Evaluation of Droplet Size and Deposition-Drift Distribution Characteristics of Herbicide Application by UAV in Winter Wheat Fields: Postprint

Authors: Wang Guobin, Han Xin, Song Cancan, Yi Lili, Lu Wenxia, Lan Yubin

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Abstract

With the increasing operation area of plant protection unmanned aerial vehicles (UAVs), the risk of droplet drift has become increasingly prominent, particularly the hazard posed by herbicide drift. To clarify the effects of herbicide solutions on droplet size and the deposition-drift distribution characteristics of herbicide droplets sprayed by plant protection UAVs, this study measured the droplet size distribution of water and 15 commonly used wheat field herbicide solutions sprayed by a centrifugal rotary atomizer nozzle installed on a plant protection UAV in an indoor spray chamber, and determined the droplet deposition distribution in the spray operation zone and drift zone through field experiments by adding a fluorescent tracer (60 g/hm^2) to the spray tank. Indoor measurement results indicated that herbicide solutions had significant effects on droplet size compared with water. Except for the carfentrazone-ethyl water dispersible granule formulation, the volume median diameter (VMD) of droplets from other solutions was reduced compared with water after being sprayed by the centrifugal rotary atomizer nozzle, with a maximum reduction of 22.0%; the proportion of small droplets ($V < 150$ m) increased, with a maximum increase of 50.8%. Field drift experiments demonstrated that when a plant protection UAV sprayed 150 m droplets under an ambient crosswind speed of 3.76 m/s, the droplet deposition coverage and droplet deposition density in the operation zone were only 41.3% and 42.2% of those at a wind speed of 0.74 m/s, with uniformity significantly reduced. At 12 m downwind in the drift zone, droplet deposition was less than 10% of that in the operation zone; at 50 m downwind, droplet deposition was below the detection limit (0.0002 L/cm^2). The drift ratio increased with wind speed, reaching 46.4% when wind speed reached 3.76 m/s. Under different crosswind speeds, the position of 90% cumulative drift was within 4.8–22.4 m. Fitting of deposition in the drift zone with drift distance and crosswind speed indicated that downwind deposition was proportional to wind speed. This study provides data support for droplet drift distances during winter wheat field operations with plant protection UAVs under different wind speeds, and offers a basis for spray drift buffer zones and drift risk assessment.

Full Text

Evaluation of Droplet Size and Drift Distribution of Herbicide Sprayed by Plant Protection Unmanned Aerial Vehicle in Winter Wheat Field

WANG Guobin1,2, HAN Xin1,2, SONG Cancan1,2, YI Lili1,2, LU Wenxia1,2, LAN Yubin1,2,3*

1 College of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255049, China
2 Shandong Provincial Engineering Technology Research Center for Agricultural Aviation Intelligent Equipment, Zibo 255049, China
3 College of Electronics Engineering/College of Artificial Intelligence, South China Agricultural University, Guangzhou 510642, China

Abstract: With the continuous increase of the spraying area, the problem of droplet drift risk in the spraying process of UAV is becoming increasingly prominent, especially the herbicide drift. In order to clarify the effect of the herbicide solution on the droplet size and the deposition and drift distribution characteristics sprayed by UAVs, the droplet sizes of 15 herbicide solutions sprayed by the centrifugal rotary atomizer nozzle installed in the plant protection UAV were measured in the laboratory, and the distribution of droplet deposition and drift in the spraying area and drift area were measured by adding a fluorescent tracer (60 g/hm^2) to the tank in the field. The results showed that the herbicide solution had a significant effect on the droplet size distribution. The DV$_{50}$ of all the other solutions was reduced after sprayed by the centrifugal atomizer except the Carfentrazone-ethyl water dispersible granule, and the maximum decrease ratio was 22.0%. The proportion of small droplets (V<150 m) increased, with the maximum value of 50.8%. When the environmental crosswind speed was 3.76 m/s, the coverage and number of droplets in the spraying area were only 41.3% and 42.2% of that at 0.74 m/s, and the deposition uniformity was significantly reduced. In the drift zone, the deposition amount of droplets was under 10% of in-swath zone at the downwind of 12 m, and the deposition of all the treatments at 50 m was lower than detection limits (0.0002 L/cm^2). The drift ratio increased with the wind speed increased. When the crosswind speed reached 3.76 m/s, the drift ratio of droplets was 46.4%. Under different crosswind, 90% of the total measured spray drift were 4.8 22.4 m. By fitting the deposition in the drift zone with drift distance and crosswind speed, the downwind deposition was proportional to the crosswind speed. This study provides data support for droplet drift distance of plant protection UAV spraying in wheat fields at different wind speeds in winter and provides a basis for spray drift buffer zone, drift risk assessment, and relevant standard formulation.

