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Comparison of Droplet Size, Coverage, and Drift Potential from UAV Application Methods and Ground Application Methods on Row Crops

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Abstract

Worldwide, the use of uncrewed aerial vehicles (UAVs) for pesticide application has grown tremendously in the past decade. Their adoption has been slower for Midwestern row crops. This study compared droplet size, coverage, and drift potential of sprays from UAV application methods to those from ground (implement) sprayer methods on corn in the Midwest. Droplet sizes measured during UAV spray trials [geometric mean diameters of 179 and 112 μm for UAV (boom) and UAV (no boom), respectively] were substantially smaller than those deposited during implement spray trials [mean diameters of 303 and 423 μm for implement (regular) and implement (pulse)]. Droplet coverage was high and localized in the middle swath of the field for the UAV with boom (10 to 30 droplets cm^{-2}) and with no boom (60 droplets cm^{-2}). Droplet coverage was broader, covering the entire field width for the implement methods (10 to 40 droplets cm^{-2}). Vertical coverage of droplets was more uniform for UAV methods than implement methods. Although the UAVs produced smaller droplets than the implement methods, we still observed greater potential for downwind pesticide drift during the implement spray trials. Because localized application may be beneficial for pest control and drift reduction, the findings indicate a strong potential for "spot" or "band" spray coverage using UAV methods. This is likely due to the smaller size, reduced spray volumes, and increased agility of UAVs as compared to more conventional methods.

Keywords

Agriculture; Application; Corn; Coverage; Drift; Droplet; Implement; Particles; Pesticides; Pesticide drift; Precision agriculture; Row crops; Spray trial; Uncrewed aerial vehicle (UAV); Unmanned aerial vehicle (UAV)

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Pesticide application is crucial to improve crop yields across the globe. However, precision application is important because inappropriate pesticide use may have adverse effects on the environment and humans (Aktar et al., 2009). In the Midwestern U.S., com and soybeans are the two row crops that receive the highest amounts of pesticide application (Femandez-Comejo et al., 2014). The most common forms of pesticide application include ground application (via implement or attachment sprayers) and aerial application (via manned agricultural aircraft). Typically, these conventional methods target a uniform coverage over the entire field. Herbicides, such as glyphosate, atrazine, 2,4-D, and acetochlor, are the most common pesticides used on corn and soybeans throughout the growing season. Insecticides and fungicides are used in lesser quantities and are typically applied in the late spring and summer (Femandez-Comejo et al., 2014).

In the last decade, the use of uncrewed aerial vehicles (UAVs) for pesticide application in agriculture has grown tremendously, particularly for hilly terrain and to replace backpack sprayers (Li et al., 2019; Wang et al., 2019). Although UAV application technology has developed rapidly for use on crops such as wheat and rice, it has been slower to adopt on common row crops, such as com and soybean. Agriculture experts expect UAV methods to increase because they can be used in combination with crop monitoring and wireless sensor networks to achieve high-precision application (Mogili and Deepak, 2018). This includes potential for using pesticides only on high-risk areas (e.g., “band” or “spot” spraying). The working efficiency of UAVs could result in more acres covered with less volume of pesticide (Faiçal et al., 2014, 2017). Producers are interested in this aspect due to potential reductions in production costs. UAV application may also reduce worker exposure to pesticides (Mogili and Deepak, 2018).

Many factors influence the coverage, droplet size, and drift potential of pesticides applied by UAVs. UAVs are more commonly equipped with electrostatic-induction nozzles as compared to other spray methods because their tank volumes are smaller. Electrostatic-induction nozzles are used to charge droplets and increase adherence to foliage. The use of electrostatic spray has been found to improve spray “evenness”, uniformity of droplet size, and coverage under foliage (sometimes referred to as the “wrap around” effect), as compared to more conventional methods (Law, 1983; Zhao et al., 2008; Ru et al., 2014, 2015; He et al., 2016; Wang et al., 2016). Therefore, low spray volumes are not synonymous with lower spray quality because coverage is evenly spread across the foliar surface.

There is a concern about pesticide drift when using UAVs. Spray drift is defined as the off-target movement of droplets during or shortly after pesticide application (USEPA, 2019; Miller, 2014). UAV droplets are smaller (270 to 350 μm mean diameter) than ground spray devices (300 to 1000 (μm mean diameter) (Ling et al., 2018; Yallappa et al., 2017). Smaller droplets (particularly those smaller than 200 μm diameter) are associated with a highest risk of drift (Klein et al., 2008). In addition to droplet size, meteorological conditions (e.g., increased wind speeds, high temperatures, changes in humidity) are also important factors that influence drift potential (Hanna and Schaefer, 2008; Klein et al., 2008; Miller, 2014; ISU, 2014, USEPA, 2019). Pesticide labels specify acceptable wind speeds, temperature, and buffer distances for proper ground or agricultural aircraft application, including both manned and unmanned applications. Many of these labels are not specific to UAVs because they are a recent innovation.

