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Experimental Study of Quizalofop-p-Ethyl Herbicide Drift Damage to Corn and the Safety Amount of Drift Deposition

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Abstract: Under soybean–corn intercropping in China, quizalofop-p-ethyl is recommended as a herbicide for stem and leaf treatment after soybean seedling. Nonetheless, herbicide drift during spraying may lead to environmental contamination and damage to the corn plants. In order to clearly show the threshold of the drift deposition amount of quizalofop-p-ethyl that causes herbicide damage to corn, we used a bioassay spray tower to spray quizalofop-p-ethyl herbicide on corn in the laboratory and a boom sprayer to spray quizalofop-p-ethyl herbicide, which drifts to corn in the field, to study and evaluate the damage quizalofop-p-ethyl herbicide causes to corn under different spray volumes and drift deposition rates. The results showed that under a drift deposition rate of 1% of three spray volumes, the corn showed no symptoms of herbicide damage and their plant height was not inhibited 14 days after spray; under a spray volume of 150 L/ha and a drift deposition rate of 5%, the corn showed symptoms of mild herbicide damage but their plant height was not inhibited 14 days after spray, while the corn showed symptoms of moderate herbicide damage and their plant height was slightly and moderately inhibited, respectively, under the spray volumes of 300 L/ha and 450 L/ha; under drift deposition rates of 10% and 30% of three spray volumes, half or more of the corn in each treatment withered and their plant height was severely inhibited or completely inhibited. Under the same spray volume, the symptoms of herbicide damage and the inhibition rate of plant height increased with the increase in the drift deposition rate; under the same drift deposition amount, the symptoms of herbicide damage and the inhibition rate of plant height increased with a decrease in the spray volume. The effect of the drift deposition rate on the symptoms of herbicide damage and plant height was extremely significant, but the spray volume was not significant. The drift deposition rates for 10% inhibition and no inhibition of corn plant height were 5.70% (R_{10}) and 5.05% (R_0) under spray volume of 150 L/ha, 4.56% (R_{10}) and 1.23% (R_0) under 300 L/ha, and 3.31% (R_{10}) and 1.86% (R_0) under 450 L/ha, respectively. When the herbicide was sprayed in the field using a soybean–corn-dedicated plant protection machine under the spray volume of 450 L/ha, the drift deposition rate ranged from 1.22% to 1.69%, and the corn did not produce symptoms of herbicide damage and plant height was not inhibited 14 days after the spray. In actual weeding operations, it is better to ensure that the drift deposition rate of quizalofop-p-ethyl is below R_0 by setting reasonable operational parameters, using anti-drift nozzles or additives, and so on, and, at most, not more than R_{10}. This study clarified the drift hazard of quizalofop-p-ethyl herbicide on corn and the safety value of the herbicide drift deposition amount, which provided data support for the standardized use of quizalofop-p-ethyl herbicide under soybean–corn intercropping and guidance for the safe production of field corn.

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Keywords: quizalofop-p-ethyl; corn; herbicide damage; spray volume; drift deposition rate; inhibition rate of plant height

1. Introduction

As important crops in China, corn and soybean are multipurpose crops for grain, oil, feed, and processing raw materials and have been planted for hundreds of years in China [1,2]. In recent years, soybean–corn intercropping has been widely promoted in China. This planting mode can not only improve the yield of corn and soybean, but can also increase land coverage, improve soil fertility, and enhance the stability of the farmland ecosystem [3,4]. It has played a vital role in ensuring China's food security and revitalizing the corn and soybean industries.

Farmland weeds refer to plants that grow in the farmland and are not purposefully cultivated by humans. They run through the whole growth period of crops, and are usually a composite population composed of a variety of annual gramineous or broadleaf weeds [5,6]. There are many kinds of weeds with a strong ability to spread and long damage time under soybean–corn intercropping. They compete with corn and soybean for nutrients and light and will directly affect the yield and quality of corn and soybean without proper control [7]. As one of the measures to save labor and time and achieve considerable control effect, chemical controls have been applied in soybean–corn intercropping [8]. However, the problem of herbicide drift has been widely found since the first use of chemical weeding [9,10]. The row spacings of corn and soybean under intercropping are narrower than those under the single planting mode, so herbicides are more likely to drift to adjacent crops to cause herbicide damage, which may pose a great threat to the growth of crops [11,12].

