Evaluating effective swath width and droplet distribution of aerial spraying systems on M-18B and Thrush 510G airplanes

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Abstract: Aerial spraying plays an important role in promoting agricultural production and protecting the biological environment due to its flexibility, high effectiveness, and large operational area per unit of time. In order to evaluate the performance parameters of the spraying systems on two fixed wing airplanes M-18B and Thrush 510G, the effective swath width and uniformity of droplet deposition under headwind flight were tested while the planes operated at the altitudes of 5 m and 4 m. The results showed that although wind velocities varied from 0.9 m/s to 4.6 m/s, and the directions of the atomizer switched upward and downward in eight flights, the effective swath widths were kept approximately at 27 m and 15 m for the M-18B and Thrush 510G, respectively, and the latter was more stable. In addition, through analyzing the coefficients of variation (CVs) of droplet distribution, it was found that the CVs of the M-18B were 39.57%, 33.54%, 47.95%, and 59.04% at wind velocities of 0.9, 1.1, 1.4 and 4.6 m/s, respectively, gradually enhancing with the increasing of wind speed; the CVs of Thrush 510G were 79.12%, 46.19%, 14.90%, and 48.69% at wind velocities of 1.3, 2.3, 3.0 and 3.4 m/s, respectively, which displayed the irregularity maybe due to change of instantaneous wind direction. Moreover, in terms of the CVs and features of droplet distribution uniformity for both airplanes in the spray swath, choosing smaller CV (20%-45%) as the standard of estimation, it was found that the Thrush 510G had a better uniform droplet distribution than the M-18B. The results provide a research foundation for promoting the development of aerial spraying in China.

Keywords: aerial spraying, effective swath width, droplet distribution, coefficients of variation, agricultural airplane
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1 Introduction

How to prevent the rapidly spread of the diseases and pests and effectively protect ecological environment in large scale, has been given highly attention by scholars and researchers worldwide[1,2]. Aerial spraying, due to

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its mobility, high work efficiency, and large area covering, has advantages in diseases and pests control and management in agricultural production[3,4]. However, the effectiveness of flight spraying is commonly influenced by factors including airplane types, mounted instruments and systems, flight height and weather conditions, etc[5-6]. Aiming at these conceivable problems, Fritz et al.[7-8] evaluated spray drift and droplet deposition of the spray system on the Air Tractor 402B airplane (Air Tractor, Inc., Olney, Texas, USA); Alan[9] measured the effective swath width and the uniformity of droplet distribution of the spray devices on the Thrush 510P (Thrush Aircraft Inc., Albany, Georgia, USA); Huang et al.[10] evaluated the effect of application height on in-swath and downwind spray deposition and droplet spectra using CP flat-fan nozzles on fixed wing aircraft[5]; Hoffmann et al. modified the spraying setups and estimated its capacity. These are all helpful for improving the application effect of aerial spraying.

In the past years, although Chinese government has paid more attention on development of agricultural aviation applications[6], actually studies of aerial spraying in China were mostly based on the platforms of unmanned aerial vehicles (UAVs)[11-13] and few studies focused on the evaluation of application system on manned agricultural aircraft[14-15]. With the successive import of new spray systems with agricultural aircraft from abroad from 2009 to 2015, which included atomizers, nozzles, and flow control system, the question remains on how to adapt to different environmental conditions to test the spray parameters[16]. The M-18B (Polskie Zakłady Lotnicze Sp.zo.o, Inc., Mielec, Poland) and Thrush 510G, as two major types of agricultural aircraft imported and used in China, have not been evaluated for their effective swath width and uniformity of droplet distribution to guide practical application. In addition, owing to the factors such as windbreak plantings and electrical facility layouts in farmland, the flight height of agricultural airplane typically varies from 4 m to 20 m over the crop canopy in China[1], which is higher than the recommendation height (3 m) in American Society of Agricultural and Biological Engineers (ASABE) Standards S561.1 (2004)[7]. Therefore, it is necessary to evaluate and determine the effective swath width and uniformity of droplet distribution for the spray systems on M-18B and Thrush 510G airplanes. The objectives of this study were to test the performance parameters of spraying system on two fixed wing airplanes and provide a guideline for aerial spraying in agricultural production of China.