The purpose of this study was to compare droplet characteristics, spatial variability, and drift potential of UAV application methods to conventional ground application methods (via an implement sprayer). The study focused on com because it is one of the most common row crops grown in the Midwestern U.S. The "evenness" of vertical pesticide coverage on com is especially important because com can grow to heights above 4 m. We compared data on droplet sizes, droplets per surface area (called "coverage"), and spatial spray distribution for both application methods. We believe that such comparison studies will be essential in the future because the average size of the U.S. farm is expected to increase substantially in the next few decades (MacDonald et al., 2013). As farms grow larger, so will their dependence on precision agriculture and broader application technologies provided by outside labor forces, including UAV application.

Methods

Study Location and Meteorological Data

The field study took place on a large, private row crop farm in Cedar County, Iowa. The farm rotates soybean and com crops annually, which is a typical production practice in the upper Midwestern region of the U.S. Samplers were set up in a field of com measuring 120 m wide by 70 m long (0.84 ha). A smaller subsection of the field, measuring 25 m wide by 50 m long (0.13 ha), was used for the study trials (fig. 1). The com was planted ~0.65 m apart. The study took place in the late summer (September 2019) before harvest season. At that time, the com was 1.93 to 2.24 m tall and had husks. The study area was bordered by a grass buffer zone on the north side and a fence line near an alternate soybean field on the east side. The south and west sides were bordered by com. There were no potential impedances located nearby. For example, the nearest out-building was 80 m from the study site, and the nearest tree was 88 m away. The nearest road, a paved county highway, was 149 m to the north.

An on-site meteorological station (6250 Vantage Vue, Davis Instruments, Hayward, Cal.) was used to record the temperature, wind direction, and wind speed (15 min average) at the beginning of each spray trial to ensure that the wind direction was consistently from the north. The station was mounted on a mast at a height of 2 m, located 10 m north of the perimeter of the sprayed field. This on-site station did not record real-time data. Therefore, a second meteorological station, identified 30 km southwest of the study location, was used for real-time (20 min logging intervals) data on wind speed, wind direction, temperature, and relative humidity during the trials. The data from the second station were downloaded from the Iowa Environmental Mesonet ASOS website, which compiles data from airport weather monitoring networks used by the National Weather Service (ISU, 2019). Weather conditions were relatively consistent during the 4 h period when the spray trails were conducted, and the data from the two meteorological stations were consistent. The prevailing wind was from the north, and wind speeds ranged from 2.6 to 3.9 m s^{-1}. The temperature ranged from 20°C to 21°C, and the relative humidity was 90% to 95%. According to most pesticide application guidelines, these conditions are acceptable for application (Hanna and Schaefer, 2008).

Sampling Methods

Water-sensitive spray cards (20301–2N, TeeJet Technologies, Springfield, I11) were used as spray deposition samplers to evaluate droplet size and spray coverage. Previous studies have relied on similar methods, including glass plates, filter papers, polythene/polyester lines, and the water-sensitive cards used in this study (Wang et al., 2017; Bueno et al., 2017; Kasner et al., 2018). Because coverage varies with crop height, other researchers have recommended vertical sampling (Xinyu et al., 2014; Wang et al., 2019; Kasner et al., 2018). Therefore, the cards, with the water-sensitive side facing up, were clipped onto 2 m sampling masts at three heights (0.61, 1.22, and 1.83 m). During each UAV application trial, 15 masts were set up within the rows of the sprayed field, each 3.05 m apart on both the N/S and E/W axes. During each implement application trial, ten masts were set up within the rows of the sprayed field, each 3 m apart on the N/S axis and approximately 4 m apart on the E/W axis (fig. 1). All masts had cards at the three heights to replicate com foliage. Fewer masts were used in the implement trials to accommodate the width of the implement sprayer as it drove through the field.

Following Blanco et al. (2019), real-time particle monitors (DC1100, Dylos Corp., Riverside, Cal.) were used to evaluate droplet drift. All Dylos monitors were calibrated by the manufacturer immediately prior to use. The Dylos monitors were mounted on tripod sampling masts at a height of 2 m (upper canopy level) at two locations (3 and 10 m) downwind (south) of the sprayed field. The monitors were situated with their inlets facing toward the sprayed field (fig. 2). The monitors recorded 1 min average particle number concentrations of two size measurements (“small” or particles nominally smaller than 2.5 μm, and “large” or particles larger than 2.5 μm). Each monitor operated throughout the experiment. Background air concentrations were obtained prior to the spray trials, so each monitor served as its own control. An additional Dylos monitor was used to collect information on particle background levels. This background Dylos was situated 4 m upwind (north). Water-sensitive cards were also deployed on the Dylos sampling masts to ensure that the spray trials occurred within the specified area.

Spray Trials and Equipment

Four trials were conducted to compare UAV application to the ground application methods. The four trials included: UAV without boom, UAV with boom, implement (boom) without pulse technology, and implement (boom) with pulse technology. Pulse technology works by rapid pulsing (starting and stopping) of the spray at the nozzle. This is done to maintain a more consistent droplet size during application (Butts, 2018; Mangus et al., 2017). The implement operator and UAV operator were instructed to spray the shaded area (shown in fig. 1) and to replicate true application. During each spray trial, the pesticide applicator made a single pass with the implement sprayer. The UAV made two or three passes to cover the same area. The application equipment specifications and wind speeds for each trial are reported in table 1. Data on temperature, relative humidity, and wind direction are not reported in table 1 because those variables were consistent. Equipment specifications and weather data were identified using the USEPA protocol for testing pesticide application spray drift technologies on row crops (USEPA, 2016).