Keywords: plant protection unmanned aerial vehicle (UAV); wheat; herbicide formulation; droplet size; crosswind speed; droplets deposition and drift

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1 Introduction

Since the Ministry of Agriculture formulated the "Action Plan for Zero Growth of Pesticide Use by 2020" in 2015, the pesticide utilization rate of China' s three major grain crops has increased year by year under the promotion of precision application technology. By 2020, China' s pesticide utilization rate reached 40.6%, an increase of 4 percentage points compared with 2015 [1]. During these five years, plant protection UAVs, as one of the precision application equipment [2], have been widely and rapidly developed due to their advantages of high operational flexibility, strong emergency prevention and control capability, high operation efficiency [3], and high pesticide utilization rate, playing an important role in promoting the improvement of China's pesticide utilization rate [4,5]. By 2019, the number of plant protection UAVs in China exceeded 50,000, with an operation area of over 450 million mu, a 108-fold increase within five years [6]. Currently, plant protection UAVs have become an indispensable and powerful tool for the prevention and control of plant diseases, pests, and weeds in China, greatly improving the backward situation of plant protection machinery and enhancing China' s pesticide application technology.

To promote the rapid development of plant protection UAVs, researchers have conducted extensive studies on UAV spraying technology. In terms of spraying equipment optimization, various low-volume spraying nozzles suitable for plant protection UAVs have been developed, including ultra-low volume swirl nozzles [7], rotary cup atomizers [8], and electrostatic nozzles [9], and systematic evaluations of nozzle spray performance and atomization quality have been carried out [10], basically meeting the current low-volume spraying requirements of plant protection UAVs. In terms of operational parameter optimization, for various crops such as rice [11], wheat [12], corn [13], and fruit trees [14,15], the relationship between droplet deposition and crop canopy has been analyzed using deposition rate and coefficient of variation as evaluation indicators, the operating height and speed have been optimized, and the effective spray swath suitable for UAV operations has been determined [16,17], improving the quality of pesticide application. In terms of field efficacy evaluation, studies have been conducted on the control of various field grain crop diseases, pests, and weeds [18-20] and cotton defoliation effects [21,22] regarding parameters such as pesticide type, spray volume, and droplet size, and optimal spraying parameters have been formulated for different control targets to ensure good control effects of UAV spraying. In 2018, the National Center for International Joint Research on Precision Agricultural Aviation Spraying Technology cooperated with FMC Corporation of the United States to complete the “Plant Protection UAV Spraying Operation Specification” [23], publicly releasing the selected optimal plant protection products and spray adjuvants, key technical parameters for pesticide application, and appropriate environmental variables, which have played an important reference role in UAV spraying operations.