As one of the herbicides with excellent control effect on gramineous weeds, quizalofop-p-ethyl was recommended by the China National Agro-Tech Extension and Service Center to be used in spray form for stem and leaf treatment after the planting of soybean seedlings under soybean–corn intercropping [13–16]. However, this herbicide causes damage to corn easily if it drifts during the spray. At present, there are few studies on herbicide damage under soybean–corn intercropping, and there is no relevant study on the herbicide damage of quizalofop-p-ethyl to corn. Pacanoski et al. [17,18] evaluated the damage of herbicides such as Linuron, pendimethalin, and isoxaflutole to corn and soybean when used alone or in combination. As a result, no herbicide damage was found to the appearance of corn and there was no difference between the corn yield and the control within two years, but isoxaflutole alone and in combination with pendimethalin caused serious injuries to the soybean. Dong et al. [19] studied the effects of simazine, pendimethalin, and alachlor alone and in combination on the growth and yield of corn and soybean under Korean environmental conditions. It was found that simazine had no effect on corn yield but would cause soybean yield reduction and should not be used in intercropping. Alachlor and pendimethalin have no adverse effects on the growth and yield of corn and soybean, among which alachlor can slightly improve the yield of corn and soybean. Although the above research screened some herbicides suitable for soybean–corn intercropping, most of them were pre-seedling herbicides, and some were inconsistent with domestic herbicide use, which could not directly be used for reference. Therefore, this study evaluated the herbicide damage of quizalofop-p-ethyl to corn under different spray volumes and drift deposition rates, and clearly showed the spray volume and drift deposition rate that cause no or slight herbicide damage to corn, providing theoretical reference and data support for the formulation of chemical weeding specifications and ensuring the safe production of corn.

2. Materials and Methods

2.1. Potted Corn Test

2.1.1. Test Materials

Object: potted corn, variety Suyu 39 (Biocentury Transgene (China) Co., Ltd., Shenzhen, China). The greenhouse pot culture method was used to cultivate corn. Sifted air-dried sandy loam with 4% organic matter content, neutral (PH6.0~8.0), and good permeability was put into a 9 cm diameter plastic culture basin, and the dry soil quantity was 4/5. After the soil was fully moistened by osmotic irrigation at the bottom of the bowl, the corn seeds with white buds were evenly spread on the surface of the soil, 2–3 seeds per pot, and the soil was covered by 0.5~2.0 cm. The seedlings were thinned in the period of 1~2 leaves, and 1 corn plant was kept in each pot. The cultivation amount of corn plants was twice as much as the test amount in order to select the corn plants with similar or the same height for the test, as shown in Figure 1.



Figure 1. Potted corn.

Pesticide: 10% quizalofop-p-ethyl EC (Shandong Sannong Biotechnology Co., Ltd., Linyi, China) was prepared according to the upper limit of the recommended dosage, which is 600 mL/ha. In this test, the dosage of herbicide under the three spray volumes was the same, only the water amount was different.

Main instruments: hygrometer, one ten-thousandth balance, ultrasonic cleaner, pipette gun, mixing bar, measuring cup, etc.

Test equipment: 3WP-2000 Bioassay Spray Tower (developed by Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs). The spray time can be set at will and the corn was placed on the sample plate in the tower. The distance between the sample plate and the nozzle was 250–750 mm adjustable. After the door of the tower is closed, the environment inside the tower will not be affected by external airflow and other factors, as shown in Figure 2.



Figure 2. 3WP-2000 bioassay spray tower.

Test time: 30 July 2022; Meteorological conditions inside the spray tower: temperature 30~34 °C, relative humidity 66~75%.

Record time of herbicide damage: the 7th and 14th days after spray.
Location: Lishui Plant Science Base of Jiangsu Academy of Agricultural Sciences.

2.1.2. Methods

According to the actual field operation, the spray volume was 10, 20, 450 L/ha. Four levels of drift deposition rate were selected as 1%, 5%, 10%, and 30%, and there were 10 drift deposition amounts in total. The drift deposition amount under the 10% drift deposition rate of 150 L/ha was the same as the 5% drift deposition rate of 300 L/ha. Similarly, the 30% drift deposition rate of 150 L/ha was the same as the 10% drift deposition rate of 450 L/ha, as shown in Table 1.

Table 1. Drift deposition amount of single pot corn under different parameters (mg/pot).

Drift Deposition Rate (%) / Spray Volume (L/ha)	1	5	10	30
150	0.954	4.772	9.543	28.629
300	1.909	9.543	19.086	57.258
450	2.863	14.315	28.629	85.887

Due to the small drift deposition amount, the TEFEN0.7-80 microspray nozzle was used. The spray pressure was fixed at 3 bar and the spray flow was 43 mL/min. The required drift deposition was obtained by adjusting the spray time. Healthy corn plants with a plant height of 30 ± 1.5 cm were selected after plant height measurement before spray. There were 13 treatments 10-1, 10-5, 10-10, 10-30, 20-1, 20-5, 20-10, 20-30, 30-1, 30-5, 30-10, 30-30, and a blank control CK. Each treatment was set with 6 corn plants for repetition and numbered on the cultivation basin. For example, 10-1-6, where 10 represents 150 L/ha of spray volume, 1 represents 1% of drift deposition rate, and 6 represents the sixth corn plant. The abbreviations in the following are the same with this meaning.

The corn was moved into the greenhouse for routine management after spray, and different treatment was placed at intervals, as shown in Figure 3. Water was replenished once every 1–2 days according to the moisture condition of the substrate in the basin. After management, insect-control nets were used to cover the corn plants.



Figure 3. Arrangement after herbicide spray.

2.2. Field Corn Test

2.2.1. Test Materials

Object: field corn under the standard "4 + 2" soybean–corn intercropping, with the same varieties as the potted corn, as shown in Figure 4.