Although the individual spray trials were short (the UAV applications lasted approximately 1 min, and the implement applications were 30 s), the trials occurred 45 to 60 min apart. This allowed time to collect the water-sensitive cards and deploy new cards between trials. It also allowed time for any potential droplets from the previous application to settle.

Data Analysis

Each water-sensitive card was scanned to an image file (1716 × 1176 pixels) using a scanner (10000XL, Epson, Long Beach, Cal.). ImageJ (ver. 1.52p, National Institutes of Health, Bethesda, Md.) was used to determine the surface area of each location on the card that had changed color due to contact with droplets. For each droplet, the spot diameter (D_s) for each particle was estimated assuming spherical droplets. Following Salyani et al. (2013), the droplet diameter (D_d) was then calculated as $D_d = 0.95 D_s^{0.91}$. For each card, the geometric mean diameter, geometric standard deviation, and number of droplets per surface area were calculated. Normality tests (Shapiro-Wilk method, quantile-quantile plots) were performed on the mean diameter and number of droplets per surface area. Because the data for both UAV trials and the implement (regular) trial were not normally distributed, comparisons of mean diameter and number of droplets per surface area and sampling height were examined using non-parametric methods (Kruskal-Wallace test). Because the data for the implement (pulse) trial were normally distributed, comparisons of diameter and number of droplets per surface area by sampling height were examined using one-way analysis of variance (ANOVA). Statistical tests were performed using RStudio (ver. 1.3, RStudio, Boston, Mass.). The size distribution was plotted for the highest number droplets per surface area measured at the high foliage height for each trial.

Results

Droplet Characteristics

In table 2, the coverage and geometric mean droplet sizes are summarized by application type and foliage height. Overall, the UAV (no boom), implement (regular), and implement (pulse) spray trials had mean coverages of 16.6, 16.7, and 14.8 droplets cm^{-2}, respectively. The UAV (boom) had a lower overall mean coverage of 3.8 droplets cm^{-2}. Both UAV trials reported substantially higher coefficients of variation for particle count by surface area [1.39 for UAV (boom) and 2.30 for UAV (no boom)] than the implement trials [0.49 for implement (regular) and 0.53 for implement (pulse)]. No statistically significant differences in particle count by surface area at the low, medium, or high foliage heights were observed for UAV (boom) or UAV (no boom). In comparison, the implement (regular) trial showed greater coverage at the high foliage height (1.83 m) ($p = 0.00117$). The implement (pulse) trial showed better coverage at both the medium (1.22 m) and high foliage heights (1.83 m) ($p = 0.0003$). This effect is also shown in the decrease in coverage between the high and low foliage heights for UAV (boom) with a 27% decrease and UAV (no boom) with a 25% decrease, as compared to implement (regular) with a 54% decrease and implement (pulse) with a 61% decrease.

As expected, the geometric mean droplet sizes observed during the UAV trials (boom 179 μm; no boom 112 μm) were smaller than those observed during the implement trials (regular

303 µm; pulse 423 µm). No clear trends were observed for droplet size with foliage height for both UAV trials or the implement (pulse) trial. There was a slight trend of smaller droplet sizes at the low height (0.61 m, $p = 0.04$) for the implement (regular) trial. The overall coefficient of variation in droplet size was substantially higher for the UAV trials (boom 0.58; no boom 0.61) than for both implement trials (0.18). The size distributions of droplets for each trial are shown in figure 3. The size distribution was substantially narrower and smaller for the UAV (no boom) trial than for the other trials.

Spatial Distribution

The spatial distribution of coverage (droplets cm^{-2}) by foliage height is shown in figure 4. All spray trials showed lower coverage at lower foliage heights. Both UAV trials had high coverage in the middle swath of the field, while both implement trials had more even coverage across the entire width of the field. In particular, the UAV (no boom) trial had the highest coverage in the middle swath of the field (>60 droplets cm^{-2}). This is explained by the relatively narrow swath that was covered by the UAV (no boom). In comparison to the implement sprayer, which made a single pass through the field, the UAV sprayers made two or three passes to cover the same area. Because the UAV sprayer and boom sprayer were much smaller in length than the implement sprayer boom, figure 4 shows that the UAVs, particularly UAV (no boom), may not have fully approached the field perimeter.

Drift Potential

Airborne particle concentrations before and during each spray trial (as recorded by the Dylos monitors) are shown in figure 5. During most spray trials, increases in both small and large particle concentrations were observed at 3 and 10 m downwind from the sprayed field. Prior to the spray trials, background concentrations were 270 to 371 m^{-3} for small particles and 30 to 38 m^{-3} for larger particles. During the trials, concentrations were 302 to 509 m^{-3} for small particles and 27 to 140 m^{-3} for larger particles.

Figure 5a shows that near the field perimeter (3 m), the percentage increase in small particle concentrations over background was 3% for both UAV trials, 0% for implement (regular), and 49% for implement (pulse). Figure 5b shows that the percentage increase in large particle concentrations over background was 29% for UAV (boom), 0% for UAV (no boom), 0% for implement (regular), and 188% for implement (pulse).