2 Materials and methods

2.1 Experimental site

The experiments were conducted at Jiaxi Airport (130°16'13"E, 46°47'35″N) of Jiamusi City in Heilongjiang province in China. A map of field trial is shown in Figure 1.

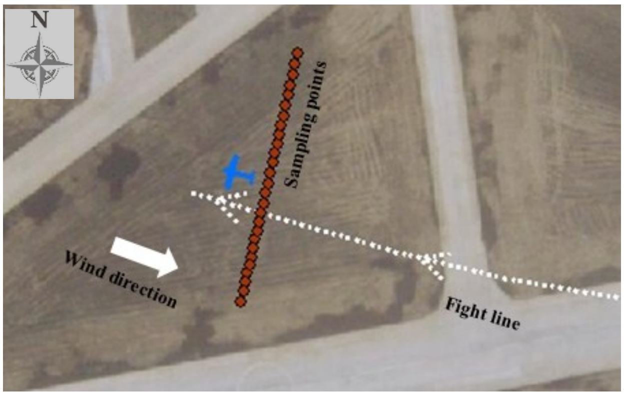

Figure 1 A map of the experimental site

2.2 Agricultural airplane

The agricultural airplanes, M-18B and Thrush 510G, imported from Polskie Zakłady Lotnicze Sp.zo.o, Inc. (Mielec, Poland) and Thrush Aircraft Inc. (Albany, Georgia, USA) in 2009 and 2014, respectively, were used in the experiments. They both are currently the most advanced models among the airplanes used for aerial application in China (Figure 2). The two airplanes are primarily used to apply pesticide and fertilizers, and sow rice seeds in northeast China. The specifications of the two airplanes are listed in Table 1.

2.3 Experimental design

Weather condition is one of the most important factors affecting aerial application. An east to west (E-W) flight path was first determined in light of the wind direction collected from the weather station of Jiaxi Airport. Fifteen sampling points with 3 meter intervals were arranged from south to north (S-N) on the lawn of Jiaxi Airport. Owing to dynamic changes in wind velocity and direction, we added sampling points both at the starting point (SP) and ending point (EP) to ensure the accuracy of the spraying experiments. The layout of sampling points is shown in Figure 3 and Table 2; meanwhile, the corresponding spray parameters and meteorological data are also listed in Tables 3 and 4.


a. M-18B b. Thrush 510G

Figure 2 The agricultural airplanes

Table 1 Specifications of the M-18B and Thrush 510G

Parameters	M-18B	Thrush 510G
Length/m	9.47	9.85
Height/m	3.70	2.84
Wing span/m	17.70	14.48
Wing area/m^2	40.00	33.90
Empty weight/kg	2710	2132
Max. takeoff weight/kg	5300	4763
Maximum speed/km·h^{-1}	230	241
Spray width/m	45	42

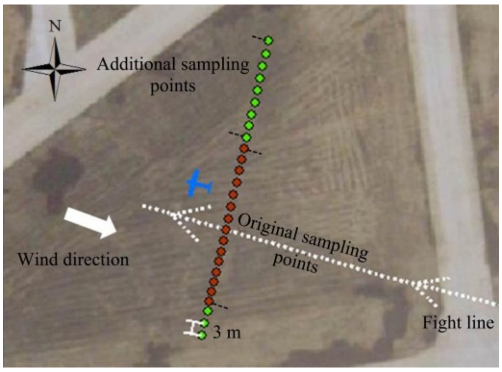

Figure 3 Layout of sampling points

Table 2 Experiments arrangement

Aircraft	Total sampling points	Original sampling points	Added sampling points	Distance between points/m	Height of water sensitive paper/cm	Sampling point direction	Flight direction
M-18B（1）	21	15	SP 3, EP 3	3	60	S-N	E-W
M-18B（2）	25	15	SP 3, EP 7	3	60	S-N	E-W
M-18B（3）	25	15	SP 3, EP 7	3	60	S-N	E-W
M-18B（4）	30	15	SP 3, EP 12	3	60	S-N	E-W
Thrush 510G（1）	21	15	SP 3, EP 3	3	60	S-N	E-W
Thrush 510G（2）	24	15	SP 3, EP 6	3	60	S-N	E-W
Thrush 510G（3）	24	15	SP 3, EP 6	3	60	S-N	E-W
Thrush 510G（4）	24	15	SP 3, EP 6	3	60	S-N	E-W