With the continuous increase of operation area, the problem of droplet drift risk in the spraying process of plant protection UAVs has become increasingly prominent. In 2018, a serious herbicide drift incident occurred in Harbin, Heilongjiang Province, where a plant protection UAV spraying herbicide in a corn field caused severe damage to adjacent soybean fields [24]. In 2019, in Xinjiang Autonomous Region, plant protection UAVs spraying herbicides such as “MCPA + clopyralid + florasulam” and “clodinafop-propargyl” in wheat fields caused serious phytotoxicity to adjacent cruciferous crops [25]. In communication with various UAV operation organizations, the author found that such phytotoxicity and environmental safety accidents occur from time to time. Researchers have previously conducted classified studies on factors that may cause drift during UAV spraying. Regarding rotor wind field and downwash airflow, computational fluid dynamics software has been used to simulate the rotor wind field of single-rotor [26] and quad-rotor [27] UAVs, revealing the influence of wingtip vortices and spiral trailing vortices on droplet drift, and using these results to optimize nozzle placement directly below the rotor to avoid the disturbance influence of wingtip vortices. Regarding environmental and operational parameters, researchers have conducted measurements of droplet drift distribution of various UAV models in different regions with different environmental characteristics, including Shandong [28], Xinjiang [29], Hainan [30], and Jiangsu [31], and found that UAV model, environmental parameters, and operational parameters have significant effects on droplet drift distance. Regarding spray adjuvants and nozzle selection, researchers have measured the effects of adjuvant types and concentrations on nozzle atomization effects and droplet drift, and screened suitable spray adjuvants [32] and anti-drift air-induction fan nozzles [33] for UAV spraying. Although researchers have conducted preliminary explorations on various factors affecting UAV spraying drift and optimized UAV models and spraying system installation positions based on research results, and characterized the influence weights of different environmental and flight parameters on droplet drift, there is still a lack of research on droplet drift characteristics for specific pesticides and corresponding spraying environments, especially measurements of droplet drift distribution during herbicide spraying periods.

According to the “2021 Technical Scheme for Scientific Prevention and Control of Weeds in Farmland” issued by the National Agricultural Technology Extension Service Center, China’ s wheat fields can be divided into the Yellow River Basin dryland-dryland rotation winter wheat region, the Yangtze-Huaihe River Basin paddy-dryland rotation winter wheat region, and the spring wheat planting region. The Yellow River Basin dryland-dryland rotation wheat region mainly includes Hebei, Shandong, Henan, and other places, where there are fewer adjacent crops during winter wheat weed control, resulting in lower drift phytotoxicity risk. The Yangtze-Huaihe River Basin paddy-dryland rotation wheat region mainly includes Jiangsu, Anhui, Hubei, Hunan, and other places, where rapeseed and broad beans are often planted adjacent to wheat fields during winter wheat weed control, resulting in higher drift phytotoxicity risk. The northwest spring wheat region mainly includes Xinjiang, Gansu, and other places, where broadleaf crops such as cotton, sunflower, corn, pepper, melon, and tomato are often planted adjacent to spring wheat fields during weed control, also having high drift phytotoxicity risk. Therefore, this study focuses on the high-risk scenario of herbicide spraying drift in winter wheat fields by plant protection UAVs. Through laboratory measurement of the effects of high-concentration wheat field herbicides on droplet size sprayed by centrifugal rotary atomizer nozzles and field measurement of deposition and drift distribution in the operation zone and drift zone after UAV spraying, the drift ratio and 90% cumulative drift position of UAV spraying were determined, and the droplet drift distribution curve was fitted, aiming to provide a reference for the assessment of herbicide spray drift in wheat fields by plant protection UAVs.

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2 Materials and Methods

2.1 Droplet Size Measurement

Droplet size is one of the important factors affecting droplet drift. The measurement device for droplet size included a DP-02 laser particle size analyzer (Zhuhai OMEC Instruments Co., Ltd.) and a centrifugal spraying system. The centrifugal spraying system consisted of a DC power supply, a peristaltic pump, and a centrifugal rotary atomizer nozzle (Guangzhou XAG Co., Ltd.). The distance between the receiving and transmitting ends of the laser particle size analyzer was 1.5 m. The nozzle was fixed 0.4 m above the centerline of the laser particle size analyzer, directly above the receiving end. The spray pattern was circular, and the droplet ring vertically settled and passed through the laser beam (Figure 1 [Figure 1: see original paper]). The input voltage of the centrifugal rotary atomizer nozzle was 20 V, the input voltage of the peristaltic pump was 25 V, the nozzle rotation speed was measured by an SW-6234C laser tachometer, and the flow rate K24 was measured by a turbine flowmeter.

This experiment first measured the effect of high-concentration herbicide solutions required for UAV spraying on the droplet size after spraying by the centrifugal rotary atomizer nozzle. Fifteen commonly used winter wheat field herbicides were selected, including seven formulations: emulsifiable concentrate (EC), suspension concentrate (SC), oil dispersion (OD), water dispersible granule (WDG), suspo-emulsion (SE), aqueous solution (AS), and emulsion in water (EW) (Table 1). The herbicide dosage was prepared according to the lower limit of the registered recommended dose (g/hm^2 or mL/hm^2), and the concentration was calculated based on the recommended dose and the commonly used spray volume of plant protection UAVs (12 L/hm^2).