Pesticide: 10% quizalofop-p-ethyl EC at a concentration of 600 mL/ha, mixed with a concentration of 2.5 g/L Allura Red AC.

Main instruments: visible light spectrophotometer, portable anemometer, one ten-thousandth balance, sampling rod, etc.



Figure 4. Soybean-corn intercropping.

Test equipment: 3WPZ-600 dedicated sprayer for soybean–corn compound planting (Sangpu Agricultural Machinery (Changzhou) Co., Ltd., Changzhou, China) with anti-drift blocking curtains, as shown in Figure 5.



Figure 5. 3WPZ-600 dedicated sprayer for soybean–corn compound planting.

Test time: 20 August 2023; meteorological conditions: average wind speed 0.8 m/s, average temperature 31 °C, average humidity 69%.

Recorded time of herbicide damage: the 7th and 14th days after spray.

Location: Liji Township, Guannan County, Lianyungang City, Jiangsu Province, China.

2.2.2. Methods

The width of the sampling area was set at 4 soybean rows + 2 corn rows and the length of one route was 115 m. Considering not to cause serious damage to the corn, we only verified the herbicide damage under low drift deposition rate. The spray volume was selected as 450 L/ha, and the machine was equipped with anti-drift nozzle LANAO FP 90-03, driving speed of 1 m/s, and spray pressure of 3 bar. We chose a soybean–corn compound planting row 10 m away from the field ridge because this row was the neatest and most uniformly planted when compared. Single driving distance was set to 20 m and the first 10 m was the acceleration region of the machine, and the last 10 m was the sampling area where the sprayer sprayed the soybean rows with quizalofop-p-ethyl herbicide, which may drift and deposit on the corn. Spraying with only the nozzles above the soybean rows was turned on, and water-sensitive paper and polyester disks were arranged on the outside of the corn row in the two rows adjacent to the soybeans. The water-sensitive paper was used to observe whether there was droplet drift and the polyester disks were used to collect the drift droplet. The samples on the left side of the forward direction of the machine were named left 1–left 10, and on the right side of the forward direction were named right 1–right 10. The height of samples was equal to the height of the corn, and the sampling was repeated three times on a single route, as shown in Figure 6.

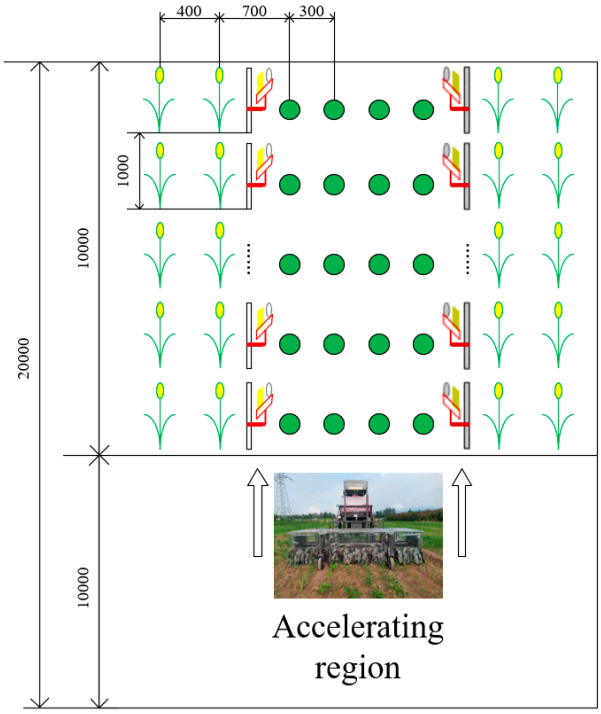


Figure 6. Sampling schematic.

Gloves were worn to avoid contamination and to recover the water-sensitive paper and polyester disks in time after the spray was completed. Each group of water-sensitive paper was air-dried and placed in the same sealed bag while each polyester disk was placed in a separate sealed bag and brought back to the laboratory for analysis and processing. A visible light spectrophotometer was used to measure the absorbance after 12 mL distilled water was poured into the sealed bag containing polyester disks, and the concentration of Allura Red AC in the eluent was calculated according to the "concentration-absorbance" standard curve of Allura Red AC. The spray drift per unit area of the polyester disk was calculated according to Equation (1) and the spray drift rate was calculated according to Equation (2).

$$SD = \frac{(C_S - C_B) \times F \times V}{C_M \times A} \quad (1)$$

where

SD—spray drift of per unit area of polyester disk, mL/cm^2;
C_S—sample eluent concentration, mg/L;
C_B—blank sample eluent concentration, mg/L;
F—calibration factor, 1 for polyester disks;
V—volume of distilled water used to elute the sample, mL;
C_M—concentration of spray stock solution, mg/L;
A—area of polyester disk, cm^2.

$$SDR = \frac{SDV \times 100\%}{V_S} \quad (2)$$

where

SDR—spray drift rate;
SDV—spray drift volume of polyester disks, mL;
V_S—spray application volume, mL.

2.3. Herbicide Damage Evaluation

The herbicide damage symptoms 7 and 14 days after spray were recorded by observation method. The plant height 14 days after spray was recorded by growth inhibition method and the inhibition rate of plant height was calculated.