Slightly farther from the field perimeter (10 m), lower levels of potential drift were observed during both UAV spray trials. Figure 5c shows that at 10 m, the percentage increase in small particle concentrations over background was 0% for both UAV trials, 73% for implement (regular), and 88% for implement (pulse). Figure 5d shows that the percentage increase in large particle concentrations over background was 14% for UAV (boom), 3% for UAV (no boom), 240% for implement (regular) and 324% for implement (pulse).

Discussion

Overall, these findings support the potential of UAV methods for use in “spot” or “band” spray applications. Coverage was high and uniform vertically in the middle swath of the field for both UAV trials, particularly UAV (no boom). Although overall coverage was lower for the UAV trials than for the implement trials (table 2), this was likely due to the localized spatial coverage shown in figure 4. In particular, for the UAV (no boom) trial, the coverage was remarkably high in the southern, middle portion of the field, with >60 droplets cm^{-2}. This may have been due to the UAV's approach from the southern direction. Nevertheless, these results in the middle swath of the field are consistent with simulated lab experiments, where researchers have shown than correct use of UAVs should result in more droplets per surface area (Ru et al., 2014; He et al., 2016; Yanliang et al., 2017).

In comparison, the implement showed broader coverage of 10 to 40 droplets cm^{-2} across the entire surface of the field. Similar findings have been observed in other implement field studies, which included pulse methods (Womac et al., 2017; Butts, 2018; Butts et al., 2019). During the implement trials, fewer masts were used in the middle swath of the field to accommodate the sprayer width, so it was difficult to determine a more precise spray pattern. However, the even spatial coverage in figure 4 shows that an implement sprayer may be more appropriate for broad pesticide application. This may also be due to the large differences in boom length between the implement sprayer (33.5 m) and the UAV sprayers (4 to 5.5 m), which may not have fully approached the field perimeter.

Vertical coverage was substantially more uniform with the UAV methods than with the implement methods (table 2). The percent coverage decrease at low foliage heights were moderate in this study. For example, the UAV methods reported a 25% to 27% decrease in coverage between the high and low foliage heights. In the middle swath of the field (fig. 3), more than 60 droplets cm^{-2} were deposited at the low foliage height in the UAV (no boom) trial. Other researchers have reported that UAV spray coverage is better at higher foliage heights than middle and low foliage heights (Xinyu et al., 2014; Wang et al., 2019). In comparison, both implement methods showed a 54% to 61% decrease in coverage between the high and low foliage heights. This difference is important because agriculture experts continue to highlight the optimization of equal coverage on vertical crop tissues. For example, damage to lower foliage in row crops can have a substantial impact on yield and quality (Gossen et al., 2008).

As expected, geometric mean droplet sizes were much smaller in the UAV trials than in the implement trials. Overall geometric mean diameters were 179 μm for UAV (boom) and 112 μm for UAV (no boom). These sizes are slightly smaller than previously reported droplet sizes (200 to 300 μm measured diameter) (Ling et al., 2018; Yallappa et al., 2017). The implement droplet sizes were much larger than the UAV droplets in this study, which supports the results of other studies. The largest geometric mean diameters occurred in the implement (pulse) trial (Butts, 2018; Butts et al., 2018, 2019). Increases in droplet size are not associated with increased pest control because a large range of droplet sizes may be necessary, depending on the type of chemical used. In fact, previous research has demonstrated increased weed and pest control as droplet sizes decreased to 100 μm (Ennis and Williamson, 1963; Lake, 1977; Wolf, 2002).

Drift potential was observed in the implement (regular) trial but not in the implement (pulse) or UAV trials (fig. 5). In most comparisons, the particle concentrations downwind (3 and 10 m) were higher in the implement trials than in the UAV trials. This was not surprising, given the differences in boom width (4.14 m for the UAV with boom and 33.5 m for the implement), and the UAV's focused coverage on the middle swath of the field. However, the difference in drift potential was unexpected, as smaller droplets tend to be associated with highest risk of drift. A limitation of the study is that the real-time monitors were placed at a single height (2 m). Ideally, there would have been several real-time monitors at varying heights. Therefore, it is unknown if the UAV plume consisted of smaller droplets that were distributed at higher elevations.

Although the UAVs did not completely approach the field perimeter, their smaller size and increased agility demonstrated their advantage for precise application, as compared to larger implements with more nozzles and extended boom lengths. More research is needed to determine if the UAV spray path can be altered in certain situations to prevent potential spray drift when relying on droplet sizes of 100 to 200 μm. The percentage increases in particle concentrations during both UAV spray trials are similar to what has been reported in other UAV studies, although those studies were also conducted in low wind speed conditions (Wang et al., 2017; Xinyu et al., 2014). Wang et al. (2017) examined drift characteristics of a single-rotor UAV and similarly recommended a 15 to 25 m buffer zone for safe spraying. Although more research is needed on appropriate wind speeds for UAV application, the current study supports the 15 to 25 m buffer zone recommendation.