2.2 Droplet Deposition and Drift Distribution Measurement

2.2.1 Plant Protection UAV The plant protection UAV was a P30 electric quad-rotor aircraft (Guangzhou XAG Co., Ltd., Figure 2 [Figure 2: see original paper]), with a standard takeoff weight of 38 kg, a tank capacity of 16 L, and dimensions of 2018 mm × 2013 mm × 490 mm (length × width × height). It was powered by an 18,000 mAh lithium battery. The UAV had four rotors and four centrifugal rotary atomizer nozzles located directly below the rotors, with a nozzle spacing of 1262 mm × 1250 mm. The droplet size and operational parameters could be input through an intelligent handheld terminal, and real-time kinematic (RTK) technology was used for precise flight positioning. The relevant indicators of the UAV during the test were set as follows: spray droplet size 150 m, spray volume 12.0 L/hm^2, spray swath 3.5 m, flight speed 5 m/s, flight height 4 m, and only the two rear nozzles were turned on during drift tests. The selection of these operational parameters was based on commonly used parameters for field weed control operations.

2.2.2 Collection of Droplet Deposition and Drift Distribution The test site was located at the Ecological Unmanned Farm of Shandong University of Technology in Zhutai Town, Zibo City, Shandong Province. There were no obstructions within 500 m around the test site, and the wheat height was (6.1 ± 1.1) cm. Since multiple applications of herbicides would pose a risk of phytotoxicity to wheat, this test used a fluorescent tracer + surfactant solution instead of herbicide solution to measure droplet drift. Before the test, 5.0 g/L of fluorescent tracer Rhodamine-B (Shanghai San Chemical Technology Co., Ltd.), a water-soluble, low-toxicity, low-detection-limit, and high-recovery-rate tracer widely used in droplet drift tests, was added to the tank. To simulate the properties of herbicide solution, 1‰ OP-10 water-soluble surfactant (Shandong Kepler Biotechnology Co., Ltd.) was also added to the spray solution.

According to published literature, the drift distance of plant protection UAVs is significantly greater than its effective spray swath, with the 90% cumulative drift position at 9.0–40.0 m [28-31]. Therefore, droplet drift would occur in multiple swaths adjacent to the edge of the operation zone upwind, and single-pass spray tests would be difficult to reflect the actual cumulative drift amount. For this reason, this test measured the cumulative drift deposition of three passes. The droplet collection of the plant protection UAV was divided into the operation zone and drift zone (Figure 3 [Figure 3: see original paper]).

The operation zone refers to the area within the effective spray swath of the plant protection UAV, while the drift zone refers to the off-target area outside the effective spray swath where droplets drift due to environmental wind during the spraying process. The deposition amount (g/cm^2) in the operation zone and drift zone was collected using PVC cards (4 cm × 8 cm). Each group of PVC cards was arranged parallel to the wind direction, with a total of 16 cards, of which 6 were located in the operation zone, 9 in the drift zone, and 1 at the boundary. Each group of PVC cards was arranged in triplicate with a 10 m interval, totaling 48 cards. The interval between PVC cards in the operation zone was 1.75 m. The PVC cards in the drift zone were located at distances of 0, 2, 4, 8, 12, 16, 20, 30, 40, and 50 m downwind from the edge of the effective spray swath. The PVC cards were horizontally fixed on hard plastic boards and arranged on tripods using double-headed clips. To avoid the influence of rotor airflow ground effect, the PVC cards were 1 m above the ground, and the plant protection UAV was 3 m above the PVC cards. To further characterize the deposition characteristics in the operation zone, a coated paper (3 cm × 8 cm) was also placed on the plastic board where the PVC cards were placed in the operation zone to collect droplet deposition coverage and density (Figure 4 [Figure 4: see original paper]).