Table 3 Parameters of the spray systems on two airplanes and flight paths

Devices description	M-18B	Thrush 510G
Flight times	4	4
Atomizer	AU-5000	AU-5000
Nozzle orientation	Upward, -, Downward, -	Downward, -, Upward, -
Flow control valve	13	13
Atomizer fan blade angle/(°)	55, 45, 45, 45, 55	45, 45, 45, 45, 45
Spray volume/L·hm^{-2}	20	20
Rate of flow/L·min^{-1}	270	336
Flight height/m	5	4
Speed/km·h^{-1}	180	240
Flight path	E-W, upwind <15°	Flight 1: E-W, upwind <15° Flights 2-4: E-W, adjusted based on wind direction

Notes: E-W represents the flight path from east to west, upwind <15° means that the angle of flight orientation and headwind was maintained within 15°. The fan blade angles of atomizers were fixed and consistent with practical operation for M-18B and Thrush 510G.

Table 4 Meteorological data

Aircraft	Time	Wind speed	Temperature	Humidity	Wind description
M-18B	7:57-7:59	0.9 m/s	9.7℃	87%	West wind, steady
	8:08-8:10	1.1 m/s	12.3℃	85%	West wind, steady
	9:10-9:12	1.4 m/s	15.7℃	66%	West wind, steady
	9:22-9:24	4.6 m/s	15.9℃	60%	West wind, steady
Thrush 510G	6:57-6:59	1.3 m/s	4.6℃	94%	Northwest wind, steady
	7:13-7:15	2.3 m/s	8.9℃	91%	Northwest wind, variable
	7:51-7:53	3.0 m/s	9.1℃	85%	Northwest wind, variable
	8:28-8:30	3.4 m/s	11.6℃	75%	Northwest wind, variable

Note: Meteorological data was provided by Jiaxi airport weather base. When the values of wind speed were recorded each ten minutes, other indicators, the temperature and humidity were only collected in half an hour.

Figure 3 and Table 2 showed the original sampling points and extended ones when the flight path was determined. Seven sampling points were arranged both sides of flight centerline, and more sampling points were added with the change of weather condition. The sample point located at the centerline was set as 0 m; the first point on its left side was indicated -3 m, the corresponding that of right side was 3 m. An example was shown in Figure 3, the sampling point were -30, -27, -24, -21, -18, -15, -12, -9, -6, -3, 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42, 45, 48 m, respectively. The detailed position information of eight flights in the study was similar, only some extent adjustment was done by additional sampling points.

2.4 Sample collection and data processing

2.4.1 WSP sampling

Sample collection instruments included a shelf with water-sensitive paper (WSP) (Figure 4), a handheld scanner (Figure 5), rubber gloves, sealed bags and colored pens.

Figure 4 The shelf with water-sensitive paper

Figure 5 Handheld scanner

2.4.2 Data processing

When each flight was finished, the water-sensitive papers placed in the sampling area were quickly gathered in sealed bags and 600 dpi digital images were acquired using a handheld scanner in the lab. Then, a self-developed imagery recognition system was utilized to extract droplet deposits and calculate spray parameters such as coverage rate, deposit rate, density of deposit rate, and density of deposit spots. Meanwhile, mean coverage rate, mean deposit rate, and coefficient of variation (CV) were also calculated.