There were some limitations to this study. The first limitation was that chemical tracers (i.e., fluorescent compounds or micronutrients) were not used, even though they have been used in other studies examining pesticide drift (Cai and Stark, 1997; Longley et al., 1997; Barber and Parkin, 2003; Foque et al., 2014; Kasner et al., 2018). The Dylos monitor provides real-time measurement for all particles including (but not limited to) pesticide droplets, dust (soil and foliar residue), and combustion particles. Although the downwind particle concentrations measured during the implement spray trials may have included other particle types in addition to spray droplets, these findings still demonstrate the difference in potential for dust generation when using much larger spray devices as compared to smaller, agile devices. During application, dust generation is critically important because many pesticides can quickly adhere to soil, foliage, and other residues (Gao et al., 2012).

The second limitation was that, although the real-time monitors were set for the shortest data-logging interval possible (1 min), the spray trials occurred much more quickly than expected (only 30 to 60 s). Therefore, the number of real-time measurements used to evaluate drift was limited, and variability could not be assessed. The application time noted for each trial (start/stop time) was used to sync with the appropriate Dylos measurements.

The third limitation was that the four spray trials in this study occurred on the same day when meteorological conditions were relatively consistent. This was intentional to allow comparison of different spray types in ideal conditions. The observed wind speeds during this study were moderate (<4 m s^{-1}). Other studies examining potential drift from UAVs have also occurred in low wind conditions (Wang et al., 2017; Xinyu et al., 2014). Therefore, more research is needed to identify a tolerable upper limit for wind conditions during UAV applications, especially if these methods are to be used on row crops. If wind speed conditions are critical when relying on UAV application, this may concern producers in the Midwestern U.S., where spraying within a short timeframe can be challenging. In this region, high wind speeds and wind gusts are common. For example, a 2017 study conducted by researchers at Purdue University identified only 49 hours of appropriate meteorological conditions in the month of June to apply a popular post-emergent product (dicamba) on row crops (Ickley and Johnson, 2017). Future studies should examine potential drift in a range of weather conditions experienced during a Midwestern growing season. This would include sprayer performance with higher wind speeds (4.5 to 9.0 m s^{-1}), higher temperatures (22°C to 32°C), and lower relative humidity (40% to 85%).

Conclusion

The use of UAVs for pesticide application has grown tremendously in the past decade, although their adoption has been slower on Midwestern row crops. Our study examined the droplet size, spatial coverage, and drift potential of UAV application methods compared to ground (implement) sprayer methods on com. Droplet sizes measured during the UAV trials were much smaller than those deposited during the implement trials. Compared to the implement methods, coverage was higher and more localized in the middle swath of the field for the UAV methods. Coverage was also more even between the high and low foliage heights. Greater potential for downwind drift observed during the implement trials was partially attributed to the fact that the UAVs did not fully approach the field perimeter. These findings support high spatialized coverage using UAVs under ideal weather conditions, indicating a strong potential for the use of UAV methods in “spot” or “band” spraying. This may be due to their smaller size, reduced spray volume, and increased agility compared to conventional methods. More research is needed to identify a tolerable upper limit for wind conditions during UAV applications and how the UAV spray path could be altered in such situations to prevent potential spray drift when applying such small droplets.

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Highlights

- Droplet size, coverage, and drift potential of pesticide spray in com with UAV application methods were compared with ground methods.
- Measured droplets were smaller in UAV trials (102 to 182 μm geometric mean diameter) than in ground trials (265 to 432 μm geometric mean diameter).
- UAV methods (particularly those without a boom) achieved high coverage in the middle swath of the field (>60 droplets cm^{-2}) compared to ground methods (10 to 40 droplets cm^{-2}).
- Real-time particle monitors indicated potential for downwind spray drift during ground trials but not UAV trials.
- The findings indicate a strong potential for “spot” or “band” spray coverage using UAV methods.