2.2.3 Measurement of Droplet Deposition and Drift Distribution After the completion of the field drift spray test, the PVC cards and coated papers at each sampling point were numbered and collected in ziplock bags. Care was taken not to contaminate the PVC cards during collection. They were refrigerated after being brought back to the laboratory. The PVC card processing procedure and recovery rate analysis followed the method in reference [34]. Twenty milliliters of anhydrous ethanol was added to the ziplock bag containing the PVC card for elution. After elution, 3 mL of the eluent was pipetted into a cuvette, and the fluorescence value was measured using an Agilent Cary Eclipse fluorescence spectrophotometer (Agilent Technologies). The collected coated papers were scanned one by one using an HP ScanJet Pro 2500 f1 scanner (HP China Co., Ltd.) at a resolution of 600 dpi, and the images were analyzed using DepositScan image processing software (USDA) to obtain droplet deposition coverage (%) and droplet deposition density (droplets/cm^2).

2.2.4 Meteorological Parameter Collection The field drift measurement test was conducted in the Yellow River Basin region in Zibo City, Shandong Province. However, there are few adjacent crops near wheat fields in the Yellow River Basin during winter, resulting in low drift phytotoxicity risk. Therefore, the test time was selected during a period with higher temperatures before normal weed control in the Yellow River Basin wheat region to ensure that the environmental temperature and humidity were basically consistent with the representative temperature and humidity environment during winter wheat weed control in the Yangtze-Huaihe River Basin paddy-dryland rotation wheat region. Meteorological conditions for each of the 17 groups of tests were collected using a Kestrel 5000 LiNK weather station (Beijing Jinshite Instrument Co., Ltd.) at a frequency of 2 s/time. The collected data included ambient temperature, relative humidity, and wind speed and direction. To avoid interference from the UAV rotor wind, the weather station was placed 20 m downwind from the edge of the effective spray swath. To ensure that the angle between wind direction and operation direction was within 90° ± 30°, sampling devices were set up in corresponding directions according to wind conditions during the test. Three different direction samplings were set up in this test, with sampling line directions of 55°, 115°, and 350°, respectively.

2.3 Data Processing

The droplet size from the nozzle spray was evaluated using DV10, DV50, DV90, V<150 m, and RS (Relative Span) indicators. DVm refers to the droplet volume median diameter value when all droplets are sorted by size and account for m% of the total volume, where DV50 is also known as the droplet volume median diameter. V<150 m refers to the proportion of droplets smaller than 150 m in the droplet spectrum, which is an important parameter for evaluating easily drifted small droplets. RS is the droplet distribution span or droplet spectrum width, an indicator measuring the width of droplet size distribution. A larger RS indicates lower droplet uniformity. RS is calculated using formula (1):

$$RS = \frac{DV_{90} - DV_{10}}{DV_{50}} \tag{1}$$

Based on the fluorescence values measured in Section 2.2.3, the deposition amount in the operation zone and drift zone was calculated using formula (2):

$$\beta_{dep} = \frac{(\rho_{smpl} - \rho_{blk}) \times F_{cal} \times V_{dil}}{\rho_{spray} \times A_{col}} \tag{2}$$

where β_{dep} is the spray deposition amount, L/cm2; ρ_{smpl} is the fluorometer reading of the sample; ρ_{blk} is the fluorometer reading of the blank sampler without tracer; F_{cal} is the calibration coefficient, the concentration corresponding to the unit scale of the fluorescent agent, g/L; V_{dil} is the volume of the diluent used to dissolve the tracer collected by the collector, L; ρ_{spray} is the spray liquid concentration, g/L; and A_{col} is the projected area of the collector for collecting spray drift, cm2.

The deposition rate in the operation zone or drift zone was calculated using formula (3):

$$\beta_{dep\%} = \frac{10000 \times \beta_{dep}}{\beta_v} \tag{3}$$

where β_{dep} is the spray deposition amount, L/cm2; and β_v is the spray volume, L/hm2.

