Research Article

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Comparison of UAV and fixed-wing aerial application for alfalfa insect pest control: evaluating efficacy, residues, and spray quality

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Abstract

BACKGROUND: Integrating unmanned aerial vehicles (UAV) as a new method of pesticide application into existing commercial crop protection systems requires extensive research and comparison to conventional, proven application technology. Pest control expressed as efficacy against target pests, and spray quality expressed as coverage and chemical residue are three key criteria. We investigated and compared these quantitative parameters between a multi-rotor UAV and conventional piloted airplanes in two commercial alfalfa production systems.

RESULTS: Effective and equivalent control of leaf-feeding insect pests was achieved by both methods of aerial application when delivering chlorantraniliprole at the same labeled use rate in different spray volumes (46.8 and 93.5 L ha^{-1}) on commercially grown alfalfa in California. Residue levels and spray coverage were also comparable and consistent between the UAV and airplane applications across three sampling techniques, specifically residue levels on alfalfa, insecticide recovery from filter paper, and spray coverage on water sensitive cards. Differences in droplet size and deposit characteristics were more variable for the UAV than airplanes based on analysis of deposition images.

CONCLUSION: The results of this study provide confidence supporting the use of small-scale multi-rotor UAVs for pesticide application on agricultural crops. According to the parameters tested, UAV application quality and crop protection performance were comparable to that of the conventional fixed wing airplane application. However, the droplet spectrum and the short-term fate of droplets from unmanned aerial spray system require further optimization for effective and efficient crop protection with minimal risk to the environment.

Keywords: remotely piloted aerial application systems (RPAAS); unmanned aerial spraying systems (UASS); pesticide application; chlorantraniliprole; efficacy; residue; deposition; alfalfa; crop protection; manned agricultural airplane

1 INTRODUCTION

Agricultural use of unmanned aerial vehicles (UAVs) for pesticide application offers a new high-tech tool for crop protection.[1,2] Electric multi-rotor UAV sprayers featured with autonomous flight control to deliver pesticides to an array of crops is now a common substitute for traditional knapsack application in East Asia.[3–5] In the Asia-Pacific region, the UAV technology helps to mitigate intensifying labor pressure caused by an aging farm population. For example, substantial hectares of small-scale rice paddies in China are now treated by multi-rotor drones. Other crops, such as corn, sugarcane, potato, and cotton, are increasingly targeted for UAV pesticide or defoliation application as well. Unlike using UAV as a platform for acquiring remotely sensed crop data, its use for pesticide application requires updated and modified aviation and pesticide regulatory treatments. In the US, UAV spraying is being slowly integrated into commercial agriculture mainly for specialized application scenarios, such as vineyard spraying on steep terrains, insect vector control with ultra-low spray volume, spot treatment for resistant weeds, replacing manual applications, and applying disinfectants to prevent human and greenhouse plant infections.[6–9] In these cases, UAV sprayers are complementary to existing aircraft and ground-based methods of application. Increased market adoption is expected to occur as tank capacity and battery longevity improve, regulations allow beyond of sight flight, and, most importantly, growers are assured that UAV spray technology will be economical and reliable in their crop production business.

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The adoption of unmanned aerial spray systems will accelerate as crop protection companies' research, support, and promote the use of this method of application with their labeled products, both synthetic and biological-based.[10] Crop protection companies as well as spray service providers, require confidence that remotely piloted (multi-rotor and fixed wing) aerial application systems can deliver quality sprays at least comparable to existing commercial equipment without greater environmental or economic risk. This requires more intensive research on droplet size and fate, minimal spray volume, off-target droplet movement, pesticidal efficacy under varied pest pressures, and canopy penetration with key drone models. Field evaluations are required to document drone performance compared to common local spray equipment, such as fixed wing airplanes, rotary helicopters as well as various ground-based sprayers. While the traditional fixed-wing airplane can carry between 1500 to 3000 L (400 and 800 gal) of spray volume and travel across large fields at a wide speed range between approximately 40 to 80 m s^{-1} (90 to 180 mph), multi-rotor UAV sprayers normally equipped with a smaller spray tank (10–40 L) travel at a much lower speed (2–8 m s^{-1}).[10–12] Without sufficient field data and comparative studies producing a baseline reference between UAV and piloted airplane applications, it is difficult to analyze gaps and strengths of the unmanned aerial application technology.

Alfalfa caterpillar (*Colias eurytheme*), beet armyworm (*Spodoptera exigua*), and western yellow-striped armyworm (*Spodoptera praefica*) can be highly damaging to alfalfa hay, a high-quality livestock feed, especially for dairy cows. During summer months, the larvae feed on the foliage causing significant losses in forage yield and quality for several cuttings if left uncontrolled (Fig. 1(A)). Traditional manned-airplane application is currently the most common way to control these larval pests in California alfalfa. Insecticide treatments are often performed once and approximately 1 to 2 weeks prior to each harvest, depending on pest pressure. There is a significant lack of direct comparative data for these two commercially available aerial application methods: fixed-wing aircraft *versus* multi-rotor drone following best spray practices. Therefore, we chose a more holistic process to evaluate UAV application quality that went beyond biological response (insecticidal efficacy) and adopted multiple independent criteria to characterize pesticide delivery performance under commercial farming conditions. Although most multi-rotor UAV applications favor low spray volume (7.5–30 L ha^{-1}) mainly due to payload restrictions and commercial business models, applying a spray volume between 46.8 L ha^{-1} and 93.5 L ha^{-1} (5 and 10 gpa) is currently the most common commercial practice adopted to control lepidopteran larval pests in California alfalfa using manned aircraft.[12] Accordingly, two spray volumes (46.8 L ha^{-1} and 93.5 L ha^{-1}) were tested in this study for the purpose of side-by-side comparisons between the two different methods of aerial application, which were all compliant with current label recommendations.

The present work characterized efficacy, residue, and deposition features based on current spray standards for commercial fixed-wing airplanes *versus* a US Federal Aviation Administration (FAA) approved UAV sprayer when used to control alfalfa insect pests with a registered insecticide at labeled rates. The specific objectives were to (i) compare alfalfa insect control performance between a multi-rotor drone and fixed-wing aircrafts both at different spray volumes (93.5 L ha^{-1} and 46.8 L ha^{-1}) at two commercial production sites in California, USA; (ii) evaluate spray quality using different evaluation metrics: insecticide efficacy, spray coverage, droplet deposition, and pesticide residues in a side-by-side comparison using the two aerial application methods, and (iii) in a separate swath study, investigate UAV spray patterns and associated deposition uniformity. These field trials focused on leaf feeding lepidopteran larval control in alfalfa fields, however, observations and results from these studies may be applicable to predict the fit of UAV application technology for plant protection from many other pests and crops.

2 MATERIALS AND METHODS

2.1 Aerial application equipment used in field trials

Three trials were conducted during the 2020 alfalfa growing season in Yolo County, California: two insect pest control trials comparing UAV and manned aircraft application methods in commercial alfalfa fields, and one spray pattern test executed in a non-crop field using the same UAV and spray system configurations as in the efficacy trials. The two insecticidal efficacy trials were conducted late summer on the fifth and sixth alfalfa cuttings, approximately a week before harvest. Insecticide timing and rate were decided by the respective grower consulting with a licensed pest control adviser. The first application was conducted August 22 on a 32 ha (80 acres) alfalfa field (Woodland farm - field site A) (Fig. 2(B)), where 2 ha (5.1 acres) were treated by the unmanned drone model PV35™ (Leading Edge Aerial Technologies Inc.) while the remaining acres were treated by a

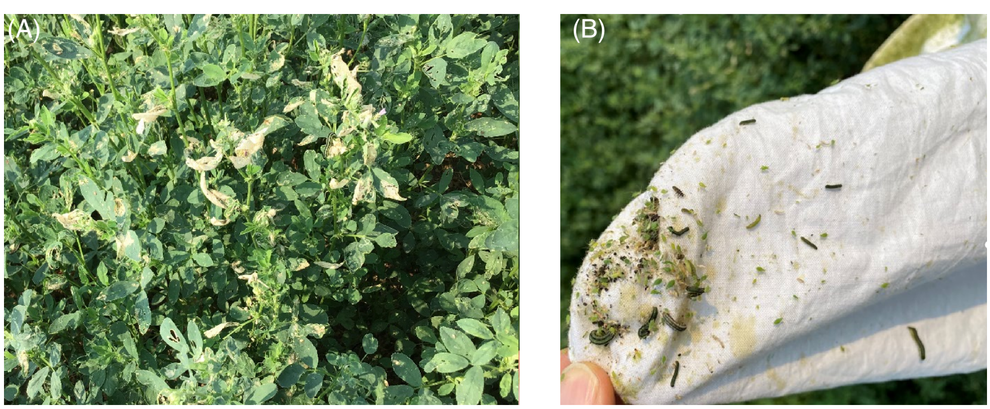

Figure 1. (A) Alfalfa damaged by alfalfa caterpillar and beet and western yellow-striped armyworms. (B) Sampling by sweep net to quantify larval pest and beneficial insect populations.