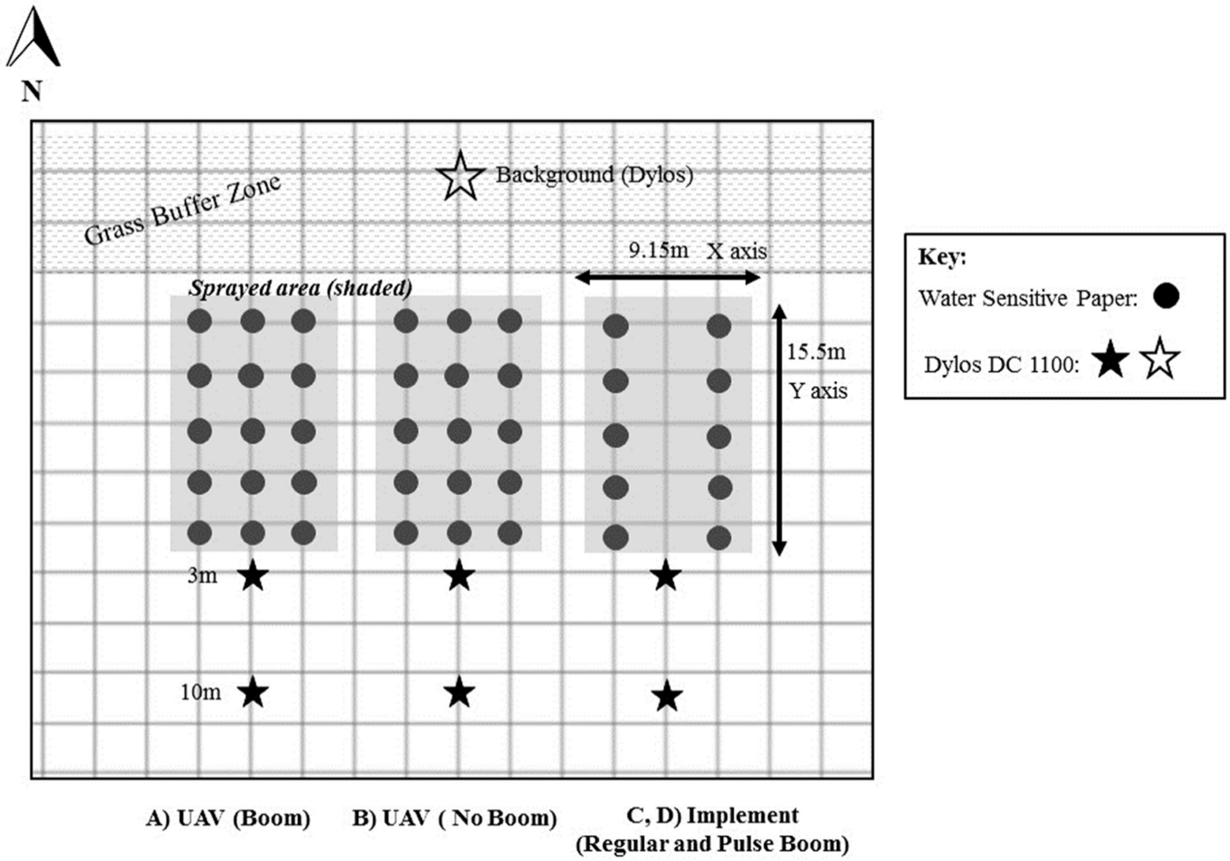

Figure 1.

Field sampling layout by application type. The sprayed areas are shaded. One trial field was used for both implement spray trials to accommodate a wider path for the implement sprayer. Each box on the grid represents ~3 m. The prevailing wind was from the north.

Figure 2.
Dylos monitor in the field. The solar panel was used as backup power to the device in case of battery failure.

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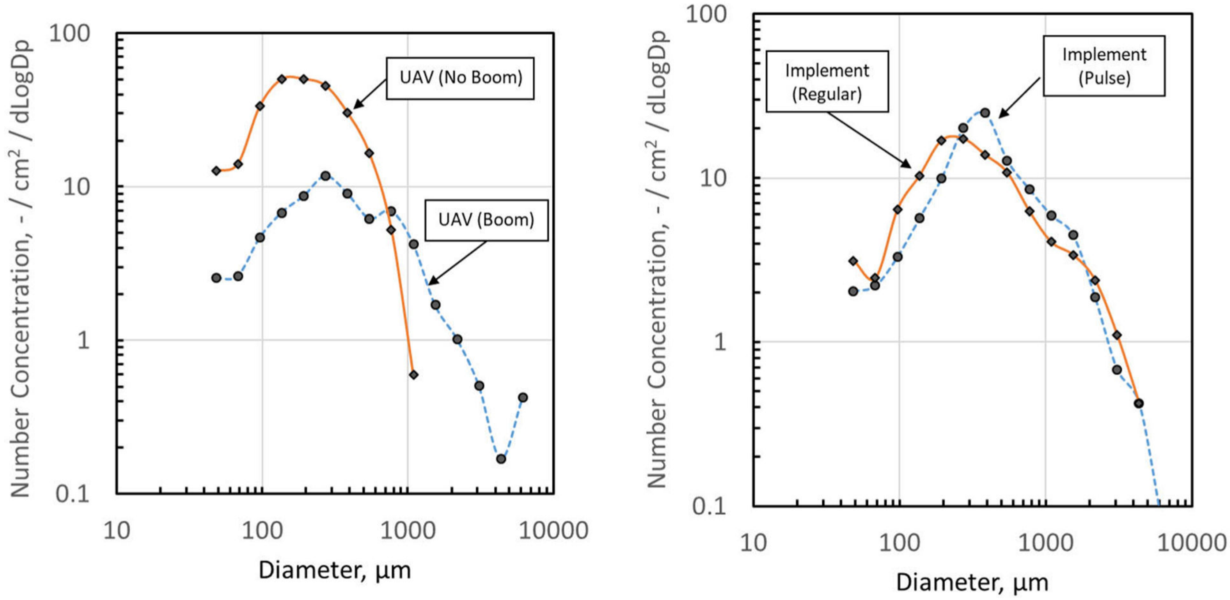


Figure 3.
Droplet size distribution by application type. The size distribution shown is for the measurement taken at the high foliage height with the highest droplet count.