3 Results and analysis

3.1 Effective swath width and uniformity of droplet distribution of the M-18B

3.1.1 Effective swath width of the M-18B

In this experiment, the flight centerline perpendicular to the sampling line and passed through the center (Figure 3), and apparent shift of the droplet deposition centerline with increase of wind speed were observed. The mean coverage rate of all sampling points was calculated at each flight and the values in the four tests greater than the mean were used to determine the centerline of droplet deposition. The results are shown in Table 5. Due to the influence of wind direction and speed, the centerlines of droplet deposits were different and located at 0 m, 6–9 m, 9–12 m and 12–15 m in the four tests, respectively. There was a trend to shift down with the increase of wind velocity.

Table 5 Coverage rates, CVs and mean values of the M-18B

Sample Position /m	Coverage rate (1st flight) /%	CV /%	Coverage rate (2nd flight) /%	CV /%	Coverage rate (3rd flight) /%	CV /%	Coverage rate (4th flight) /%	CV /%
-30	0.22		0		0		0	
-27	0.21		0		0		0	
-24	0.41		0		0		0	
-21	0.52		0		0		0	
-18	0.05		0		0		0	
-15	0.17		0		0		0	
-12	1.83		0.93		0		0	
-9	*9.29*	38.97	0		0		0	
-6	*3.18*	28.63	*6.69*	46.06	0.26		0	
-3	*4.57*	24.59	*3.10*	36.32	*1.25*	42.75	0	
0	***3.30***	26.92	*3.67*	38.96	*3.12*	40.18	*0.60*	53.87
3	*5.52*	11.77	*5.05*	42.28	*1.40*	42.75	*2.16*	50.38
6	*6.67*		***1.82***	33.42	*1.82*	40.76	*2.10*	52.76
9	*5.43*		***2.72***	32.16	***2.75***	41.38	*2.20*	55.03
12	1.91		*4.08*	37.27	***2.12***	46.87	***0.54***	50.84
15	2.26		*1.78*	18.94	*1.63*	51.65	***0.50***	46.37
18	3.72		*2.62*		*4.07*	50.13	*1.07*	35.46
21	3.02		*2.21*		*3.18*		*1.93*	39.78
24	3.32		1.32		*1.28*		*0.99*	
27	2.56		1.58		0.70		*1.04*	
30	1.58		1.65		0.35		0.43	
33			1.39		0.42		0.79	
36			1.51		0.33		0.30	
39			0.94		0.38		0.60	
42			0.18		0.50		1.06	
45							0.37	
48							0.20	
51							0.35	
54							0.09	
57							0.16	
Mean	2.84		1.73		1.02		0.58	

Note: The italic numbers represent the range of the effective swath width, where the boid numbers indicate the centerline of droplet deposition in the effective swath width; the 1st, 2nd, 3rd, 4th mean the sequence of four flights.

To determine the effective spray width of M-18B, this study utilized the method described by the Aerial Application Technology Research Unit, Agricultural Research Service, and Department of Agriculture of United States[17]. The detailed results are as follows.

At first, the average coverage rate for sampling points of each flight was calculated. The calculated values for the four flights were 2.84%, 1.73%, 1.02%, and 0.58%, respectively. Then the effective swath width was determined by identifying the largest range of coverage rates that were greater than the mean. These were -9–9 m, -6–21 m, -3–24 m and 0–27 m as marked as italic in the four tests (Table 5), respectively. Secondly, the CV of the coverage rates was calculated within the swath width. The results are shown in Table 5. The CV of the first flight was 38.97% located at -9 m, which means that the range varied from -9 m to 9 m; the CV of 11.77% at 3 m shows that the range changed from 3 m to 9 m. Thirdly, the range of CV was less than 20%, which is considered as an acceptable effective swath width[15]. As shown in Table 5, the sample position of effective swath width ranged from 3 m to 9 m in the first test and 15 m to 21 m in the second. Thus, the effective swath width was 6 m in the first two tests. In contrast, all the CVs for the third and fourth tests were greater than 39.78% and the effective swath width could be not determined. This was probably caused by two factors: (1) the flight height was 5 m, which was different from the height of 3 m reported in the operation standard (ASAE S386.2, 2009); (2) the wind speed gradually increased in the latter tests, which may have directly influence on the results.