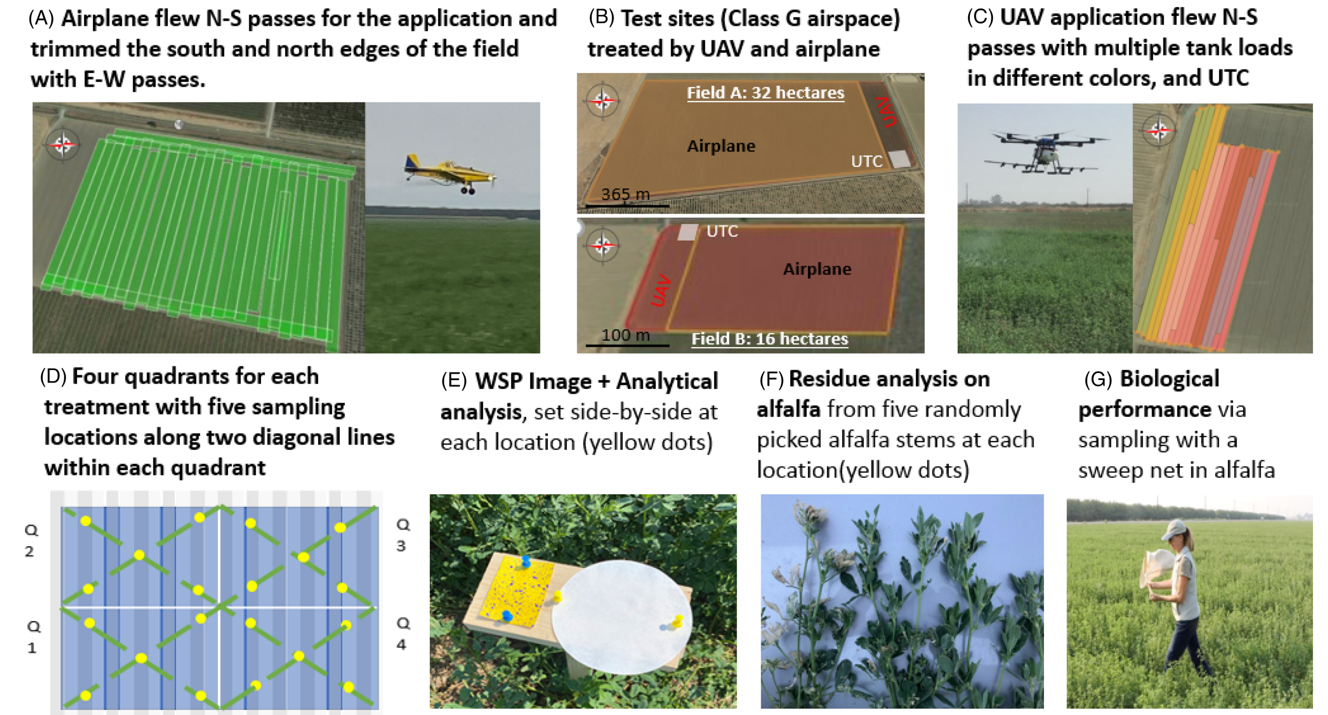

Figure 2. Sampling and measurement strategies: field trial layout at alfalfa hay sites.

manned fixed-wing airplane. Both aerial aircraft sprayed chlorantraniliprole (Prevathon® Insect Control 5% SC insecticide) at 60.5 g ai ha^{-1} (16 fl. oz product/acre, 0.054 lbs ai/acre) in a spray volume of 93.6 L ha^{-1} (10 gal/acre) that is commonly used in California commercial alfalfa pest control programs. A spray adjuvant was also added to the tank as listed in the chemicals section. The average alfalfa height at the field site A was 51–61 cm (20–24 in.) at treatment. The second application was conducted on September 3 at the Esparto farm (field site B) on a 16 ha (40 acres) alfalfa field, where approximately 14 ha (35 acres) (Fig. 2(A)) were treated by a different fixed-wing airplane while 2 ha (5 acres) (Fig. 2(B)) were treated by the drone model PV35 at the same application rate of 60.5 g ai ha^{-1} (16 fl. oz/acre, 0.054 lbs ai/acre) using a spray volume of 46.8 L ha^{-1} (5 gal/acre). The alfalfa height at that spray time was about 30–36 cm (12–14 in.). At each site, an unsprayed area was left as the untreated control (Fig. 2(B)).

The UAV aircraft (model PV35™) used in this study was a battery-powered hexacopter retrofitted with an application system and flight control software developed by Leading Edge Aerial Technologies, Inc. (Leading Edge Associates, Asheville, NC, USA). Major spray components consisted of two, two-chamber diaphragm pumps, 1.2 m (4′) fixed boom with six flat fan nozzles and a 16-l (4.25 gal) tank. The XR11004 nozzles were used in both field trials. The flow rate for each nozzle was calibrated prior to application at the operating pressure of 140 kPa (20 psi). The average coefficient of variation (CV) of flow rate from the six nozzles was 0.48%. The drone sprayer had an extensive agricultural use history and was approved by the FAA under Part 137 and by California Department of Pesticide Regulation for agricultural crop spraying. All drone applications in this study followed back and forth passes (Fig. 2(C)), where the UAV flew the field progressively back and forth to produce a left-on-left and right-on-right deposition (not racetrack pattern). In each drone spray scenario, GPS-guided autonomous flight was used during the aerial application and the remotely piloted operations were adopted for non-spray missions such as take-off, landing, and ferrying. The entire application operation was performed by a licensed agricultural pilot. A separate ground crew was responsible for mixing and loading the products and observing drone flight as required by California regulation. Specifications of the UAV aerial platform and spray parameters are listed in Table 1. The actual and targeted spray volumes were well aligned by carefully examining the volume and area sprayed at the end of each flight sortie.

Two commercial manned fixed-wing aircraft were contracted to execute the spray for alfalfa insect pest control at the two sites and for direct comparison to the UAV application method. The Air Tractor (AT-502) equipped with standard airfoil boom was used in the field site A, and the Ag-Cat D-model airplane with standard airfoil boom treated the alfalfa at field site B. The droplet release height from the airplanes was approximately 3 m (10 ft) with a targeted swath of 15 m (50 ft) traveling at an airplane speed at 51 m s^{-1} (115 mph). The Turbo AG-CAT model was equipped with standard CP-TT flat fan nozzles 40/15 and 40/20 nozzles that generated droplets in the ASABE coarse category (341–403 μm)[13] at 280 kPa operating pressure. Both airplanes were operated by licensed pilots with decades of experiences working in professional spray service companies.

2.2 Measurement and sample collection

Efficacy and alfalfa residue data were collected at field site A to access lepidopteran pest and beneficial populations. Efficacy, residue, and deposition data were collected at field site B. Large plot trials (LPT) are considered valuable in the crop protection industry for measuring practical and commercial fit. In this LPT, the drone and airplane treated areas were each divided into four quadrants with each quadrant considered a pseudo-replicate for analysis (Fig. 2(D)). Within each quadrant, residue samples, including alfalfa tissue, water sensitive paper (WSP), and filter paper samples were collected across two diagonal lines. Water sensitive paper and glass fiber filter paper were positioned side-by-side on the

Table 1. Parameters and testing conditions for the three UAV applications using model PV35™

Parameters	Values at different application times		
	22 August 2020	3 September 2020	14 October 2020
Target swath width (m)	3.51	4.88	4.88
Release height (m)	3.0	3.3	3.3
Application ground speed (m s^{-1})	2.9	4.6	4.7
Spray volume (L ha^{-1})	93.5	46.8	46.8
Flow rate per nozzle (L min^{-1})	0.95	1.05	1.05
Nozzle type	XR TeeJet® 11004	XR TeeJet® 11004	XR TeeJet® 11004
Operating pressure (kPa)	124	140	140
Drop size category at operating pressure**	Medium	Medium	Medium
Average temperature* (°C)	26	27	22
Relative humidity (%)	49	52	41
Mean wind speed (m s^{-1})	1.79	2.23	1.12
Mean wind direction	139° (South East)	130° (South East)	350° (North/North West)

*Note: The weather data are retrieved and averaged from the California Weather Database (https://cimis.water.ca.gov).
** Droplet size category refers to ASABE standard s572.3.

T-post collector to measure spray deposition and residue, respectively (Fig. 2(E)). Each T-post collector was placed along the diagonal lines at the level similar to the maximum height of the alfalfa canopy, representative of the most common area of insect attack. After application, each filter paper was placed in a prelabeled conical tube, quickly stored in an ice chest in the field, promptly frozen, and then retained under refrigeration for analysis of chlorantraniliprole insecticide deposition. All water sensitive papers were secured in the field, and then optically scanned at the 300 dpi resolution for image analysis to assess the deposit morphology parameters by using DropVision® Ag software (Leading Edge Associates, Asheville, NC). Measured deposit parameters included Dv10, Dv50, Dv90, relative span, percent area coverage, and droplet density.

