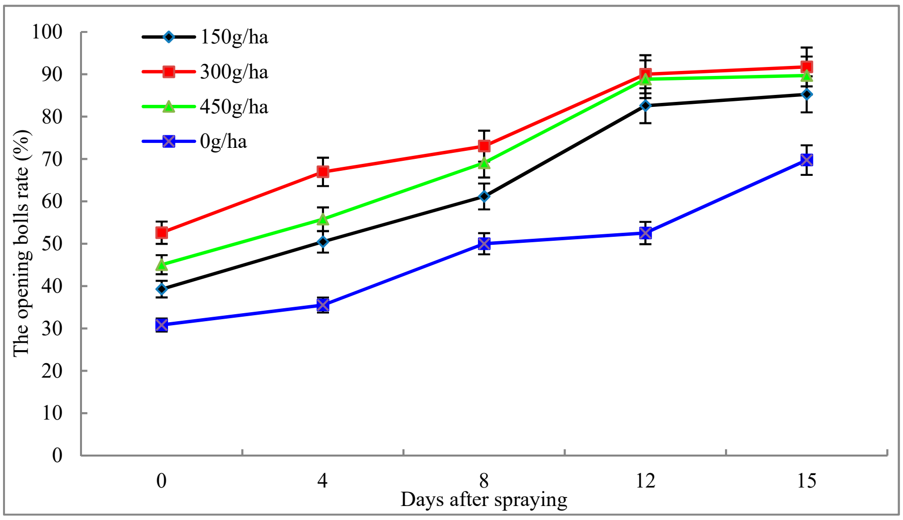

Figure 5. Effect of defoliant dosage on opening boll by UAV 1.

The above research conclusions indicated taking the spray twice defoliant strategy, the first spray of 80% thidiazuron, the second spray of the compounded formulations 37% thidiazuron + 17% diuron could guarantee the defoliation and boll opening effectively. Meanwhile, the dosage of 80% thidiazuron and 40% ethephon could be reduced.

3.1.3. Yield Characters and Fiber Quality

Defoliant application timing has a significant effect on cotton yield and quality [5–7,13]. However, there are few reports on the effects of defoliant dosage on cotton yield and quality. The study indicates defoliants dosage had no significant effect on seed cotton yield and fiber quality (Table 7). All the treatments had similar results as the untreated control for each of these parameters when applied at three dosages. Therefore, this showed that the treatments could be applied safely at either of the application timings without affecting these cotton fiber quality parameters.

Table 7. Effect of defoliant dosage on yield characters and fiber quality of cotton sprayed by UAV 1.

Treatment	BW	UHML/mm	ML/mm	UI/%	Mic	Str/cN·Tex^{-1}	Elg/%	MR	SFI
1	5.70 ^{a}	28.58 ^{b}	24.41 ^{b}	85.4 ^{a}	5.16 ^{a}	27.8 ^{b}	6.7 ^{a}	0.85 ^{a}	7.1 ^{b}
2	5.29 ^{b}	28.46 ^{b}	24.22 ^{b}	85.1 ^{a}	5.05 ^{b}	28.2 ^{b}	6.7 ^{a}	0.84 ^{a}	7.3 ^{b}
3	5.64 ^{a}	27.74 ^{b,c}	23.17 ^{b,c}	83.5 ^{c}	5.18 ^{a}	26.3 ^{c}	6.6 ^{a}	0.84 ^{a}	8.2 ^{a}
4	4.97 ^{c}	30.07 ^{a}	25.52 ^{a}	84.9 ^{a,b}	4.54 ^{c}	32.2 ^{a}	6.8 ^{a}	0.84 ^{a}	7.0 ^{b}

$^{a–c}$ ($p < 0.05$; Duncan's Test); BW, Boll weight; UHML, Upper half mean length; ML, Mean length; UI, Uniformity index; Mic, Micronaire; Str, Strength; Elg, Elongation; MR, Maturity; SFI, Short fiber index.