(1) Observation method

The main symptoms of herbicide damage are as follows:

Color changes: macula, yellowing, bleaching (mainly due to pesticides that hinder the normal photosynthesis of chlorophyll), etc.;

Morphological changes: dwarfing, deformity, leaf curling, withering, etc.;

The classification of herbicide damage is based on the symptoms of corn 14 days after spray and the level of herbicide damage shall refer to the Chinese agricultural industry standard, as shown in Table 2 [20].

Table 2. Classification of herbicide damage symptoms.

Damage Grade	Description of Herbicide Damage Symptoms
0	The growth is consistent with CK.
1	The plant height and leaf color are slightly different from CK.
2	The plant is slightly deformed and its height is lower than CK.
3	The plant is obviously dwarfed, the stem is thickened, the leaves are slightly thickened and the color is deepened, or the leaves turn yellow.
4	The plant stops growing, has severe deformity and stiff seedlings, or the whole leaf withers and dies.
5	The plant dies.

(2) Growth inhibition method

The plant height refers to the distance between the substrate plane of the cultivation basin and the top of the main leaves of corn. The inhibition rate of plant height of each treatment was calculated according to Formula (1), and the inhibition degree was evaluated according to Table 3 [21]. According to the standard [22], when evaluating the safety of herbicides on crops, the herbicide dose ED_{10}, which has 10% inhibition on crop plants, is taken as the evaluation index, and the higher the value, the better the safety of crops. In reference to this method, drift deposition rate R_{10} and R_0, which can inhibit plant height of corn by 10% and 0%, was used as the evaluation index.

$$R = \frac{X_0 - X_1}{X_0} \times 100 \quad (3)$$

where

R—inhibition rate of plant height, %;

X_0—plant height of CK, cm;

X_1—plant height of treatment, cm.

Table 3. Classification of inhibition degree.

Inhibition Rate	Inhibition Degree
≤0	Normal growth
0.1~20%	Mild inhibition
20.1~40%	Moderate inhibition
40.1~60%	Significant inhibition
60.1~80%	Severe inhibition
≥80%	Complete inhibition

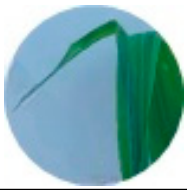
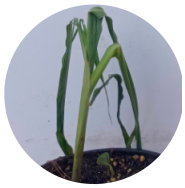
3. Results

3.1. Potted Corn Test

3.1.1. Observation of Herbicide Damage

See Table 4 for the symptoms of corn damage caused by quizalofop-p-ethyl herbicide, which mainly included dwarfization, malformation, macula, yellowing, leaf rolling, and wilt. Table 5 shows the herbicide damage of corn 7 and 14 days after spray, with No. 1-6 corn from left to right. No matter the symptoms of herbicide damage 7 days or 14 days after spray, two obvious rules can be found. First, under the same spray volume, the higher the drift deposition rate, that is, the higher the amount of herbicide deposition, the more serious the herbicide damage. Second, under the same drift deposition amount, the lower the spray volume, that is, the higher the herbicide concentration, the more serious the herbicide damage. Fourteen days after spray, corn showed no symptoms of herbicide damage under the 1% drift deposition rate of three spray volumes. Under the 5% drift deposition rate, only one corn plant wilted under the spray volume of 450 L/ha and the severity of herbicide damage was 450 L/ha > 300 L/ha > 150 L/ha. Under the 10% and 30% drift deposition rates, half or more of the corn in each treatment died and the severity of herbicide damage was 300 L/ha > 450 L/ha > 150 L/ha and was 150 L/ha = 300 L/ha > 450 L/ha, respectively. Under the same drift deposition rate, there was no case that the lower the spray volume, the more serious the herbicide damage due to the different drift deposition amounts under different spray volumes. However, it can be seen that the influence of the drift deposition rate on herbicide damage is greater than that of spray volume. The symptoms of herbicide damage were more serious 14 days than 7 days after spray, indicating that only the 5% drift deposition rate under the three spray volumes leads to the inability of corn to recover from herbicide damage for at least 7 days.

Table 4. Damage symptoms of corn caused by quizalofop-p-ethyl herbicide.

	Dwarfization	Deformity	Yellow Spot	Yellowing	Leaf Rolling	Wither
Symptoms						

3.1.2. Inhibition Rate of Plant Height

The plant height and inhibition rate of each treatment 14 days after spray are shown in Table 6. As can be seen from the table, there were no significant differences in plant height between 10-1, 20-1, and 30-1, which had no symptoms of herbicide damage, 10-5, which had only two corn plants yellowed, and CK. The plant height of the above treatment was not inhibited. Except for the slight inhibition of plant height of the 20-5 treatment due to one deformed corn plant and the moderate inhibition of plant height of the 30-5 treatment due to one withered corn plant, the plant height under the condition of half or more corn plants having withered due to other treatment was severely or even completely inhibited.