Treated alfalfa stems for quantifying insecticide residues were collected near each water sensitive card and filter paper sampling locations along the diagonal in each quadrant (Fig. 2(F)). At each sampling location, the top 16–20 cm (6 in.) alfalfa stems were cut from five to six randomly chosen alfalfa plants (10–20 g of leaf and stem tissue) (Fig. 2(F)). The cut stems were placed in 125 mL wide-mouth pre-weighted HDPE containers and stored in an ice chest in the field before freezing a few hours later. Field samples were shipped on dry ice overnight to Stine research center (FMC Corporation, Newark, DE 19711) where samples were then returned to a −20 °C freezer. Before field trials, it was confirmed that both field sites had not been exposed to chlorantraniliprole product spray during the 2020 season. Untreated alfalfa samples (at least 25 stems at the same length as the treated stems) were collected prior to the spray event and used for extraction efficiency testing to validate the analytical method. Efficacy data and residue alfalfa samples were collected at field site A following similar procedures without using the four pseudo-quadrant divisions. Metrological conditions for the three trials were monitored using a kestrel device and reported data were retrieved from the California Weather Database.

The spray pattern test was carried out using the same drone equipment from the alfalfa trials and sprayed chlorantraniliprole insecticide on a flat field devoid of vegetation near Esparto, CA. The PV35 drone with a full tank load sprayed 46.8 L ha^{-1} to mimic the application setup of the field site B for alfalfa pest control trial. The drone flew a single pass along a 90 m (100 yards) flight line. Spray deposition within the swath was measured by coverage on WSP and insecticide deposition on filter paper. WSP and filter paper samples were placed side-by-side for a total width of approximately 8.5 m (28 ft) perpendicular to the flight center line (Fig. 3). Fifteen sampling positions were arranged at an interval of 0.6 m (2 ft). Three replicates collected for each flight pass at a space of 45 m (50 yards). The resulting passes were then averaged together to get an average spray pattern.[14]

2.3 Chemicals

Prevathon® insect control (active ingredient chlorantraniliprole), an FMC registered insecticide for alfalfa insect pest control, was used at the same rate in both field sites A and B. This commercial product contains 5% chlorantraniliprole as the active ingredient (50 g active ingredient/liter finished product) and is formulated as a Suspension Concentrate (SC) for foliar application via ground and aerial application equipment.[15] Chlorantraniliprole, an IRAC (Insecticide Resistance Action Committee) classified Group 28 mode of action insecticide, is an anthranilic diamide insecticide targeting ryanodine receptor modulation and disruption of calcium ion flow to control lepidopteran pests.[16] Different adjuvants preferred by farm owners were tank mixed with chlorantraniliprole in the two efficacy trials. R11® spreader activator (Wilbur-Ellis Agribusiness, Aurora, CO, USA), a non-ionic surfactant,[17] was tank mixed (0.156% v/v) and applied at the spray volume of 93.5 L ha^{-1} in field site A. Dyne-Amic® adjuvant (Helena® Agri-Enterprises, LLC, Collierville, TN, USA), a surfactant blend of methylated seed oil (MSO) and non-ionic organosilicone,[18] was tank mixed (0.125% v/v) with chlorantraniliprole and sprayed in a water volume of 46.8 L ha^{-1} in field site B. Tank mixing and loading in all field trials were sequenced with first dispersing Prevathon® insect control in the tank with well water followed by adding the adjuvant last. The product addition sequence was in accordance with the product label and FMC's UAV application best management practices (BMPs).[10]

2.4 Analytical analysis

Chlorantraniliprole residue on the alfalfa plant samples is reported as mass of active ingredient (a.i.) per biomass (μg a.i. g^{-1} plant). Chlorantraniliprole recovery on filter papers was reported as mass

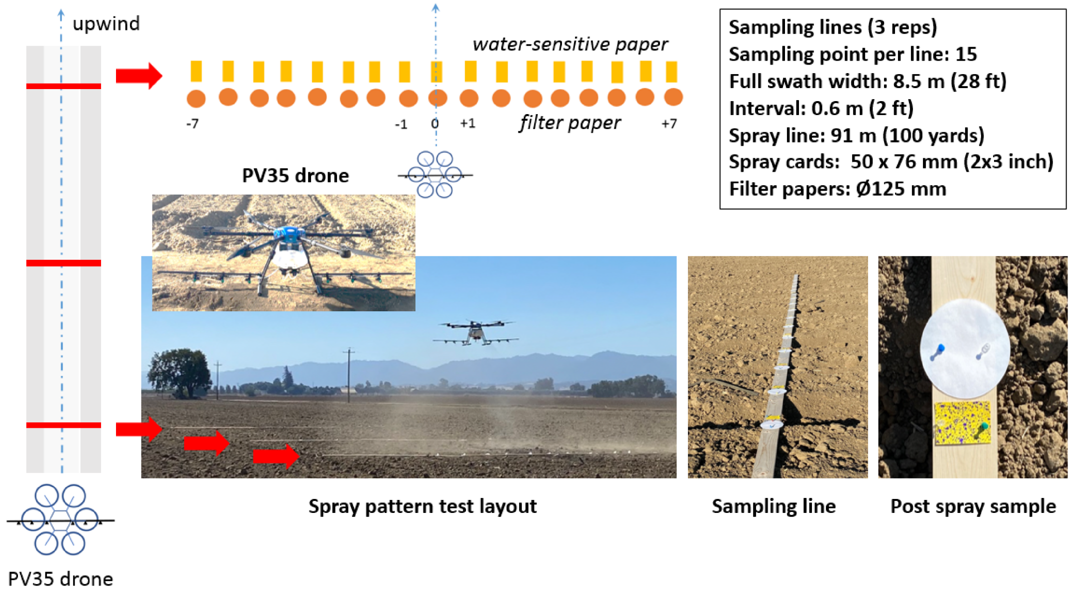

Figure 3. Test layout for spray pattern analysis from a single UAV flight pass.

of active ingredient (a.i.) per unit area (μg a.i. cm^{-2}). The theoretical expectation for perfect deposition of chlorantraniliprole is 0.605 μg a.i. cm^{-2} based on the application rate of product per unit land area. Chlorantraniliprole residues were extracted from filter papers by adding 45 mL of acetonitrile to each conical tube and rotating (Rugged Rotator, Glas-Col LLC., Terre Haute, IN) overnight at 40 rpm. A small volume of extract, approximately 1.5 mL, was transferred to microfuge tubes and centrifuged for 5 min at 15000 rpm before transferring to HPLC vials for quantitation using analytical standards prepared in acetonitrile. Earlier work with this method found 108% average recoveries from ten replicate samples of filter papers treated with 20 μg a.i. per filter paper. Chlorantraniliprole residues were extracted from plant tissues using a series of milling steps on a GenoGrinder 2010 (SPEX® SamplePrep LLC., Metuchen, NJ). Samples were removed from the freezer and allowed to thaw for approximately 1 h. Ten 9.525 mm diameter carbon steel beads were added to each sample bottle and homogenized for 2 min at 1500 bpm, rotating the bottles 180°, and milling again for 2 min at 1500 bpm. Fifty milliliters of acetonitrile were added to each sample and returned to the mill for an additional 2 min at 1500 bpm. A small volume (~1.5 mL) of extract was transferred to 2 mL microfuge tubes and centrifuged for 5 min at 15000 rpm. A 200 μL of supernatant was transferred to HPLC vials for analysis using matrix matched analytical standards prepared in extracts of untreated alfalfa. Previous method validation work found 80% average recoveries from ten replicate alfalfa samples fortified at 5 μg a.i./10 g alfalfa tissue.

Quantification of chlorantraniliprole residues in filter paper and plant extracts were performed with a Waters Acquity H-Class UPLC coupled to a Waters Xevo TQD mass spectrometer (Waters Corp., Milford, MA). Chromatography was performed at 40 °C with a flow rate of 600 μL min^{-1} using an Acquity HSS T3 (2.1 × 50 mm, 1.8 μm) column. Eluents were LC grade water (eluent A; Omnisolv, EMD Millipore Corp. Darmstadt, Germany) and acetonitrile (eluent B; Omnisolv, EMD Millipore Corp. Darmstadt, Germany) and each were amended with 0.1% formic acid (Suprapur, EMD Millipore Corp. Darmstadt, Germany). Chromatographic runs started at 95% eluent A followed by a 1 min linear gradient to 90% eluent B. After a 0.3 min hold at 90% eluent B the column was returned to 95% eluent A for 0.6 min before the start of the next run. All chlorantraniliprole residues were monitored with ESI+ at a mass transition of 484–286.