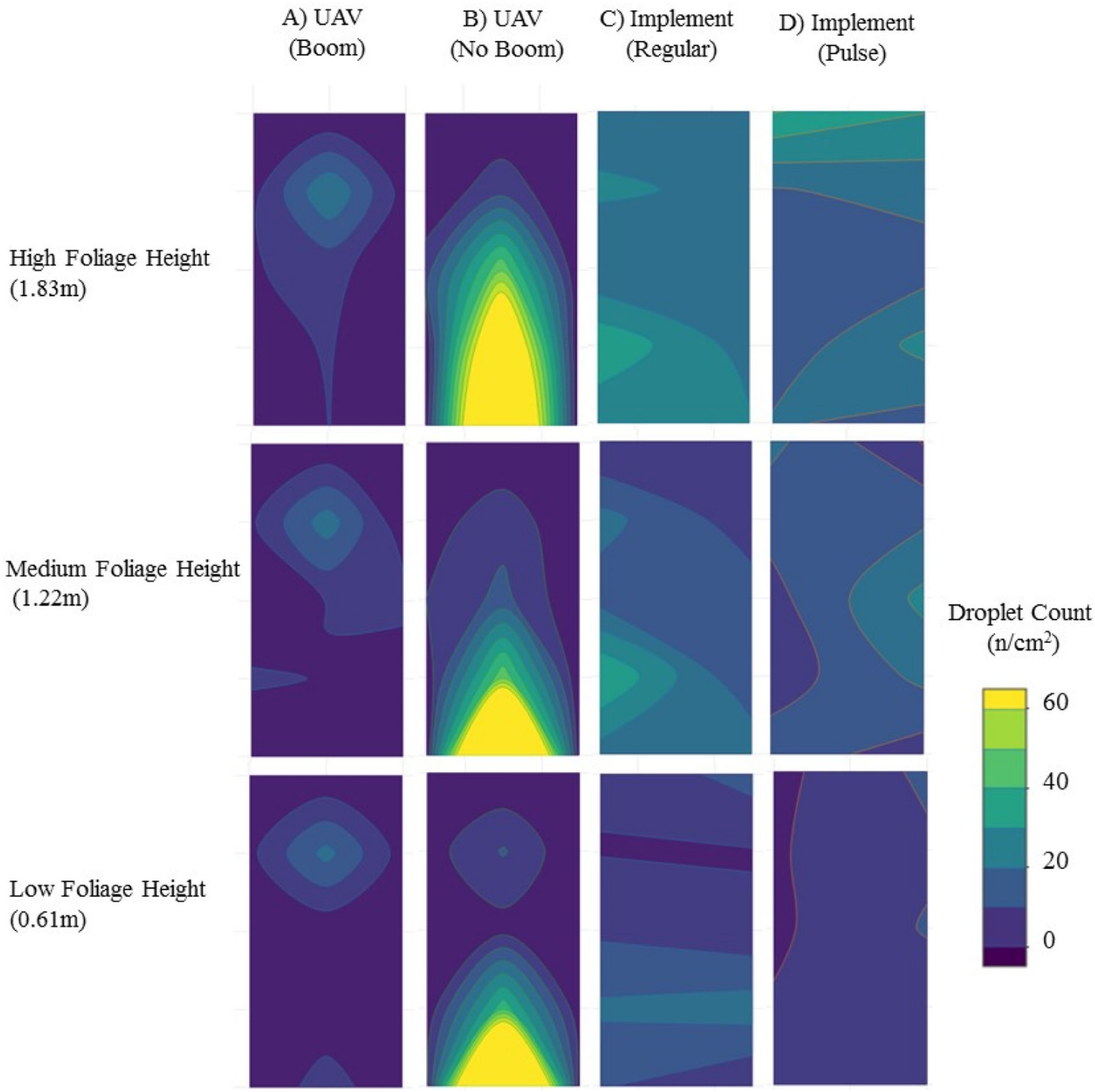
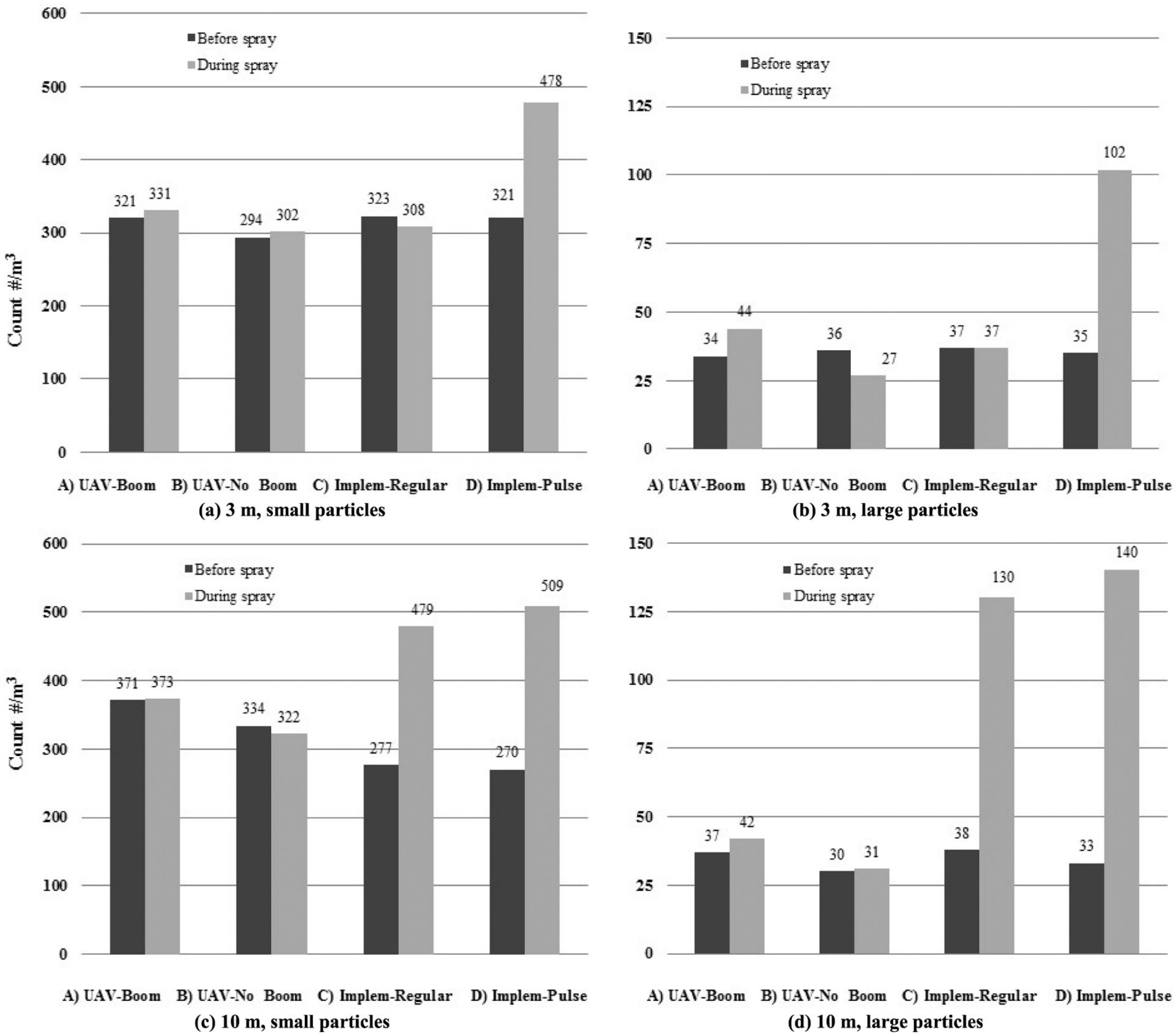