The variance analysis of the effects of the spray volume and drift deposition rate on the corn plant height is shown in Table 7. It can be found that the spray volume and the interaction between the spray volume and the drift deposition rate had no significant impact on plant height, while the drift deposition rate had an extremely significant impact on plant height. The reason is that the increase in spray volume leads to an increase in deposition under the same drift deposition rate. However, under the premise of the same dosage of herbicide, an increase in spray volume leads to a decrease in the concentration of herbicide. Both of them enhance and weaken the symptoms of herbicide damage, respectively, resulting in the non-obvious influence of the spray volume. In general, it is particularly important to minimize herbicide drift during weeding operations.

Table 5. Growth and herbicide symptoms of corn plants 7 and 14 days after spray.

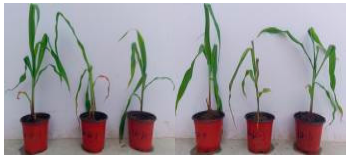
Treatment	7 days after Spray	14 days after Spray	Herbicide Damage Symptoms	Damage Grade
CK			/	/
10-1			No Symptoms	7 d: Grade 0 14 d: Grade 0
10-5			14 d: Corn No. 5 appeared yellow spot and corn No. 6 yellowed	7 d: Grade 0 14 d: 2 corn plants Grade 1
10-10			7 d: Corn No. 1, 3, and 6 yellowed, and corn No. 5 withered 14 d: Corn No. 1, 2, and 4 yellowed and rolled leaves, and corn No. 3 and 6 withered	7 d: 3 corn plants Grade 1 and 1 corn plant Grade 5 14 d: 3 corn plants Grade 3 and 3 corn plants Grade 5
10-30			7 d: Corn No. 1, 2, 4, 5, and 6 withered; 14 d: Corn No. 3 withered	7 d: 5 corn plants Grade 5 14 d: 6 corn plants Grade 5

Table 5. *Cont.*

Treatment	7 days after Spray	14 days after Spray	Herbicide Damage Symptoms	Damage Grade
20-1			No Symptoms	7 d: Grade 0 14 d: Grade 0
20-5			7 d: Corn No. 1 dwarfed 14 d: Corn No. 1 yellowed and deformed, corn No. 4 yellowed and rolled leaves, corn No. 5 yellowed, and corn No. 6 appeared yellow spot	7 d: 1 corn plant Grade 1 14 d: 2 corn plants Grade 1 and 2 corn plants Grade 3
20-10			7 d: Corn No. 1, 2, and 5 withered, and corn No. 4 yellowed and deformed 14 d: Corn No. 3 and 4 withered, and corn No. 6 yellowed	7 d: 1 corn plant Grade 3 and 3 corn plants Grade 5 14 d: 1 corn plant Grade 1 and 5 corn plants Grade 5
20-30			7 d: Corn No. 2 and 3 yellowed and rolled leaves, corn No. 4 deformed and rolled leaves, and corn No. 1, 5, and 6 withered 14 d: Corn No. 2, 3, and 4 withered	7 d: 3 corn plants Grade 3 and 3 corn plants Grade 5 14 d: 6 corn plants Grade 5

Table 5. *Cont.*

Treatment	7 days after Spray	14 days after Spray	Herbicide Damage Symptoms	Damage Grade
30-1			No symptoms	7 d: Grade 0 14 d: Grade 0
30-5			7 d: Corn No. 2 and 4 dwarfed and rolled leaves 14 d: Corn No. 1 dwarfed, corn No. 2 deformed, corn No. 5 and 6 yellowed, and corn No. 4 withered	7 d: 3 corn plants Grade 3 and 1 corn plant Grade 5 14 d: 3 corn plants Grade 1 and 1 corn plant Grade 5
30-10			7 d: Corn No. 3 dwarfed, corn No. 5 rolled leaves, and corn No. 1 and 4 dwarfed and yellowed 14 d: Corn No. 5 yellowed and rolled leaves, and corn No. 1, 3, 4 and 6 withered	7 d: 2 corn plants Grade 1 and 2 corn plants Grade 3 14 d: 1 corn plant Grade 3 and 4 corn plants Grade 5
30-30			7 d: Corn No. 1, 3, 4, 5, and 6 dwarfed and yellowed; 14 d: Corn No. 2 yellowed and corn No. 1, 3, 4, 5, and 6 withered	7 d: 5 corn plants Grade 3 14 d: 1 corn plant Grade 1 and 5 corn plants Grade 5

Table 6. Corn plant height and inhibition rate 14 days after spray.