2.5 Assessing insect Pest and beneficial populations

Insect pest and beneficial numbers and crop damage were assessed 3 to 7 days after treatment (DAT) and were compared to that of the untreated control (UTC). Insect sampling was conducted using a standard sweep net at an approximate 15–20 cm (6–8 in.) depth within the upper alfalfa canopy, following University of California IPM alfalfa guidelines.[19,20] An insect sample consisted of ten sweeps in each of the four divided sections (Fig. 2(G)). Insect counts are expressed as the average number of insect pests or beneficials per ten sweeps. Plant damage was assessed as percent damaged foliage on a 0–5 scale (1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = >50% defoliation). The same sweep net sampling method (ten sweeps in four areas) was applied for the untreated control area that was about 0.4 ha.

2.6 Data analysis

The data obtained from all of the experiments, including spray coverage on water-sensitive papers, chlorantraniliprole residue data on filter paper and alfalfa tissue, and pest and beneficial counts were analyzed using Analysis of Variance (ANOVA) and Fisher's LSD was used for treatment means separation with a P-value of 0.05. ANOVA assumptions included variance homogeneity and normality. Analysis residuals were assessed for normality. If the assumptions of normality and/or homogeneity were violated, a transformed response (square root for insect counts, log 10 for conc μg g^{-1} leaf) was instead used in the analysis. Treatment variances (in original scale) were compared using both Bartlett and Levene tests. Analyses comparing means and variances were performed using JMP® (Version 15.2, SAS Institute, Cary, NC, USA). Principal component analysis (PCA) was applied to spray deposition data extracted from image analysis of water-sensitive paper and used to explore differences between the two methods of aerial application. All data visualization, pattern tests and PCA analyses were performed using Python™ software (Version 3.9.0, Python Software Foundation, VA, USA) and Matlab® software (R2019a, The MathWorks Inc., Natick, MA, USA).

3 RESULTS

3.1 Spray coverage and visualization

Water-sensitive spray cards, as a visual indicator of in-field application quality, provided an overall quick examination of spray coverage. Fig. 4(A) shows representative deposition images selected based on the mean, maximum, and minimum values of percent area coverage recovered from all the water-sensitive cards in the aircraft and UAV applications in field site B. Coarse, medium, and fine droplet sizes, evidenced by the blue stains, were observed in both aerial methods of application, suggesting a mixture of droplet sizes delivered to the target during the spray events. Some elliptical-shaped blue streaks were visible only on the UAV application shown by the representative card (e.g., minimum spray coverage cards) in Fig. 4(A). These blue streaks are typically a sign of droplet 'hard landing' implying that droplets from the UAV application may impinge onto the target surface with a significant horizontal motion at a high velocity. These droplets follow a trajectory forced by the strong air streams created by the UAV rotor downwash. By contrast, the spray droplets from airplanes are anticipated to release in parallel to flight direction and thus behave like projectiles following a parabolic trajectory, hitting the surface at an angle at a lower velocity and typically produce non-elliptical stains. Droplets with the same size but different striking angle onto the plant surface can lead to different droplet leaf retention and potentially more variable biological responses. Nozzles on the conventional Ag-CAT airplane in this study are oriented straight back with the boom length limited to 75% of the wingspan to reduce unnecessary droplet entrapment by wingtip vortices. No international standard for nozzle and boom configuration relative to rotor placement is yet available for the UAV sprayer design. In this study, the nozzles on the UAV applicator are distributed on a fixed boom and oriented 15° from vertical direction, a spray system configuration commercially developed and used by Leading Edge Aerial Technologies Inc. for contracted spray service. The boom length on the UAV used in these trials is wider than the size of the UAV sprayer. Fine or very fine droplets, in combination with drone rotor downwash, may produce undesirable streak-like deposits that can alter the spreading process of formulated insecticide on the leaves.

Deposition statistics extracted from image analysis of all the WSPs are listed in Table 2. Diameter-based measurements (Dv10, Dv50 and Dv90) were the only parameters with statistical differences ($P < 0.05$). Although the absolute 'Dv' values of blue stains obtained from the image analysis cannot reliably characterize the true droplet size distribution generated from the nozzle, the statistical values of deposit diameters are still distinguishable between the two aerial methods, largely because of different nozzle orifice sizes and flow rates. In this study, the CP-4020 and CP-4015 flat fan nozzles operating at a flow rate of 5.7–7.6 L min^{-1} (1.5 and 2.0 gal min^{-1}) at 276 kPa (40 psi) were used by the Ag-CAT as the results from years' experience for alfalfa pest control. The narrow spray angle (40°) generates relatively larger droplet size compared to the same type nozzles with wider spray angles. To deliver the same labeled spray volume as aircraft, nozzle choice for alfalfa pest control by drone is new and constrained by the FAA maximum of 55 lbs (25 kg) payload limitation, the lower flight speed, and the smaller tank size. For pest control in a hot and dry environment like California, a droplet size spectrum with increased VMD is critical to reduce the potential risk of evaporation and drift while maintaining good foliar coverage.

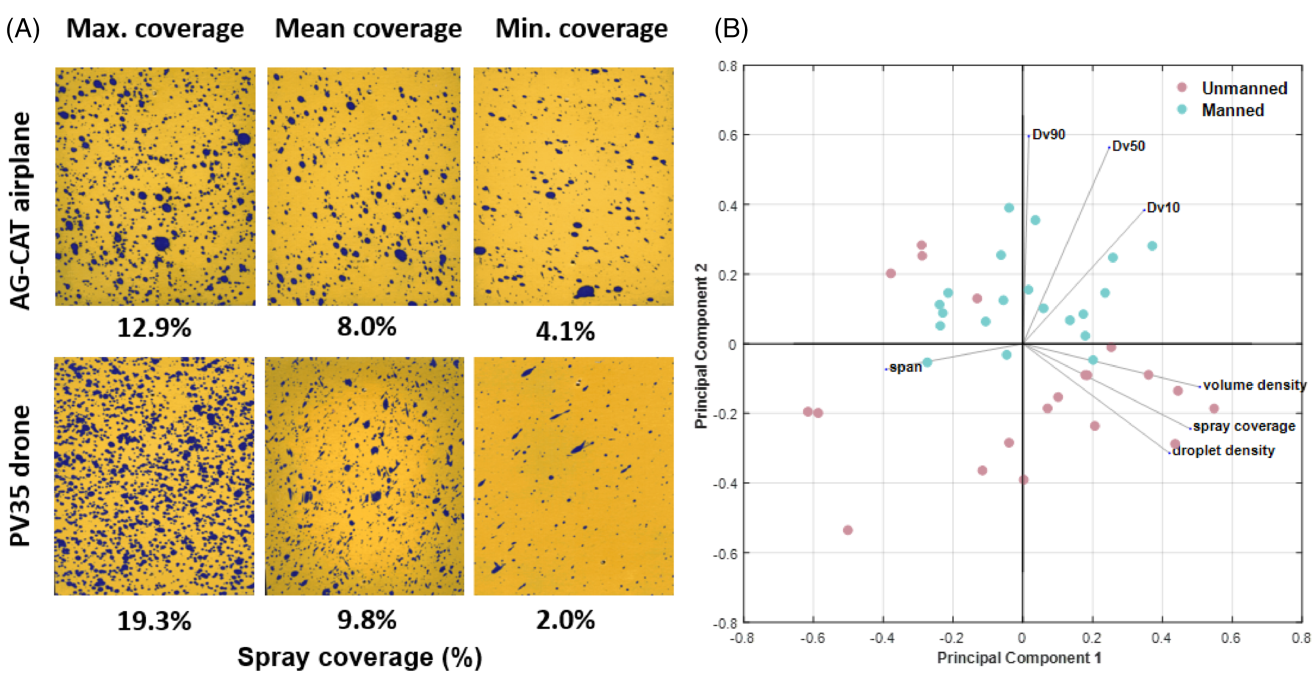

Figure 4. Visualization of spray area coverage on water–sensitive paper and segregation of the two application methods based on their deposition characteristics determined by principal component analysis (PCA). Vectors (gray lines and black labels in the loading plot) represent the loadings of deposition parameters, scattered points (green and red dots) represent the principal component scores for samples from deposition images. Principle components (PC1 and PC2) from linear combinations of the seven original variables are given below: PC1 = 0.48 × spray coverage+0.42 × droplet density + 0.51 × volume density + 0.35 × Dv10 + 0.25× Dv50 + 0.02 × Dv90-0.39 × span. PC2 = −0.24 × spray coverage −0.31 × droplet density-0.12 × volume density + 0.38 × Dv10 + 0.56× Dv50 + 0.60 × Dv90-0.07 × span.