In addition to the above method, we referenced the industrial standards ASAE S386.2 (2009) and MH/T 1040-2011 (2011) to determine the effective swath width of M-18B[18-19]. The standard procedure to define effective swath width is to determine the distance between the points on either side of the flight centerline where the rate of deposit equals one-half the peak height of the single-pass distribution. If the maximum deposition value occurs far from the flight centerline, it can be probably seen as deposition outliers that should be eliminated.

The effective swath widths were determined according to the above standard and the values were listed in Table 6. The first two were 30 m and 24 m, while the latter two were both 27 m. The effective swath width is therefore approximately 27 m in the four tests. Compared to the results in Table 5, the effective swath width is steadier. Table 6 displays the ranges of spraying sampling points in the four tests as -6 m to 24 m, -3 m to 21 m, -3 m to 24 m and 0 to 27 m, respectively.

The starting point is from -6 m to 0 m, and the end point is from 24 m to 27 m. This is because the deposition width of the chemical solution shifts with the wind speed, and increased gradually in four flights. Thus, in order to obtain an effective spray width in practical application, we advise to add sampling points in light of wind direction changes.

Table 6 Deposition values, CVs, abnormal values and effective swath widths of M-18B

Test Num.	Interval /m	Deposition /μL	CV	Instruction	Effective swath width /m
Test 1, Upward atomizer	-9	13.675		Abnormal value 13.675; located at -9 m. Max value 7.033; located at 6 m	30 (-6-24 m)
	-6	3.412	**39.57% (-6-24 m)**		
	-3	4.174	40.84% (-3-24 m)		
	0	3.168	43.47% (0-24 m)		
	3	5.801	44.52% (3-24 m)		
	6	7.033	47.44% (6-24 m)		
	9	5.436	39.42% (9-24 m)		
	12	1.624	32.07% (12-24 m)		
	15	2.438	20.83% (15-24 m)		
	18	4.052	13.68% (18-24 m)		
	21	3.085			
	24	3.500			
Test 2, Upward atomizer	-6	8.671		Abnormal value 8.671; located at -6 m. Max value 4.407; located at 0 m	24 (-3-21 m)
	-3	3.252	**33.54% (-3-21 m)**		
	0	3.799	36.08% (0-21 m)		
	3	3.662	38.29% (3-21 m)		
	6	1.557	41.23% (6-21 m)		
	9	3.157	37.24% (9-21 m)		
	12	4.407	43.61% (12-21 m)		
	15	1.531	28.97% (15-21 m)		
	18	2.805			
	21	2.352			
Test 3, Downward atomizer	-3	1.394	**47.95% (-3-24 m)**	Abnormal value 4.828; located at 18 m. Max value 3.331; located at 0 m.	27 (-3-24 m)
	0	3.331	46.20% (0-24 m)		
	3	1.437	49.68% (3-24 m)		
	6	1.964	47.86% (6-24 m)		
	9	2.771	49.27% (9-24 m)		
	12	2.103	55.49% (12-24 m)		
	15	1.752	59.66% (15-24 m)		
	18	4.828	59.26% (18-24 m)		
	21	3.372			
	24	1.157			
Test 4, Downward atomizer	0	0.842	**59.04% (0-27 m)**	Max value 2.624; located at 6 m	27 (0-27 m)
	3	2.479	58.16% (3-27 m)		
	6	2.624	61.10% (6-27 m)		
	9	2.476	59.68% (9-27 m)		
	12	0.644	45.48% (12-27 m)		
	15	0.513	44.75% (15-27 m)		
	18	0.929	36.18% (18-27 m)		
	21	1.757	39.26% (21-27 m)		
	24	0.907			
	27	0.965			

Note: 0 m was the fixed flight line; bold marks indicate the CVs of deposition values in the effective swath width.