3.1.4. Attachment and Absorption

To clarify the effect of defoliant dosage on attachment and absorption of thidiazuron and diuron in cotton leaf sprayed by UAV 1, the defoliant residue detection and degradation was studied. As shown in Figure 6, due to the high content of thidiazuron in the defoliant, the residue of thidiazuron was higher than that of diuron at each period after spraying. The residues of thidiazuron and diuron in cotton leaves were closely related to the cotton canopy structure, with the highest residue in the upper layer and the lowest residue in the lower layer (Figure 6). Coincidentally, the middle layer leaves of cotton canopy with 150 and 450 g/ha showed more thidiazuron and diuron residues than the dosages with 300 g/ha. In contrast, the lower layer of cotton canopy with 150 g/ha showed the lowest thidiazuron residues and 150 g/ha showed lowest diuron residues. This indicates that the dose of defoliant had a significant effect on thidiazuron and diuron attachment and absorption in cotton leaves which affected the defoliation and boll opening. Regarding the thidiazuron, the leaves of the upper and middle layers had maximum residues four days after spraying (Figure 6A,B); the lower layer had maximum residues eight days after spraying (one day after the second spraying, Figure 6C). Due to poor penetrability of plant protection UAVs, the first spraying could not penetrate the cotton canopy, thus the second spraying was needed to improve the defoliant absorption by lower leaves. Conversely, diuron residues in the cotton canopy were much less, with the highest residue after the second spraying (eight days after the first spraying, one day after the second spraying, Figure 6D–F). The first spraying was 80% thidiazuron wettable powder and the second spraying was 37% thidiazuron + 17% diuron suspension concentrate, resulting in the residue of thidiazuron in cotton leaves reaching the maximum four days after spraying and the residue of diuron in cotton leaves reached the maximum one day after the second spraying. Thidiazuron is a contact type plant growth regulator, which must contact and be absorbed by the cotton leaves to play the role of leaf abscission of cotton. Therefore, the attachment and absorption of thidiazuron and diuron on the cotton canopy corresponded with the defoliation and boll opening efficiency.