Treatment \ Plant No.	Plant Height/cm							Inhibition Rate/%	Inhibition Degree
	1	2	3	4	5	6	Average		
CK	70.9	74	71.1	68.7	68.2	73.7	71.10 ± 2.42 a	/	/
10-1	73.1	75.3	77.2	74.8	81.3	63.7	74.23 ± 5.87 a	−4.41	Normal growth
10-5	78	73.9	72.1	67.9	68.2	69.8	71.65 ± 3.87 a	−0.77	Normal growth
10-10	0	47.5	0	54.9	0	0	17.07 ± 26.54	76.00	Severe inhibition
10-30	0	0	0	0	0	0	0.00 ± 0.00	100.00	Complete inhibition
20-1	73.1	74.6	73.3	63.3	74.2	71.1	71.60 ± 4.24 a	−0.70	Normal growth
20-5	35.3	72	70.5	56.2	68.8	75.5	63.05 ± 14.74	11.32	Mild inhibition
20-10	0	0	0	0	0	72.1	12.02 ± 29.43	83.10	Complete inhibition
20-30	0	0	0	0	0	0	0.00 ± 0.00 b	100.00	Complete inhibition
30-1	70	82.9	71.3	78.5	72.5	77	75.37 ± 4.96 a	−6.00	Normal growth
30-5	66.3	49.6	77.3	0	66.6	64	53.97 ± 27.87	24.10	Moderate inhibition
30-10	0	77.5	0	0	56.7	0	22.37 ± 35.26	68.54	Severe inhibition
30-30	0	61.1	0	0	0	0	10.18 ± 24.94	85.68	Complete inhibition

Note: The same letter after the same column of data indicates that the difference in Duncan's test within a 95% confidence interval is not significant, and no significance analysis was performed for the treatment whose herbicide damage affected plant height.

Table 7. Variance analysis of plant height.

Source	df	F	Sig.
Spray Volume	2	0.296	0.745
Drift Deposition Rate	3	56.909	1.53×10^{-7}
Spray Volume × Drift Deposition Rate	6	0.589	0.738

Figure 7 shows the change trend of corn plant height and the inhibition rate of different treatments. It can be seen that under the same spray volume, the plant height decreased and the inhibition rate of the plant height increased with the increase in the drift deposition rate; under the same drift deposition amount, the plant height decreased and the inhibition rate of the plant height increased with the decrease in the spray volume; there is no obvious rule under the same drift deposition rate, which is consistent with the change trend of herbicide damage symptoms. The drift deposition rates for 10% inhibition and no inhibition of corn plant height were 5.70% (R_{10}) and 5.05% (R_0) at 150 L/ha of spray volume, 4.56% (R_{10}) and 1.23% (R_0) at 300 L/ha of spray volume, and 3.31% (R_{10}) and 1.86% (R_0) at 450 L/ha of spray volume, respectively. Before the actual weed control operation, it is necessary to adopt drift reduction means in order to ensure that the drift deposition of quizalofop-p-ethyl is $\leq R_0$ and, at most, not more than R_{10}, as far as possible.

3.2. Field Corn Test

3.2.1. Observation of Herbicide Damage

It can be seen that there was a trace amount of pesticide drift at each sampling point by observing the water-sensitive paper, as shown in Figure 8, and the drift deposition rate at the sampling point calculated from the polyester sheet is shown in Table 8.

Table 8. Drift deposition rate of sampling points.

Position \ Sampling Point	Drift Deposition Rate/%										Coefficient of Variation/%
	1	2	3	4	5	6	7	8	9	10	
Left	1.63 ± 0.07	1.43 ± 0.05	1.57 ± 0.09	1.61 ± 0.02	1.48 ± 0.02	1.56 ± 0.07	1.26 ± 0.05	1.42 ± 0.08	1.37 ± 0.06	1.22 ± 0.03	11.5
Right	1.41 ± 0.04	1.24 ± 0.06	1.3 ± 0.04	1.69 ± 0.07	1.35 ± 0.04	1.24 ± 0.04	1.39 ± 0.09	1.27 ± 0.07	1.39 ± 0.06	1.37 ± 0.04	9.7

Note: The drift deposition rates of 10 sampling points were averaged over three replications.

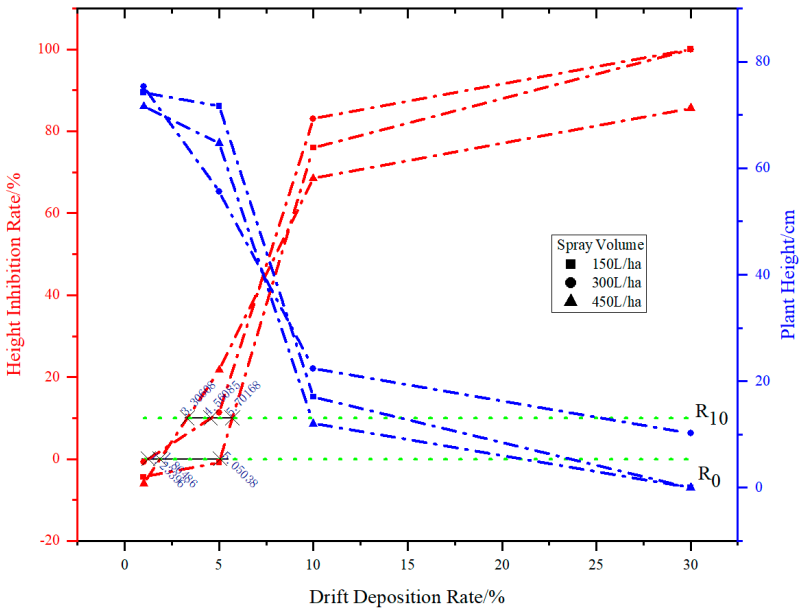
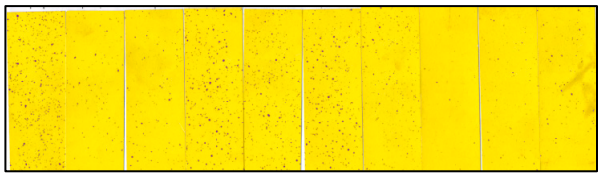
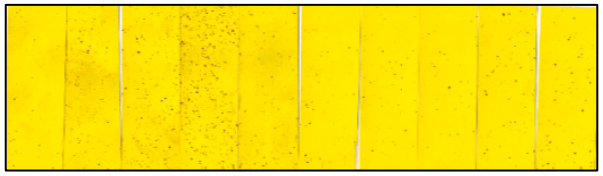