Moreover, the CV of the four tests, 39.57%, 33.54%, 47.95% and 59.04%, gradually enhanced along with the increased wind speed; the direction of atomizer included upward and downward setups; however, there was still a stable effective swath width of about 27 m for the M-18B, suggesting that the standards ASAE S386.2 (2009) and MH/T 1040-2011 (2011) can be considered as an important reference in determining the effective swath width.

3.1.2 Uniformity of droplet distribution of the M-18B

Uniformity of droplet distribution is an important factor in evaluating the effect of spray from agricultural airplane. In this study, we referred to the standards ASAE S386.2 (2009) and MH/T 1040-2011 (2011) to analyze the uniformity of droplet distribution of M-18B. The standard reflects droplet distribution of a unidirectional application in which there is some overlap in the area of application. The M-18B flew four passes in this experiment and the results were listed in Table 6, including the droplet deposition rate, CV, and abnormal values that could be used to evaluate the uniformity of droplet distribution of the M-18B.

Table 6 shows that the four coefficients of variation of droplet deposition were 39.57%, 33.54%, 47.95% and 59.04%, and they increased with the increase of wind speed. Thus, the uniformity of droplet distribution is obviously influenced by the wind speed. Research have been reported and illustrated how the CV of droplet distribution is used as an indicator in evaluating the spray uniformity of aerial application[7-8]. The smaller the coefficient of variation, the better uniform is the droplet distribution, and the better is the spray quality. Through analyzing four flights, it was found that the uniformity of droplet distribution in the first test was good with the coverage, range from 15 m to 24 m (9 m) and the CV less than 20.83%; in the second flight, the range of good uniformity of droplet distribution was from 15 m to 21 m (6 m) with the CV less than 28.97%; in the third and fourth tests, the CV exceeded 46.20% and 36.18%, respectively, and the highest CV was 61.10% in the last flight.

It was also found in this study that an upward atomizer presented a greater probability of abnormal values than a downward atomizer. The first two values of droplet deposits, 13.675 μL and 8.67l μL, were greater than those for the latter two, 4.828 μL and 0 μL. Meanwhile, the largest droplet deposits in the four flights were 7.033, 4.407, 3.331 and 2.479 μL, respectively. There was also consistent trend where the values with upward atomizer were higher than those with the downward atomizer, demonstrating that the direction of the atomizer impacts the uniformity of droplet distribution. This result agrees with being reported in other research[20-21].

3.2 Effective swath width and uniformity of droplet distribution of Thrush 510G

3.2.1 Effective swath width of Thrush 510G

The coverage rates, CV and average values of Thrush 510G in four flights are shown in Table 7.

Table 7 Coverage rates, CVs and mean values of the Thrush 510G

Sample position /m	Coverage rate (1st flight) /%	CV /%	Coverage rate (2nd flight) /%	CV /%	Coverage rate (3rd flight) /%	CV /%	Coverage rate (4th flight) /%	CV /%
-30	0		0		0.02		0	
-27	0		0		0.60		0	
-24	0		0		*1.11*	24.15	0	
-21	0		0		*2.30*	19.62	0	
-18	0		0		*1.56*	19.70	0	
-15	0		0		*1.28*	19.72	0.01	
-12	0.01		0		***1.74***	12.21	0.46	
-9	0.03		0		*2.09*	10.62	*3.72*	49.42
-6	*6.87*	69.30	0		*2.36*	13.03	*2.51*	54.19
-3	*1.47*	80.34	*7.30*	39.34	*2.05*		*4.24*	57.83
0	***9.63***	71.91	*7.53*	41.73	*1.82*		***4.73***	65.75
3	***3.07***	11.48	*3.03*	43.11	0.59		***4.32***	71.21
6	*2.60*		***6.45***	41.04	0.31		*1.05*	45.89
9	*3.26*		***8.02***	47.25	3.04		*2.20*	
12	0.97		*3.10*	14.81	0.30		*1.07*	
15	1.23		*3.63*		0.15		0.12	
18	0.47		*4.18*		0.06		0.12	
21	0.51		1.56		0.13		0.02	
24	1.44		1.43		0.06		0.03	
27	0.90		1.11		0.10		0	
30	0.60		0.25		0.03		0.01	
33			0.13		0.03		0	
36			0.10		0		0	
39			0.09		0		0	
Mean	1.57		2.00		0.91		1.03	

Note: The italic numbers represent the range of the effective swath width, where the bold numbers indicate the centerline of droplet deposition in the effective swath width.