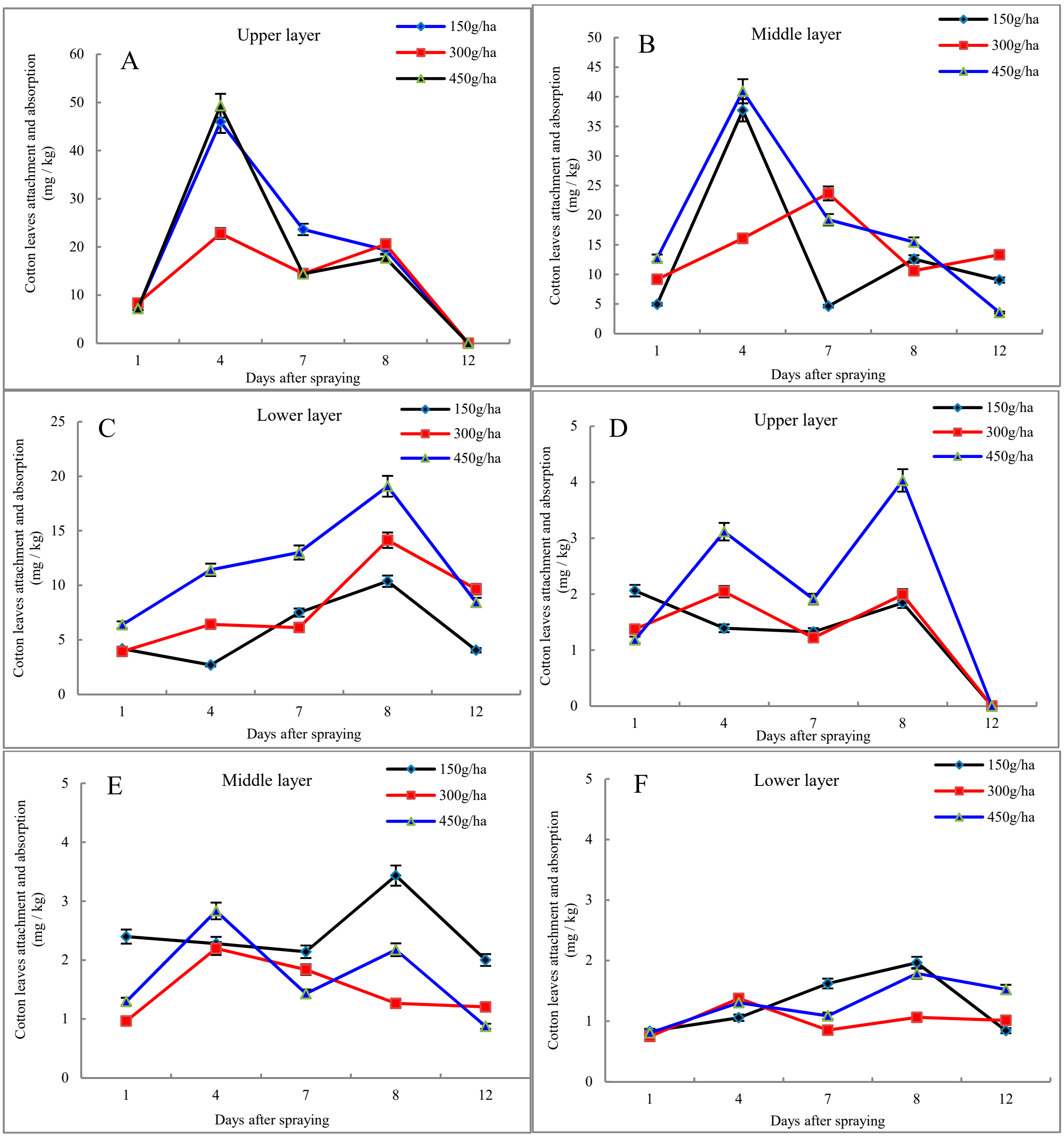

Figure 6. Effect of defoliant dosage on attachment and absorption of thidiazuron on cotton leaf sprayed by UAV 1 ((**A**) for upper layer; (**B**) for middle layer and (**C**) for lower layer) and diuron ((**D**) for upper layer; (**E**) for middle layer and (**F**) for lower layer). Twelve days after spraying, the upper layer leaves had been defoliated completely.

3.2. Effect of Spraying Volume on Attachment and Absorption by UAV 2

The spraying volume has a significant effect on the attachment and absorption in cotton leaves for plant protection UAVs spraying. When spraying the low concentration defoliant solution, the spraying volume should be increased to ensure the effect of prevention and control, which would result in the loss of the defoliant solution. When spraying the high concentration defoliant solution, the active constituents content of a single droplet would be more than the lethal dose for the pest, and cause a waste of defoliant [36]. Shown in Figure 7, spraying with the same defoliant dosage, spraying volume showed a significant effect on the residue of thidiazuron and diuron in cotton leaves. The thidiazuron and diuron residues were increased with spraying volume at 17.6–29 L/ha, and when the spraying volume was less than 17.6 L/ha, it showed less residues of thidiazuron and diuron. Therefore, in the field of defoliant spraying, the optimum concentration of defoliant and spraying volume should be determined in combination with the spraying of defoliant to ensure a better control effect. Under the same amount of active ingredient, the concentration increased with decreasing application rate. Qin et al. compared the control efficacy of insecticides sprayed against plant hoppers by UAV with spray volume of 15 L/ha and stretcher-mounted sprayer with spray volume of 750 L/ha. The results found that the insecticidal efficacy and the persistence period of UAV were greater than those achieved with a hand lance operated from a stretcher-mounted sprayer [9]. The droplet concentration when applied with UAVS were higher and there was enough defoliant deposited on the cotton plant. However, restricted by conventional sprayers and defoliants, few reports on cotton defoliation with high concentration were reported. In the pesticide application, there was no need to use large volume dilution, as a certain number of droplets could achieve a good efficacy, especially for the systemic chemicals [37]. From theoretical discussions, this is similar to the cotton defoliant application.