Figure 7. Effects of spray volume and drift deposition rate on corn plant height and inhibition rate.



(**a**) Left sample points 1 to 10



(**b**) Right sample points 1 to 10

Figure 8. Collection of water-sensitive paper (example of the first set of tests).

The drift deposition rate of each sampling point ranged from 1.22% to 1.69%, and the anti-drift nozzles and anti-drift blocking curtains used in soybean–corn-dedicated plant protection machines played a very important role in blocking the pesticide drift.

The growth of corn at all sampling points 7 days and 14 days after spray is shown in Figure 9, and there was no symptom of herbicide damage under a 1.22~1.69% drift deposition rate, which is similar to the result of no symptoms of herbicide damage in potted corn tests under a 1% drift deposition rate. It can also be seen from the figure that there was almost no weed growth between the soybean rows, indicating that this herbicide was used with good results.

3.2.2. Inhibition Rate of Plant Height

The plant height and inhibition rate of corn 14 d after spray are shown in Table 9, and the corn at all sampling points grew normally. Figure 9 shows that a 1.86% drift deposition rate under 450 L/ha spray volume is the critical value of plant height inhibition. The drift deposition rate of each sampling point was within this range, which verified that the results were consistent.



(**a**) 7 days after spray



(**b**) 14 days after spray

Figure 9. Corn growth 7 days and 14 days after spray (example of the first set of tests).

Table 9. Corn plant height and inhibition rate 14 days after spray.

Sampling Point	Plant Height/cm		Inhibition Rate/%		Inhibition Degree
CK	**81.7**		**/**		**/**
	Left	**Right**	**Left**	**Right**	
1	83.0 ± 2.5	84.3 ± 2.1	−1.59	−3.14	Normal growth
2	85.6 ± 2.0	85.8 ± 1.5	−4.77	−5.05	Normal growth
3	82.1 ± 1.4	83.4 ± 1.8	−0.49	−2.07	Normal growth
4	84.2 ± 2.7	87.6 ± 2.9	−3.06	−7.19	Normal growth
5	83.2 ± 1. 7	84.6 ± 1.3	−1.84	−3.54	Normal growth
6	88.1 ± 2.0	86.9 ± 3.2	−7.83	−6.33	Normal growth
7	82.4 ± 1.1	83.6 ± 1.3	−0.86	−2.37	Normal growth
8	88.7 ± 3.2	87.2 ± 3.8	−8.57	−6.79	Normal growth
9	86.9 ± 1.5	81.9 ± 1.5	−6.36	−0.22	Normal growth
10	85.2 ± 1.3	84.8 ± 1.6	−4.28	−3.74	Normal growth

Note: The plant heights of 10 sampling points were averaged over three replications.

4. Discussion

Combined with the current situation of herbicide use under soybean–corn intercropping in China, this paper innovatively explored the herbicide damage situation of quizalofop-p-ethyl herbicide on corn and clarified the safety value of the herbicide drift amount. We used a 3WP-2000 bioassay spray tower for laboratory experiments. This spray tower has been used many times by Chinese scholars and has a stable structure and reliable results [23–25]. We sprayed herbicides in the field using a specialized sprayer for soybean–corn intercropping, and the results were verified to be consistent with the indoor tests. The main purpose of this paper is to guide the practical application of the herbicide