According to ISO 22866 standard [35], the attenuation curve of spray drift zone deposition along the sampling distance x was measured:

$$f(x) = a + b\ln(x) \tag{4}$$

Based on the drift curve, the cumulative drift rate D_t, % (formula 5) and drift percentage D, % (formula 6) were calculated:

$$D_t = \frac{\int_0^\infty f(x)dx}{\int_0^\infty f(x_i)dx} \times 100\% \tag{5}$$

$$D\% = \frac{\int_0^x f(x)dx}{D_t} \times 100\% \tag{6}$$

The 90% drift position was defined as the sampling distance x value when $D\%$ equals 90%, m. The tracer recovery rate R, % (formula 7):

$$R = \frac{\int_0^\infty f(x)dx}{\text{spray amount}} \times 100\% \tag{7}$$

The drift ratio D_o, % (formula 8):

$$D_o = \frac{D_t}{R} \times 100\% \tag{8}$$

3 Results and Analysis

3.1 Effect of Herbicide Solution on Droplet Size

The rotation speed of the centrifugal rotary atomizer nozzle at 20 V was 9245.5 r/min, and the flow rate of the peristaltic pump at 25 V was 1.03 L/min. The measured DV50 of water sprayed by the centrifugal rotary atomizer nozzle was 154.3 m, V<150 m was 47.2%, and RS was 1.01. Except for Carfentrazone-ethyl WDG, the DV50 of the other herbicide solutions was reduced after being sprayed by the centrifugal rotary atomizer nozzle (Table 2). Among them, the solutions of mesosulfuron-methyl OD, pyroxsulam + fluroxypyr OD, and fluroxypyr EC had the greatest impact on DV50, which were reduced by 16.8%, 14.0%, and 22.0% compared with water, respectively. At the same time, these three solutions had the largest increase in the proportion of small droplets (V<150 m), with increases of 33.5%, 36.4%, and 50.8%, respectively. The increase ratio of V<150 m for other herbicides ranged from 0.8% to 18.0% (Table 2). Compared with water, after adding various herbicides, only tribenuron-methyl WDG and Carfentrazone-ethyl WDG solutions reduced the RS value after being sprayed by the centrifugal rotary atomizer nozzle, by 7.0% and 6.9%, respectively, while the other herbicides increased the RS value by 2.4% to 17.9%, but the effect was not significant (Table 2).

Previous studies have shown that solution properties, including surface tension, viscosity, and solution uniformity, interact with nozzle type and spray pressure and significantly affect droplet size distribution [36,37]. Among the 15 pesticides selected in this study, only Carfentrazone-ethyl WDG solution increased the DV50 of the centrifugal rotary atomizer nozzle, while 12 of the other 14 pesticides significantly reduced DV50 and increased the proportion of small droplets (V<150 m). Among them, oil dispersion (OD) and emulsifiable concentrate (EC) formulations with high organic solvent content had the most significant impact, which would significantly increase the risk of droplet drift after nozzle spraying. Attention should be paid to this in the field application of herbicides by plant protection UAVs.

3.2 Field Drift Test Results

3.2.1 Meteorological Data A total of 17 groups of drift data were collected, and 10 groups with relatively large wind speed differences were selected for analysis. Table 3 shows the meteorological parameters during the 10 groups of tests. The temperature ranged from 7.3 to 13.0°C, and the relative humidity ranged from 46.6% to 75.0%. The temperature and humidity of each treatment were relatively stable and consistent, basically matching the representative temperature and humidity environment during winter wheat weed control in the Yangtze-Huaihe River Basin paddy-dryland rotation wheat region. The crosswind speed ranged from 0.74 to 3.76 m/s, and the absolute value of the angle between wind direction and sampling direction ranged from 6.7° to 22.3° (less than 30°), meeting the requirements of the ISO standard [35].

3.2.2 Droplet Coverage and Deposition Density in Operation Zone The increase of crosswind speed reduced the droplet deposition coverage and density in the operation zone (Table 4). When the crosswind speed ranged from 0.74 to 3.76 m/s, the droplet deposition coverage was 1.62%-3.93%, and the droplet deposition density was 8.24-19.52 droplets/cm2. When the crosswind speed was 3.76 m/s, the droplet deposition coverage and density in the operation zone were only 41.3% and 42.2% of those at 0.74 m/s, respectively. The increase in crosswind speed also reduced the uniformity of droplet deposition in the operation zone. The coefficients of variation for droplet deposition coverage and density under different test wind speeds were 35.0%-92.1% and 31.5%-81.4%, respectively, and the deposition variation coefficients in the operation zone were all greater than 80.0% when the crosswind speed exceeded 3.0 m/s (Table 4).