Although Thrush 510G flew at a lower height (4 m), changes in wind direction and speed were much larger than those that occurred during the flights of M-18B. Therefore, the centerlines of droplet deposition were very much different from those with M-18B. The first centerline located at 0–3 m, the second was 6–9 m, the third was at -12 m and the forth was 0–3 m.

For Thrush 510G, the calculation of effective swath width was the same for M-18B. As shown in Table 7, the mean coverage rates in the four tests were 1.57%, 2.00%, 0.91% and 1.03%. The coverage values at sampling points greater than the mean were marked in red. The CV of the coverage rates in the swath width were calculated sequentially and were listed in Table 6. The CV of 69.30% located at -6 m indicates the range changed from -6 m to 9 m, and the CV of 11.48% at 3 m reflects the range changed from 3 m to 9 m. Finally, the ranges with CV less than 20% were found[7], which were considered as acceptable effective swath widths. In Table 7, the effective swath width with the lowest CV was in the range from 3 m to 9 m in the first test, 12 to 18 m in the second test, -21 m to 0 m in the third test, and the CV of the fourth was higher than 45.89%. The effective swath widths were 6 m, 6 m, 21 m and 0 m in the four flights. Compared with the results obtained with M-18B flying at a 5 m height, the 4 m flight height of the 510G produced better results. Furthermore, we also referred the standards ASAE S386.2 (2009) and MH/T 1040 (2011) to calculate the effective swath width.

By analyzing the data in Table 8, the effective swath widths of Thrush 510G in the four tests were calculated to be 15 m, 15 m, 18 m and 15 m. Compared with those got from M-18B in Table 7, a stable effective swath width of about 15 m was determined. The spray ranges of sampling points in the four flights were -6 m to 9 m, 3 m to 18 m, -18 m to 0 m and -6 m to 9 m. The starting points changed from -6 m to 3 m, and -18 m to 0 m, and the ending points varied from 9 m to 18 m to 0 m to 27 m. The factors of wind speed and wind direction led to the changes. Thus, similar to the advice for M-18B for spray in flight, sampling points should be added at starting side or end side based on changes in wind direction and wind velocity. Moreover, it was found that the CVs of the four tests, with values of 79.12%, 46.19%, 14.90% and 48.69%, which there was not obvious regularity and the direction of the atomizer (upward and downward) influenced the spray performance to some extent. Even so, Thrush 510G still had a stable effective swath width of about 15 m, which certified the standards ASAE S386.2 (2009) and MH/T 1040-2011 (2011) are better for determining the effective swath width for the system on Thrush 510G.

Table 8 Deposition values, CVs, abnormal values, effective swath widths of Thrush 510G

Test Number.	Distance /m	Deposition /μL	CV	Instruction	Effective swath width /m
Test 1 Down, atomizer	-6	7.228	**79.12% (-6-9 m)**	Abnormal value 1.378; located at -3 m. Max value 11.419; located at 0 m.	15 (-6 m to 9 m)
	-3	1.378	93.46% (-3-9 m)		
	0	11.419	84.21% (0-9 m)		
	3	3.191	16.06% (3-9 m)		
	6	2.392			
	9	3.226			
Test 2 Down, atomizer	3	3.048	**46.19% (3-18 m)**	Max value 8.895; located at 9 m	15 (3 m to 18 m)
	6	7.570	42.78% (6-18 m)		
	9	8.895	48.40% (9-18 m)		
	12	3.452	11.29% (12-18 m)		
	15	4.035			
	18	4.325			
Test 3 Up, atomizer	-18	1.632	**14.90% (-18-0 m)**	Max value 2.237; located at -6 m.	18 (-18 m to 0 m)
	-15	1.516	15.82% (-15-0 m)		
	-12	1.909	15.43% (-12-0 m)		
	-9	1.810	17.74% (-9-0 m)		
	-6	2.237	21.78% (-6-0 m)		
	-3	1.509			
	0	1.630			
Test 4 Up, atomizer	-6	2.222	**48.69% (-6-9 m)**	Max value 4.446, located at 3 m.	15 (-6 m to 9 m)
	-3	3.960	50.20% (-3-9 m)		
	0	4.222	59.25% (0-9 m)		
	3	4.446	73.38% (3-9 m)		
	6	0.949			
	9	1.961			