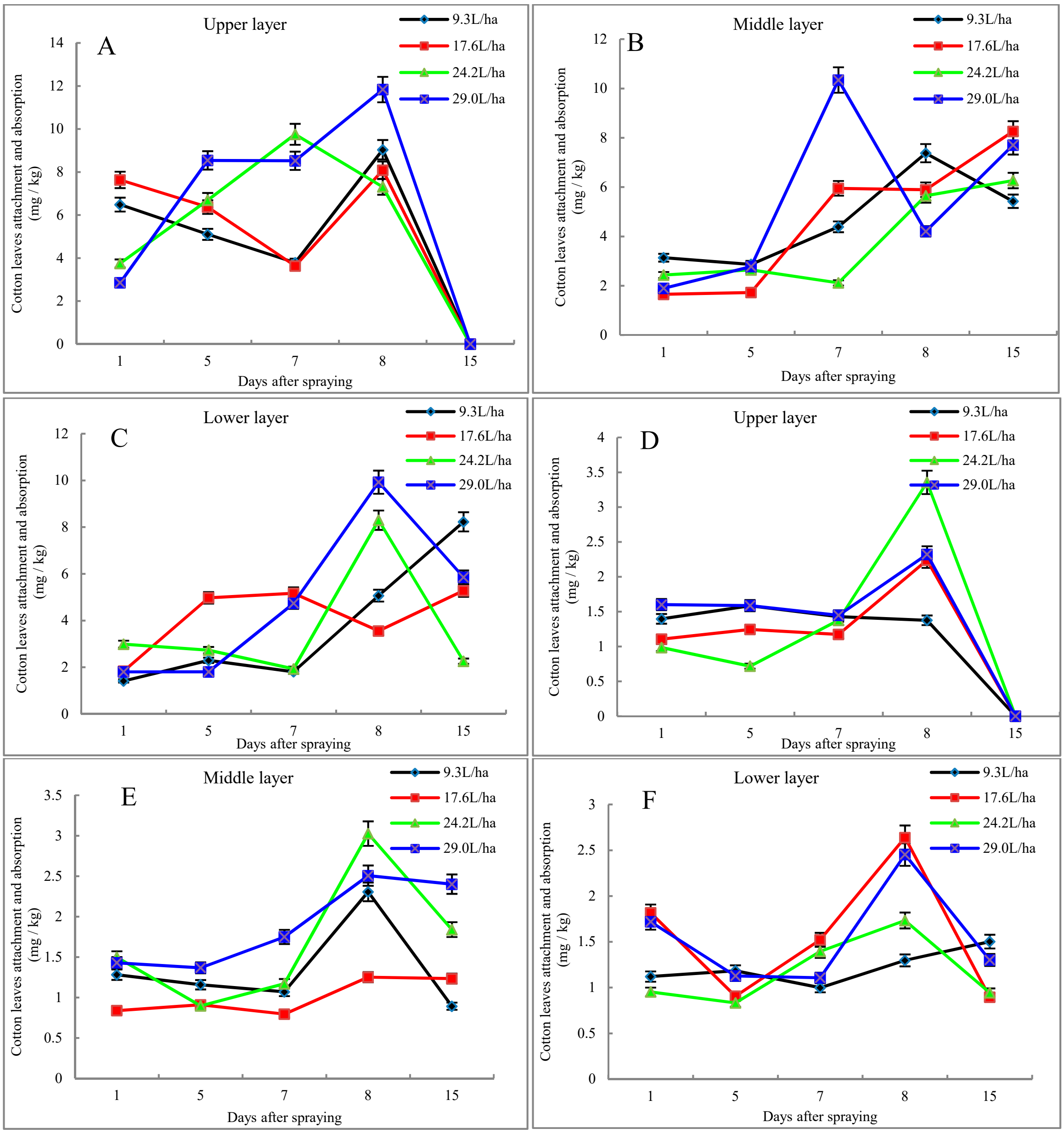

Figure 7. Effect of spraying volume on attachment and absorption of thidiazuron on cotton leaf sprayed by UAV 2 ((**A**) for upper layer; (**B**) for middle layer and (**C**) for lower layer) and diuron ((**D**) for upper layer; (**E**) for middle layer and (**F**) for lower layer). Fifteen days after spraying, the upper layer leaves had been defoliated completely.

4. Conclusions

In conclusion, the pooled data from this study indicate that plant protection UAVs could be used for cotton defoliants spraying by a twice defoliants spraying strategy, the first spray composed of 80% thidiazuron, the second spray the compounded formulations 37% thidiazuron + 17% diuron, which could guarantee the defoliation and boll opening effectively. The defoliant dosages had no significant effect on seed cotton yield and fiber quality. Meanwhile, the residue of thidiazuron in cotton leaves reached the maximum four days after spraying and the residue of diuron in cotton leaves reached the maximum one day after the second spraying. The thidiazuron and diuron residues increase with spraying volume in the range of 17.6–29.0 L/ha. When the spraying volume is less than 17.6 L/ha, the residue of thidiazuron and diuron is reduced. According to the experiment results and combined with the cotton defoliation, boll opening, fiber quality and thidiazuron and diuron residues in cotton leaves, the first spraying dosage of 300 g/ha and spraying volume of 17.6 L/ha will be recommended to the farmers for UAVs defoliant application. The research results could provide a reference for further optimization of the spraying parameters of cotton defoliant by plant protection UAVs.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/8/6/85/s1, Table S1: Weather conditions during the experiment period, Figure S1: The standard curve of thidiazuron, Figure S2: The standard curve of diuron, Figures S3–S122: Chromatograms.

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