Based on the "lethal radius" theory of droplets, the reduction of droplet deposition coverage, density, and uniformity in the operation zone decreases the control effect of plant protection UAV spraying on diseases, pests, and weeds [38]. Previous studies have shown that spraying uniformity has always been a problem with plant protection UAVs, including the influence of rotor wind field and nozzle installation position [19,20]. The results of this test indicate that uniformity would be further reduced under the influence of external crosswind, which would have a significant impact on the control efficacy of diseases, pests, and weeds. Therefore, plant protection UAV spraying operations should be conducted under low wind speed conditions as much as possible.

3.2.3 Droplet Deposition Distribution in Operation and Drift Zones

Under different crosswind speeds, the droplet size with a volume median diameter of 150 m showed deposition distribution in the operation zone and drift zone as shown in Figure 5 [Figure 5: see original paper] T1(a)-T10(a), and the cumulative distribution of deposition in the drift zone with sampling position is shown in Figure 5 [Figure 5: see original paper] T1(b)-T10(b). The fluorescence value of Rhodamine B was determined by fluorescence spectrophotometry, and based on the established standard curve between concentration and fluorescence value, the minimum detection limit of Rhodamine B was determined to be 0.0002 L/cm2. With a tracer application rate of 60 g/hm2 (0.6 g/cm2), the droplet deposition amount in the effective spray swath ranged from 0.00 to 0.77 g/cm2 (Figure 5). Affected by crosswind, the deposition amount at the -10 m position in the operation zone of all treatments was the lowest. The coefficient of variation of droplet deposition amount in the operation zone under different crosswind speeds was 36.9%-92.2%, and the deposition uniformity decreased with increasing crosswind speed.

The variation pattern of droplets in the drift zone under different wind speeds was basically consistent. Except for treatments T7, T8, and T9, where the deposition at 2 m downwind was higher than at 0 m, the deposition at other positions gradually decreased with increasing drift distance. At the position 12 m downwind, the deposition amount ranged from 0.00 to 0.04 g/cm2 (below detection limit to 6.6% of the spray amount). Although the deposition amount was already very low at 12 m downwind, droplet drift still existed, and whether this drift amount would cause phytotoxicity to sensitive crops requires further demonstration. The deposition amount at 50 m for all treatments was below the detection limit. It is worth noting that under low wind speed conditions (0.74 m/s), the droplet deposition at 4 m was still 0.01-0.03 g/cm2 (1.5%-5.0% of the spray amount), mainly due to droplet drift caused by multiple factors including crosswind, rotor wind field, and Brownian motion of droplets.

The author' s team [29] measured the droplet drift of the XAG P20 plant protection UAV in Shihezi, Xinjiang (high temperature, dry environment) and found that when the crosswind speed reached 3.5 m/s, the deposition at 12 m downwind was about 10% of that in the operation zone, and drift droplets still existed at 50 m downwind. This result showed a farther drift distance and greater drift amount than this study, which also proved the significant influence of environmental parameters on drift. In terms of drift distance, Wang et al. [39] measured the spray drift of a single-rotor UAV on areca palms and found that the farthest drift distance of droplets could reach 36.4 m, which is basically consistent with the results of this study.

A mass balance analysis was conducted on the deposition in the operation zone and drift zone, and the tracer recovery rate was calculated to be 54.2%-75.9%

(Table 5). The relatively low recovery rate in this test was mainly due to the photodegradation of Rhodamine B [40] and the deposition of some tracer on the UAV body under the 卷扬 of the rotor wind field.

The drift ratio was calculated and found to increase with wind speed. When the crosswind speed reached 3.76 m/s, the droplet drift ratio reached 46.4%, meaning that nearly half of the droplets drifted from the operation zone to the drift zone (Table 5). Under different crosswind speeds, the 90% cumulative drift position was 4.8-22.4 m. The 90% cumulative drift position is an important parameter for evaluating drift amount. Researchers found in a study on the drift distribution characteristics of oil-powered single-rotor plant protection UAVs in wheat fields that when the crosswind speed was 0.76-5.5 m/s, the 90% drift position was in the range of 9.3-14.5 m downwind from the spray area [41]. In a drift measurement study in pineapple fields, it was found that when the crosswind speed was 1.17-3.93 m/s, the 90% drift position was in the range of 3.7-46.5 m [30]. These two results differ somewhat from this test, mainly due to the influence of test UAV model, environmental parameters, nozzle type, and other factors.