Note: 0 m was the fixed flight line; bold numbers indicate the CV of deposition values in the effective swath width.

3.2.2 Uniformity of droplet distribution of Thrush 510G

The test procedure for Thrush 510G was the same with for M-18B, but the flight height was 4 m and the flying path was adjusted three times because of the unstable wind direction and a gradually increase wind speed. Thus, compared with the spray uniformity of droplet distribution of M-18B, the results manifested more changes. Table 8 lists Thrush 510G's deposition values, CVs, abnormal values, and effective swath widths.

As shown in Table 8, the four CVs of droplet deposition were 79.12%, 46.19%, 14.90% and 48.69% with an irregular trend being caused by instantaneous wind direction. Moreover, the uniformity of droplet distribution in the first flight was good in the range from 3 m to 9 m (6 m) and the CV was less than 16.06%; the good range in the second was from 12 m to 18 m (6 m) and the CV was less than 11.29%; the third, the good range was from -18 to 6 m (24 m) and the CV was under 21.78%; the fourth, all the CVs were all higher than 48.69% with the highest being 73.38%. These differences were caused by the increase of wind speed, which changed from 1.1 m/s to 3.4 m/s. In addition, through contrasting the differences between Table 6 and 8, it was found that that Thrush 510G has a lower probability of abnormal values than the M-18B, and its uniformities of droplet deposition were better than those of the M-18B. The lower flight height (4 m) might contribute to these improvements.

4 Discussion

This study evaluated the effective swath width and uniformity of droplet distribution of two agricultural airplanes, M-18B and Thrush 510G, which flew at 5 m and 4 m height, respectively. Although weather conditions, such as wind speed, wind direction and moment wind as well as configuration of atomizer orientation, all impacted the spray swath width, the results of the swath width showed that it remained stable. Therefore, it can be concluded that flight height leads to the difference in swath width for M-18B Thrush 510G. To ensure effective operation in practical spray, the applicator should pay more attention to different airplanes along with their respective flight heights. In addition, the wind velocity and wind direction generated differences for the uniformity of droplet distribution of the spray systems on both airplanes. However, others factors such as air humidity, air temperature flight speed, flight pattern, sampling arrangement, and methods of data processing[22-23], all easily impact the experimental results, but in this study we had not studied them. Therefore, future studies should be implemented by special application goal.

5 Conclusions

In this research, the effective swath width and uniformity of droplet distribution of two agricultural airplanes, M-18B and Thrush 510G, were evaluated when flying at 5 m and 4 m height under headwind conditions. The results illustrated that although the wind speed changed from 0.9 m/s to 4.6 m/s and the direction of the atomizer switched upward and downward in the eight tests, the effective swath widths were about 27 m and 15 m for M-18B and Thrush 510G, respectively, and the latter one was more stable. Moreover, the CVs of the M-18B with 39.57%, 33.54%, 47.95% and 59.04% had a tendency to gradually increase with the increase of wind velocity; the CVs of the Thrush 510G were 79.12%, 46.19%, 14.90% and 48.69%, respectively, with no consistent regularity owing to combined effect of changes in wind direction and wind speed. In addition, in analysis of CVs and uniformities of droplet distribution for M-18B and Thrush 510G in the spray width with smaller CV (20%–45%) as assessing standard, the uniformity of droplet distribution for M-18B was only twice as good (6 m and 9 m) as Thrush 510G had better results in the four flights, they were 6 m, 6 m, 18 m and 0 m, respectively.

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