Table 2. Deposition parameters measured from water-sensitive papers treated by unmanned and piloted aerial applications

	Unmanned aerial sprayer (n = 20)			Airplane AG-CAT D sprayer (n = 20)		
Deposition parameters	Mean	SD	Range	Mean	SD	Range
Spray coverage (%)	9.81	5.22	2.00–19.27	8.02	2.49	4.10–12.94
Droplet density (count cm^{-2})	30.59	12.16	10.06–51.76	25.17	7.25	13.03–40.95
Volume density (L ha^{-1})	66.41	39.00	13.28–136.38	60.24	20.95	26.28–95.13
Dv10* (μm)	292.51	44.72	201.52–366.65	331.35	41.46	247.22–405.99
Dv50* (μm)	647.55	109.96	394.82–800.20	752.77	84.11	590.30–881.98
Dv90* (μm)	1070.93	145.18	718.34–1333.21	1200.51	105.53	1010.46–1374.55
Relative span	1.22	0.20	0.99–1.73	1.17	0.19	0.88–1.66

* indicates statistical difference (significant at $P < 0.05$) between unmanned and piloted aerial applications. Reported spreading factor on the water sensitive cards is 2.3.
SD, standard deviation.

To further compare the two aerial methods, principal component analysis (PCA) was used to quantitatively examine the seven commonly used features extracted from deposition images on WSPs. Principle components (PCs) are constructed by linear combinations of the seven spray deposition features listed in Table 2. In the PCA model, about 80% of the observed variance was explained by the first two principle components, accounting for 49.6% and 30.1% of the total variability, respectively. In the PCA space, the airplane application clearly separates from the UAV application along the axis of PC2 by trending with positive scores, where the cluster of diameter-based parameters (i.e., Dv values) drives this discrimination. This separation of treatments for Dv values was detected by ANOVA as well. Other deposition features, including spray coverage, droplet density and volume density calculated on area coverage, actually carry high weights in the two linear equations of PC1 and PC2, but the differentiation along the axis of PC1 is intermixed and appears less clear than those of PC2. Relative span, the variation feature of droplet size, is isolated in the loading plot (Fig. 4(B)) and appears the least important in terms of two-treatment differentiation. Most importantly, the droplet diameter-based parameters are directly controllable variables prior to any spray event through proper selection of spray parameters, such as nozzle type, orifice size, operating pressure adjustment, etc. However, the parameters based upon percent area coverage are observable outcomes that have less direct control by operators but are resulting from droplet size selection. As a droplet size category is often recommended on pesticide labels to reduce drift, the PCA model highlights the importance of choosing the correct nozzle and sprayer setup to produce proper droplet size that balance pest control and drift reduction for both methods of aerial application.

3.2 Insecticide residues

Figure 5 presents a comparison of the overall chlorantraniliprole plant residues recovered from alfalfa plant samples sprayed by the UAV PV35, Airplane AT-502, and Airplane Ag-CAT D at the two test sites applying spray volumes of 93.5 L ha^{-1} and 46.8 L ha^{-1}, respectively. The residue data are presented in violin plots with the white dot as the mean value in each treatment. The curved profiles represent the kernel density estimation (KDE)[21] of the residue distribution. The mean pesticide residue levels are independent of spray volumes and are mostly consistent between the two methods of aerial application and between airplane models. In Fig. 5(A), the mean insecticide residue from the airplane application is greater than the UAV treatment ($P < 0.05$) when including the outlier in the aircraft application. The UAV application in field site A produced less variation than site B ($P < 0.05$). In Fig. 5(B), there were no statistical differences between drone and airplane for sprays applied at 46.8 L ha^{-1}, although some anomaly data points indicate more variation ($P < 0.05$) in the drone application. Curves from the kernel density estimation illustrate the distribution of insecticide residues for each spray treatment and highlight the significant effect of outliers on the data distributional properties. No justification was performed on outliers to understand their origin. Field trial implementation and data collection are always subject to the realities of commercial farming circumstances and decisions such as the environmental conditions, application equipment, spray timing, product rate, logistic expenses, economic loss, and labor cost, thus adequate sample size is critical to accommodate variability in pesticide residue measurements.

Fig. 6 shows a multi-criteria comparison of pesticide deposition levels when treated by UAV and airplane in the field site B with chlorantraniliprole at 60 g a.i. ha^{-1} at a spray volume of 46.8 L ha^{-1}. Field samples within four quadrants of each treatment were evaluated by three distinct methods, including spray coverage on water-sensitive paper, insecticide residue recovered from filter papers and from alfalfa plants. The three sample matrices were analyzed by imaging or analytical methods. Consistent residue patterns and no statistical differences were observed across the four quadrants and the three methods of evaluation regardless of aerial application method, Fig. 6 (A1, B1 and C1). For spray coverage and concentration on filter paper, there were differences ($P < 0.05$) among the quadrants for the airplane treatment, but not for residues on alfalfa plants. There was a noticeable decreasing trend from quadrant 1 to quadrant 4 for the airplane treatment across the three independent measurements, although the nozzle configuration had already adjusted for the airplane prop-wash prior to the application. In Fig. 6 (A2, B2 and C2), all corresponding data in each treatment (manned and unmanned) were pooled, bootstrapped, fitted to the kernel density estimation algorithm for extra examination of each criterion. The wider distribution of UAV data differing from those from the airplane in Fig. 6 (A2, B2 and C2) indicated higher variability ($P < 0.05$) for the UAV application. Higher deviations detected in the UAV treatment throughout the three evaluation criteria are suspected to elevate the spatial variations of the drone application. The trend also aligned well with the visual comparison between the two aerial

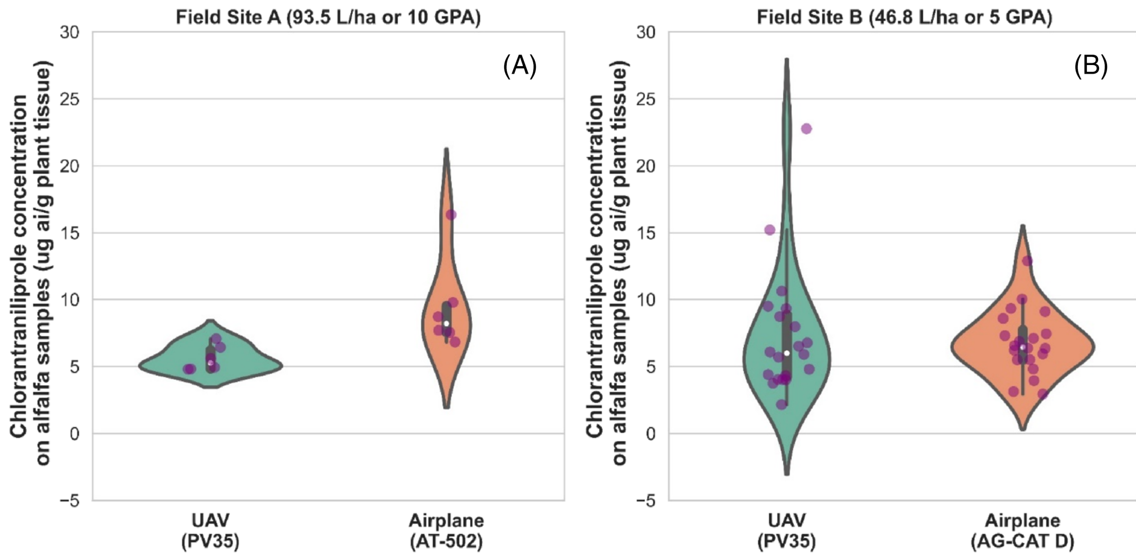

Figure 5. Chlorantraniliprole residue recovery from alfalfa stem/leaf samples between unmanned and manned aerial application methods at two field sites (A and B) with different application rates (93.5 L ha^{-1} and 46.8 L ha^{-1}, respectively): residue data are presented in violin graphs. The white dot is the mean value in each treatment and the curves represent the kernel density estimation (KDE) of the residue distribution. For site A, airplane treatment has statistically higher mean residues and higher variance ($P < 0.05$) than UAV treatment. For site B there is no difference in mean residues between treatments, but UAV treatment has statistically higher variance ($P < 0.05$) than airplane treatment. Data for comparing means has been transformed (log10) to meet either normality of homogeneity of variance assumptions for the ANOVA.

methods using the spray cards (Fig. 4(A)). Note that the spray system configuration and application parameter calibration used by the commercial airplane applicator in this study had been improved for agricultural crop sprays over multiple decades, whereas the spray configuration and application parameters for the UAV were primarily based upon the researchers' experiences. Further optimization of the UAV sprayer system according to swath pattern results and better understanding of UAV spray aerodynamics would reduce variation in droplet deposits. However, the higher variability observed with the UAV did not translate to differences in pest control, this may be in part related to the high efficacy of chlorantraniliprole against lepidopteran insect pests that could have mitigated minor variations in application quality. However, despite the variability observed, the overall average coverage and residue data among the three independent criteria validate comparable performance between UAV and airplane methods of pesticide application in this field trial.