Figure 4.

Spatial distribution of coverage (droplets cm^{-2}) by spray application type and foliage height.



Figures 5.

Particulate concentrations before and during application by trial. Concentrations were measured downwind of the sprayed field.

Table 1.

Pesticide application equipment specifications and wind speed during spray trails.

Specifications	Spray Application Type			
	UAV (Boom)	**UAV (No Boom)**	**Implement (Regular)**	**Implement (Pulse)**
Year of model	2019	2019	2019	2019
Number of rotors (UAV only)	8	8	-	-
Volume in tank[a]	10 L	10 L	300 L	300 L
Number of nozzles	4	4	88	88
Nozzle type	TeeJet TT11006	TeeJet TTI11006	Flat-fan fertilizer tip	Flat-fan fertilizer tip
Nozzle angle	90°	90°	90°	90°
Nozzle height[b]	4.11 m	4.10 m	2.90 m	2.90 m
Spray pressure	30 psi	50 psi	24.5 psi	26.5 psi
Boom swath width	5.5 m	4 m	33.5 m[c]	33.5 m[c]
Forward speed	2.97 m s^{-1}	2.93 m s^{-1}	8.50 m s^{-1}	4.92 m s^{-1}
Electrostatic spray	No	No	No	No
Pulse applied	No	No	No	Yes
Wind speed[d]	3.1 m s^{-1}	2.6 m s^{-1}	3.9 m s^{-1}	2.3 m s^{-1}

[a] Tank contained water.

[b] Estimated nozzle height above foliage.

[c] Half of the boom was used to spray the full field area.

[d] Temperature and relative humidity were consistent during the spray trials (temperature ranged from 20°C to 21°C, and RH was 91% to 94%).

Table 2.

Summary of coverage (droplets cm^{-2}) and droplet sizes (μm diameter) by application type and foliage height. High, medium, and low indicate sampling height above ground level.

	Spray Application Type							
	UAV (Boom)		UAV (No Boom)		Implement (Regular)		Implement (Pulse)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Particle count (droplets cm^{-2})								
Overall	3.78	1.39	16.60	2.30	16.70	0.49	14.58	0.53
High (1.83 m)	4.29	1.35	19.78	1.93	23.04	0.20	21.39	0.34
Medium (1.22 m)	3.89	1.33	15.6	2.52	16.41	0.53	14.1	0.43
Low (0.61 m)	3.15	1.58	14.81	2.69	10.71	0.53	8.26	0.38
Geometric mean diameter (μm)								
Overall	108	0.68	63.8	0.56	172	0.17	233	0.17
High (1.83 m)	114	0.84	63.6	0.70	186	0.09	225	0.13
Medium (1.22 m)	107	0.52	70.7	0.60	178	0.13	238	0.16
Low (0.61 m)	104	0.40	71.5	0.45	152	0.23	236	0.21

CV = coefficient of variation.