In this study, when the wind speed reached above 2 m/s, the 90% cumulative drift position did not show a good linear correlation with crosswind speed. This was mainly because the 90% cumulative drift position was calculated through fitting the cumulative distribution curve, and the fitting curve was greatly affected by the deposition amount near the edge of the effective spray swath downwind. When the wind speed was above 2 m/s, the deposition amount near the edge of the effective spray swath downwind fluctuated greatly (Figure 5), resulting in reduced stability of the fitted curve and increased fluctuation in the calculated 90% cumulative drift position.

3.2.4 Downwind Drift Curve in Drift Zone Through nonlinear fitting of the deposition amount at each sampling point with sampling position and crosswind speed using the 10 groups of data, the downwind droplet drift fitting equation was obtained as formula (9):

$$D_p = \exp(-D_t/4.71) \times (0.053W_s + 0.104) \tag{9}$$

where D_p is the droplet deposition amount in the drift zone, g/cm2; D_t is the distance from the edge of the effective spray swath downwind, m; and W_s is the crosswind speed, m/s. Table 6 shows the descriptive statistics and variance analysis table. The fitting determination coefficient $R^2 = 0.87$, indicating a good fitting effect. From the fitting equation, the downwind deposition amount has a positive linear relationship with crosswind speed, which is basically consistent with the conclusion of the drift ratio.

The comparison between measured and predicted drift values is shown in Figure 6 [Figure 6: see original paper]. Analyzing the influence of different sampling positions on the fitting results (Figure 6(a)), it was found that at the boundary between the operation zone and drift zone (0 m and 2 m downwind), the predicted values deviated significantly from the actual values. At this position, the drift droplets were affected by the rotor wind field, resulting in large fluctuations in droplet deposition, which was also the reason for the large fluctuation in the calculated 90% cumulative drift position in Section 3.2.3. Analyzing the influence of different crosswind speeds on the fitting results (Figure 6(b)), except for some individual deposition values under wind speeds of 2.93 and 3.35 m/s that had large deviations, the actual values of the remaining depositions fitted well with the predicted values.

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4 Conclusion and Outlook

To analyze the risk of herbicide droplet drift during winter wheat weed control by plant protection UAVs, this study measured the effects of winter wheat herbicide solutions on droplet size sprayed by centrifugal rotary atomizer nozzles in the laboratory and measured the deposition and drift distribution in the operation zone and drift zone after UAV spraying in the field. The main conclusions are as follows:

1. High-concentration herbicide solutions have a significant effect on droplet size distribution. After spraying by the centrifugal rotary atomizer nozzle, the DV50 of most herbicide solutions was significantly reduced, while V<150 m and RS were significantly increased, especially for formulations containing more organic solvents.
2. The increase of crosswind speed significantly reduces droplet deposition coverage, deposition density, and deposition uniformity in the operation zone. Under high wind speed (3.76 m/s), the deposition coverage and density are only about 50% of those under low wind speed (0.74 m/s).
3. With a droplet size of 150 m and wind speed of 0.74-3.76 m/s, the droplet deposition amount at 12 m downwind in the drift zone is less than 10% of that in the operation zone, and the drift amount at 50 m is below the detection limit. The drift ratio increases with wind speed, reaching 46.4% when the wind speed reaches 3.76 m/s. Under different wind speeds, the 90% cumulative drift position is 4.8-22.4 m. Therefore, a drift buffer zone of more than 25 m needs to be reserved when operating under high wind speed conditions.

The above results can provide data support for the droplet drift distance of plant protection UAVs operating under different wind speeds in winter wheat fields. However, due to test conditions and UAV model limitations, these results are only applicable to the P30 plant protection UAV (XAG) operating in winter wheat fields. Currently, the development time of plant protection UAV spraying technology is relatively short, and a large amount of drift data is still lacking to establish a comprehensive spray drift model. In future research, accumulating data to establish a complete droplet drift model will be important for improving plant protection UAV spraying technology.

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Note: Figure translations are in progress. See original paper for figures.