3.3 Crop protection performance

Insect control evaluation in the field trials were conducted 3 and 5 days after treatment (DAT) in field site A and at 4 and 7 DAT in field site B. Figure 7 shows chlorantraniliprole significantly reduced the number of lepidopteran pest species at all sampling dates regardless of aerial application method compared to the UTC ($P < 0.05$) and provided excellent larval control. There were no statistical differences in pest counts between UAV and airplane application methods at the two locations. Larval pest control was at least 90% or greater compared to the UTC, regardless of the aerial application method at both test sites and all evaluation dates. A very high pest population (70 worms/10 sweeps) existed at field site A with almost 70% of the larvae at 3rd to 4th instar stage. The insect pests evaluated comprised approximately 50% western yellow-striped armyworm (*Spodoptera praefica*), 49% beet armyworm (*S. exigua*), and 1% alfalfa caterpillar *(Colias eurytheme*). Lower insect pressure was observed in field site B, where 80% of the armyworms were mainly 1st and 2nd instars at trial initiation. The insect species comprised about 60% alfalfa caterpillar and 40% combined beet and western yellow-striped armyworms. The much higher pest pressure at the field site A led to the grower's decision to apply a high spray volume (93.4 L ha^{-1}). Crop damage assessments from insect feeding taken at both sites resulted in significant differences between the treated and UTC, as expected, because of the excellent larval control in both aerial application treatments. There were no differences in crop damage between the two aerial application methods.

There were no differences in number of predatory beneficial insects between the two aerial application methods as illustrated in Fig. 8. The beneficial insects sampled at field site A mainly included convergent lady beetles, nabids, syrphids flies and lacewings. A different predator complex was observed at field site B, where 95% of the beneficial insects were convergent lady beetles and the remaining 5% were damsel bugs (nabids), syrphid flies, and lacewings. There were no significant differences in predator numbers between unmanned and manned aerial applications at the trial sites 3, 4, 5, and 7 DAT.

3.4 Spray pattern analysis

Chlorantraniliprole deposition patterns at 46.8 L ha^{-1} spray volume were analyzed and visualized in a separate field trial to determine the overall spray uniformity under back-and-forth flight mode. Percent spray coverage from water sensitive papers and analytical insecticide recovery from filter papers were superimposed in Fig. 9(A) and fitted separately to the Gaussian distribution[22] as a single pass spray. Since the two basic patterns are both symmetric and consistently follow the Gaussian distribution,[22] the analytical data were used for the next analysis of classical coefficient of variation (CV)-swath width relationship in Fig. 9(B) and simulated overlapped spray pattern in Fig. 9(C). In Fig. 9(B), the CV-swath width relationship was computed as the mean CV in an effective swath width ranging from zero to the maximum swath width found in any of

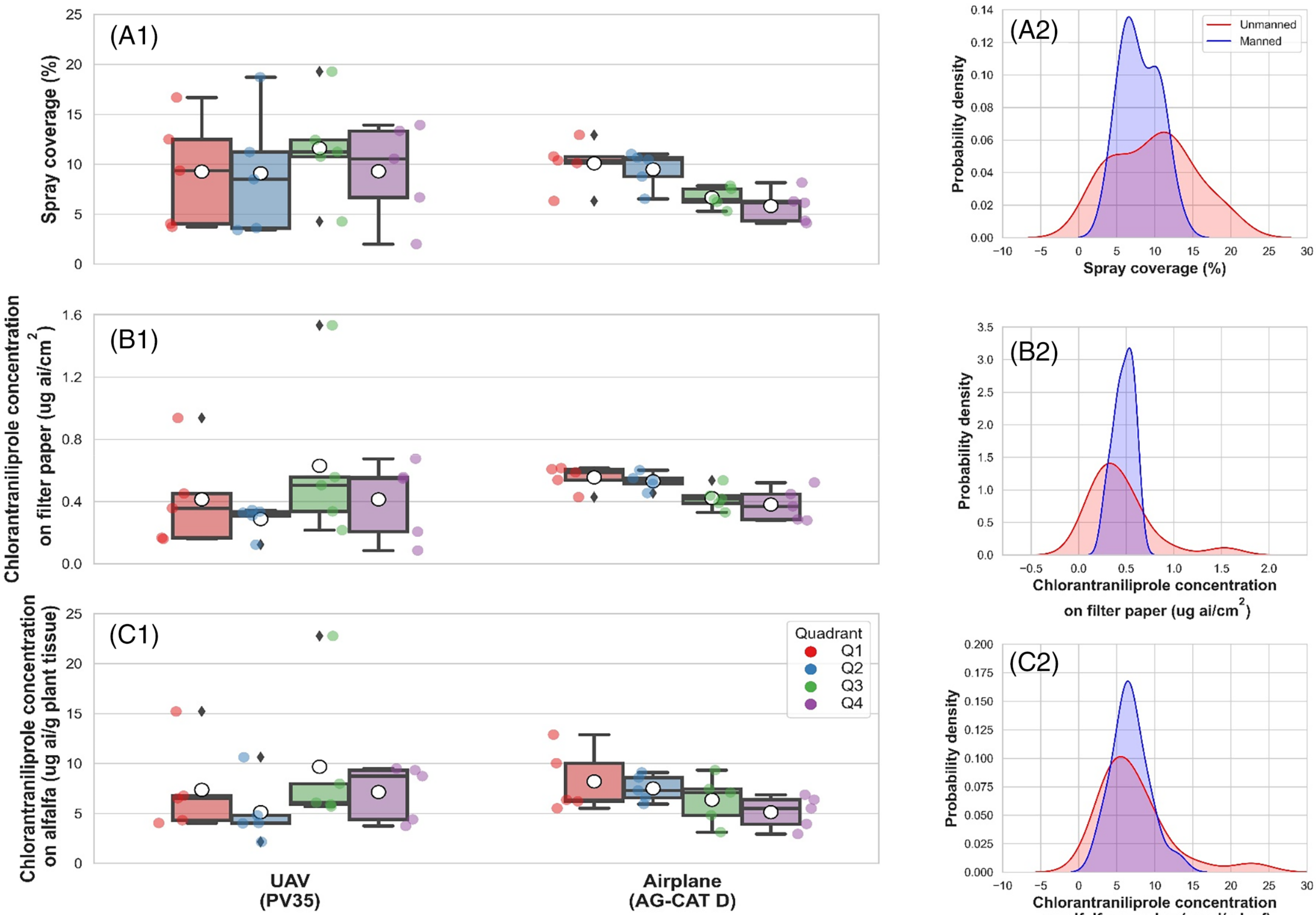

Figure 6. Comparison between UAV and manned aerial applications at the same product use rate (60 gr ai/ha) and same spray volume of 46.8 L/ha using different methods of quantification. Left column- deposition variations within four quadrants between UAV and airplane: A1, spray coverage percentage on water sensitive cards; B1, chlorantraniliprole residues on filter paper; C1, chlorantraniliprole residues on alfalfa stem/leaf samples. Right column- probability density distribution of unmanned and manned aerial sprayed volumes among four quadrants: A2, spray coverage; B2, chlorantraniliprole residues on filter paper; C2, chlorantraniliprole residues on alfalfa stem/leaf samples.

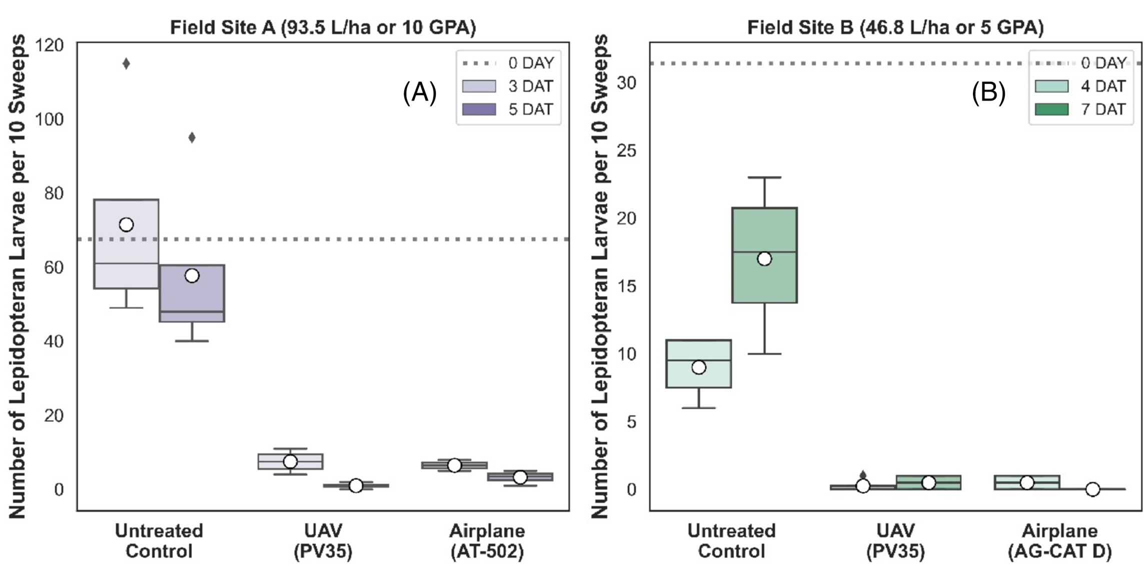

Figure 7. Comparison of lepidopteran larval pest control, including alfalfa caterpillar (*Colias eurytheme*), beet armyworm (*Spodoptera exigua*), and western yellow-striped armyworm (*S. praefica*), by unmanned and manned aerial application methods in two fields under different application rates (93.5 L ha^{-1} and 46.8 L ha^{-1}).