in the field, and the theoretical research will be supplemented in the future, such as by measuring the sensitivity and tolerance of corn to the quizalofop-p-ethyl herbicide [26,27]. Before this, some relevant applied research had been conducted on the other kinds of herbicides. Lynette et al. [28] studied the herbicide damage of corn caused by glyphosate drift and found that the herbicide damage symptoms of corn were leaf chlorosis and plant death. Seven days after spray, glyphosate at a concentration of 100 g/ha or below had no effect on the appearance of corn, while 55% of corn at a concentration of 375 g/ha had herbicide damage symptoms. When the concentration was 100 g/ha and 375 g/ha, the corn plant height decreased to 0.81 times and 0.55 times of the control group, respectively. Soukup et al. [29] studied the effect of the dose of isoxaflutole on corn herbicide damage. The main symptoms caused by the herbicide were bleaching and a decrease in leaf weight and root weight. When the dose of isoxaflutole increased from 75 g/ha to 97.5 g/ha, there was a significant difference in corn stem weight, but no difference in root weight. Watering immediately after pre-emergence herbicide treatment resulted in a strong germination delay, but watering at the growth stage after emergence had no damage to corn. The above studies showed a major trend of positive correlation between herbicide concentrations and herbicide damage degree, which is similar to the relationship between the herbicide deposition amount and herbicide damage degree in this paper. It is noteworthy that Soukup found that corn is very sensitive to watering quantity and time. A difference of 10 mm in watering quantity can lead to a significant difference in growth, and watering before and after emergence can also cause growth differences. In this study, corn after emergence was taken as the research object, and the watering quantity was fixed, but the interval was 1–2 days. Although the effect of watering on the herbicide damage of corn was not indeed found, the effect of water and fertilizer management on the herbicide damage of corn before and after seedling could be considered for further study. Moreover, Singh et al. [30] studied the residual effect of fenoxaprop-p-ethyl on the succeeding corn crop in onion fields and found that herbicide sprays of 78.75 g and 157.5 g/ha did not cause damage to corn. Singh's study brings us to the consideration of whether pre-emergence herbicides can cause residual herbicide damage on corn because we used the pre-emergence herbicide acetochlor at a dose of 1.8 L/ha in the soybean–corn-intercropped field. Janak and Grichar [31] studied the damage caused to corn by a variety of pre-emergence herbicides and combinations of them and found that the damage to corn was only growth retardation and less than 3% injury at a dose of 8.23 L/ha acetochlor herbicide. Therefore, we concluded that the effect of the pre-emergence herbicide acetochlor on corn in our study was negligible. We did not measure the final corn yield because we considered that corn yield is affected by many factors such as fertilizer application, irrigation, harvest loss rate, and so on. Some studies have shown that just the frequency of irrigation alone may lead to one-third of the yield variance [32,33]. We plan to study the influence of multiple factors on corn yield including herbicide damage during the next corn planting season.

In this paper, R_{10} of three spray volumes was obtained as the reference drift limit value of the quizalofop-p-ethyl herbicide, but the current conventional weeding operation may not be able to meet the requirement when the drift deposition rate is below 5.7% [34–36], so it is essential to take some measures to reduce drift. The common methods to reduce drift include using anti-drift nozzles such as air-induction nozzles to spray, adding anti-drift additives, and using airflow-assisted spray for directional deposition [37–39]. If it is necessary to further reduce drift, barrier structures can be designed on the spray equipment, such as a completely shielded spray boom with a curtain or protective cover, etc. [40,41]. The above methods can be used in combination for better anti-drift effects. Except for the use of drift reduction methods to reduce the damage caused by herbicide drift, herbicide damage can also be eliminated or mitigated by antidotes after weeding operations. However, one antidote may not be suitable for different crops and herbicide damage caused by different herbicides [42,43]. Moreover, the use of antidotes will not only increase labor and economic costs but also lead to the death of the affected crops if the use of the antidotes is delayed or the effect of the antidotes is weakened by uncontrollable factors such as rainy

days. Therefore, it is not advisable to rely on antidotes and to neglect drift control. It is a wise first choice to fundamentally reduce the drift of herbicides, which can also improve the utilization rate of herbicides and reduce environmental and soil pollution, making positive contributions to the safe production of corn and the ecologically sustainable development of farmland.

5. Conclusions

Aiming at the problem of herbicide damage under soybean–corn intercropping, this study studied the herbicide damage of the soybean herbicide Quizalofop-p-ethyl on the corn plants. An observation method and a growth inhibition method were used to obtain the herbicide damage symptoms and inhibition rate of the plant height of the corn under different spray volumes and drift deposition rates. In addition, the drift deposition rate R_{10}, which causes a 10% inhibition to corn plant height, was preliminarily obtained. The research results were as follows:

(1) When the drift deposition rate was 1%, corn plants showed no symptoms of herbicide damage and the plant height was not inhibited 14 days after spray under the three spray volumes. When the drift deposition rate was 5% and above, the herbicide damage symptoms of corn plants were aggravated with the increase in the drift deposition rate.

(2) Under the same drift deposition rate, the influence of the spray volume on the symptoms of herbicide damage was not obvious because of the different drift deposition amounts. The drift deposition rate had a very significant effect on the symptoms of herbicide damage and the plant height of corn, but the spray volume had no significant effect. Reducing drift is the primary consideration of herbicide spraying in soybean–corn intercropping.

(3) The drift deposition rates for 10% inhibition and no inhibition of corn plant height were 5.70% (R_{10}) and 5.05% (R_0) at 150 L/ha of spray volume, 4.56% (R_{10}) and 1.23% (R_0) at 300 L/ha of spray volume, and 3.31% (R_{10}) and 1.86% (R_0) at 450 L/ha of spray volume, respectively. Before spray, it is better that the drift deposition rate of quizalofop-p-ethyl be controlled below R_{10} by designing appropriate operating parameters, using anti-drift nozzles, adding anti-drift additives, etc.

(4) Field corn showed no symptoms of herbicide damage and plant height was not inhibited when drift deposition rates ranged from 1.22% to 1.69% under the spray volume of 450 L/ha, which is consistent with the results of the potted corn test.

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