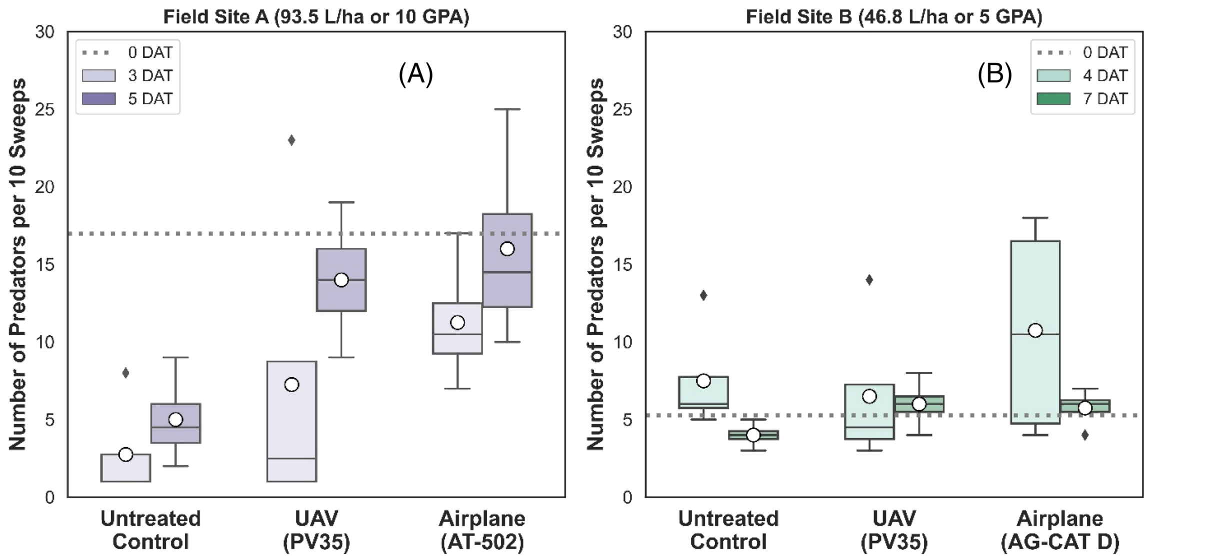

Figure 8. Evaluation of beneficial insect predator populations between unmanned and manned aerial application methods in two fields (A and B) using different spray volumes (93.5 L ha^{-1} and 46.8 L ha^{-1}).

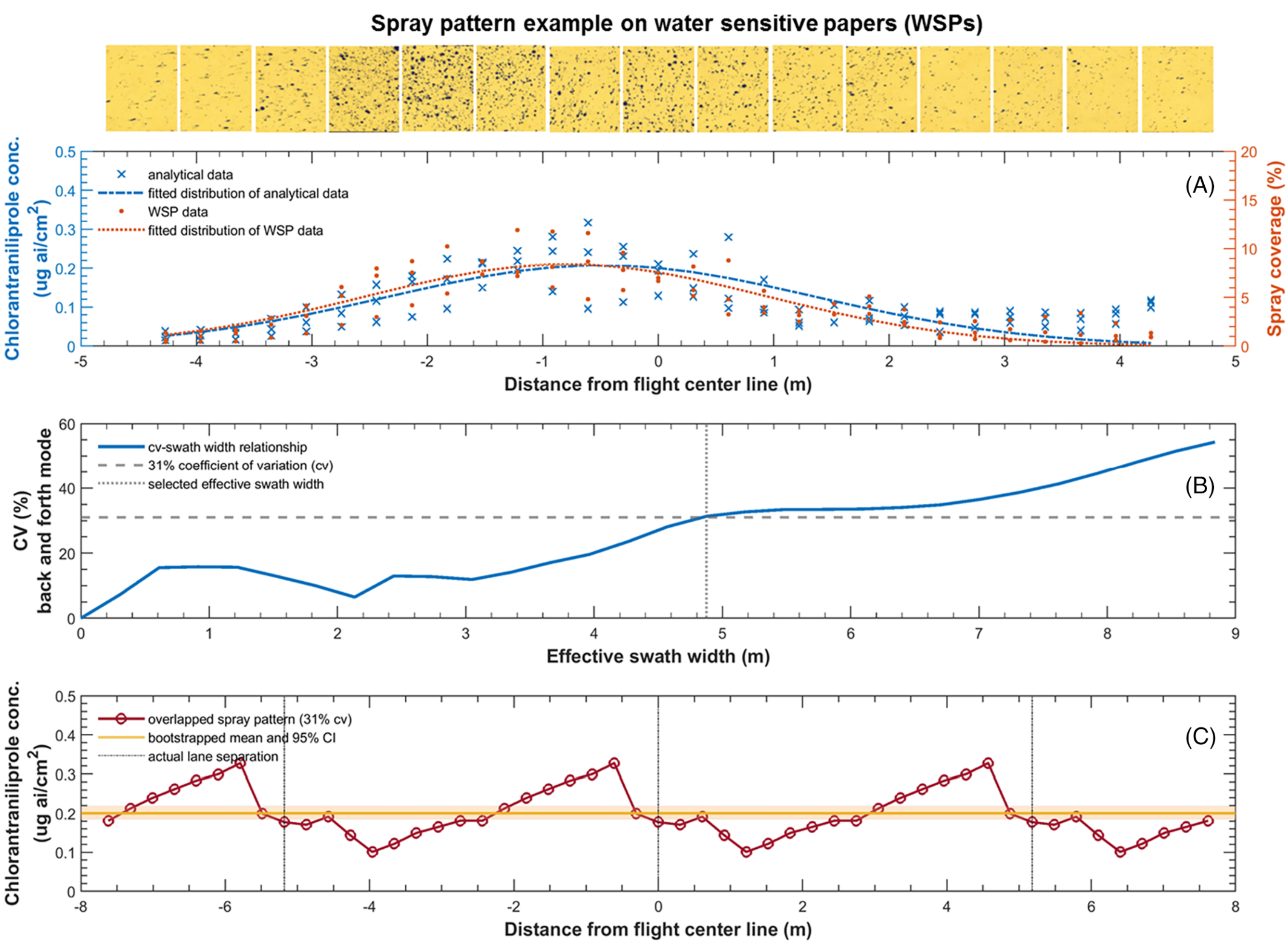

Figure 9. Characterization of a UAV spray pattern at 46.8 L ha^{-1} (5 GPA) in a back-and forth application mode to reveal its deposition uniformity and swath width.

the three flight passes. The dotted line shows the CV value is about 31% when selecting the effective swath width of about approximately 5 m (16 ft) that was adopted in the second alfalfa insect control trial. The simulated overlapped pattern of three

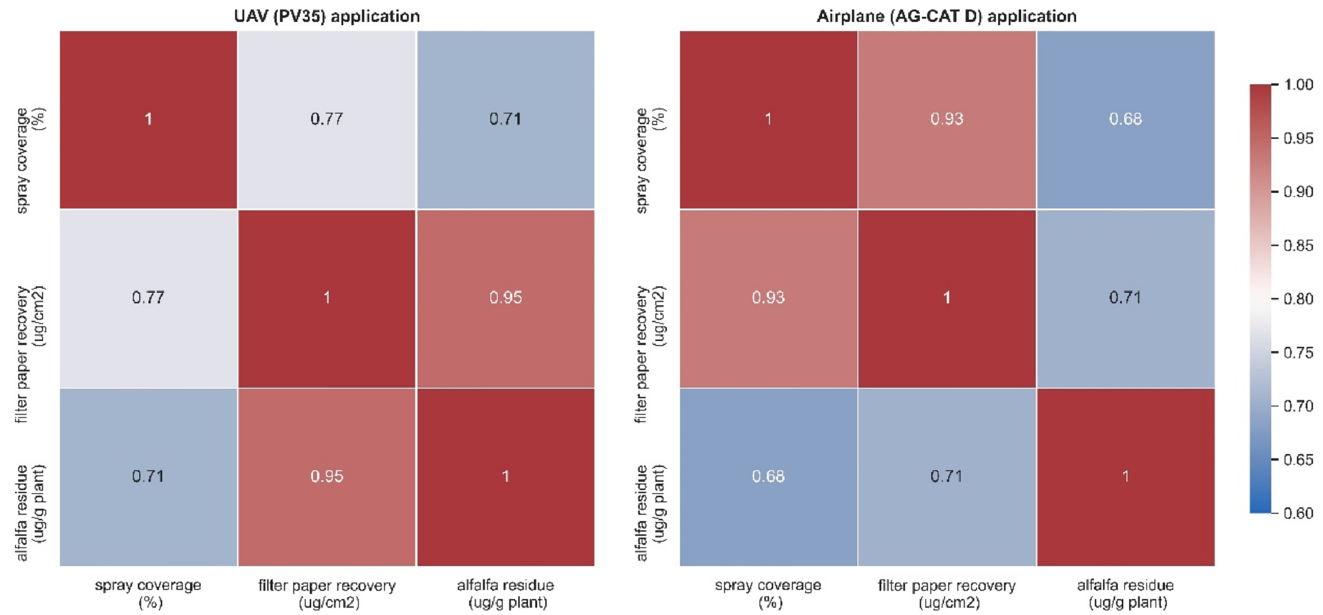

Figure 10. Correlation matrices among independent criteria for drone and airplane applications at 46.8 L ha^{-1} (5 GPA) at site B. Displayed values in heat maps are Pearson correlation coefficients.

passes in a back-and-forth flight mode is shown with an acceptable uniformity in Fig. 9(C). The bootstrapped mean and its 95% confidence interval (CI) were calculated at 0.20 μg cm^{-2} (95% CI: 0.18–0.22). The offset of about 0.6 m towards the left is observed, which is probably due to the manual pilot operation mode adopted in the pattern test, variations in operating and meteorological conditions. Note that the spray pattern in the previous efficacy trials where GPS guided autonomous flight was used may yield better spray uniformity. Overall, the spray pattern test results demonstrated that the applied rate calculated from filter paper recovery is comparable to the targeted labeled rate with an acceptable spray uniformity, although improved spray uniformity towards a CV of 15% and a symmetric pattern around the flight line would be more desirable.

4 DISCUSSION

Commercially effective crop protection from insects, diseases, and weeds is often considered the conclusive measure of success for any pesticide application method. The objective of this study was to evaluate a developing method of application, namely, UAVs or 'remotely piloted aerial application systems', one with limited published scientific data related to application efficacy and quality, compared to a conventional method of application (piloted airplanes) with a massive amount of reproducible data from over five decades of use under a broad spectrum of variables and stresses. For these reasons, evaluating parameters beyond crop protection, such as product deposition, residue, and droplet distribution, provide robust insight into how a new method of application will perform under more varied and stressful conditions[2]. In addition, comparing these key parameters between a new *versus* an established application method will aid the improvement and standardization of an unmanned aerial spraying system. For the two field trials in this study, excellent alfalfa crop protection was achieved through a high level of lepidopteran larval pest control by both UAV and airplane application methods. It is important to note that insect pest population pressure was extreme in field site A and its application timing was well beyond local action treatment thresholds resulting in larger larvae, typically harder to control.[9] Trial variables such as product use rates, spray volume, tank mix adjuvants, application timing, crop damage and pest population evaluations were held constant for UAV and airplane treatments. A critical comparison in this study was measuring the effectiveness of two different spray volumes (46.3 *versus* 93.5 L ha^{-1}) to better define label recommendations for multi-rotor drone applicators. Results from the two spray volumes were comparable for overall residue levels on alfalfa tissue and insect control. These results provide significant data that support the consideration of multi-rotor drone use in small canopy crops to control leaf-feeding lepidopteran pests in alfalfa hay fields comparable to that provided by traditional fixed-wing airplane application.

As stated earlier, efficacy data alone are insufficient to evaluate and validate an optimized sprayer configuration. Additional independent measurements, such as residue analytics combined with spray quality measurements, provide multi-criteria comparisons. A correlation matrix between spray coverage, deposition on filter paper, and residues on plant tissue were determined and visualized as a heatmap for each treatment (Fig. 10), where a high degree of linear correlations ($r = 0.7–0.9$) occurred for each treatment in this study. The residue and spray deposition results, sampled and measured separately, correlated well with the insecticide efficacy results. Moreover, the efficacy and residue results provided additional confidence that UAV applicators may follow current agrochemical company label recommendations for manned aerial application and achieve adequate control of alfalfa pests when following the label GAP (Good Agricultural Practices). Similar levels and distribution of residues observed with both aerial application methods also indicate that crop residue tolerances (maximum residue levels) will not be impacted. These findings further complement increasing market acceptance of UAV application in East Asia as well as California's recent allowance of multi-rotor unmanned aircraft use for pesticide application on agricultural crops. Despite these promising results, significant field work is required to measure the effectiveness of different multi-rotor drone models, their varied nozzle configurations, and intelligent integration of spray systems with drone software at low spray volumes. International standardization of unmanned aerial spray systems is necessary if we are to achieve the most optimal performance from this new method of application. Additionally, further research is warranted to better understand droplet fate that impacts not just crop protection but drift management,[23,24] environmental stewardship,[10,25] and worker exposure safety.[1]

In traditional fixed-wing aerial application, the spray boom is configured to release droplets into a laminar airflow with nozzles positioned to compensate for uneven dispersal from irregular air wake. Consequently, given a standardized aircraft model and sprayer setup, droplet trajectories after releasing from nozzles on a horizontal fixed boom are highly predictable by AgDisp model for drift potential.[26] However, diverse UAV sprayers with different rotor numbers and numerous spray configurations, particularly nozzle position relative to rotors, challenge the scientific understanding of aerodynamics associated with the UAV application. Maintaining constant flight speed and accurate release height, which are precisely enabled by RTK-GPS technology, are currently the best application practices for unmanned aerial spray systems to minimize drift potential.[3,27,28] In this study, the spray uniformity quantified from the pattern analysis showed that a CV value of approximately 30%, although it can be further reduced, may prevent pest damage while allowing a practical range of operating and meteorological conditions. The principle component analysis based on deposit morphological parameters on WSPs reveals that the major difference between the two tested commercially operated manned-airplanes lies in their droplet characteristics. Specifically, the initial droplet size spectrum and the subsequent trajectories of droplets interactively affected by air wake. In addition, the kernel density estimation using three distinct criteria (Fig. 6) shows deposition variability between the UAV and aircraft methods. Predictably, improper droplet size and associated incorrect application parameters increase risk of poor coverage or off-target drift. Using smaller droplet sizes released under low and ultra-low spray volume conditions to gain extra operational efficiency may increase liability for growers and spray-service providers unless additional droplet fate modeling studies are conducted. Our choice of droplets VMD shifting to the medium size category demonstrated that a small payload drone can achieve adequate coverage while minimizing production of small driftable droplets. Our analyses led us to conclude that the reinforcement of proper droplet size selection and the standardization of sprayer configuration is critical for responsible UAV application technology.

5 CONCLUSIONS

This study characterized the differences and similarities between two aerial pesticide application methods, the evolving autonomous small payload multi-rotor UAV *versus* the conventionally piloted large-scale fixed-wing manned airplane. Effective control of alfalfa leaf-feeding insect larval pests was achieved in commercially grown alfalfa hay following the product label recommendations in northern California. Specific findings include:

(1) Chlorantraniliprole demonstrated effective crop protection by significantly reducing the lepidopteran larval population attacking alfalfa while conserving the existing large predator populations in the treated alfalfa fields when applied by a six-rotor UAV. Overall, the two field trials provided comparable pesticide residue levels from alfalfa samples between airplane and UAV aerial applications when applying the same product at the same use rates (60 g ai ha^{-1}) and at two spray volumes of 46.8 L ha^{-1} and 93.5 L ha^{-1}, although statistically significant differences occurred in alfalfa residue levels at field site A between the UAV and airplane methods of application that is believed to be due to a smaller sample size. The efficacy, residue, and spray quality data provide support that a commercially labeled insecticide when applied via the UAV application method can provide acceptable pest control using adequate spray volumes. Determining the appropriate fit of UAV pesticide application technology into commercial crop protection programs is still in the evaluation stage. Further investigation is needed to evaluate pesticide efficacy and droplet drift management under numerous spray system configurations and spray volume variables represented by different multi-rotor UAV models.

(2) In general, consistent deposition patterns were observed across three independent criteria, including spray coverage on water-sensitive papers, pesticide recovery from filter papers, and pesticide residues from alfalfa plants in side-by-side comparisons between manned and unmanned aerial applications at the lower spray volume of 46.8 L ha^{-1}. No statistically significant residue and deposition differences were found between the two aerial application methods. The swath pattern analysis shows that the spray uniformity of the drone has a CV around 30%, suggesting room for technical refinement of the UAV spray system to be more comparable to that of the traditional crop duster that has undergone decades of application research and refinement.

(3) The major difference between the two aerial methods of application lies in the droplet spectra characteristics, in particular, the droplet size and their underlying movement trajectories influenced by the air wake. Blue streaks on the water-sensitive cards in conjunction with data analysis of deposit morphology imply that small droplets may exist in the transient delivery process by the drone, potentially leading to higher deposition variability. Despite comparable efficacy of pest control between UAV and fixed-wing aircraft, there exists a concern of drift potential if excessive fine droplets are produced. Regardless, improvements in UAV technology will continue through iterative research efforts to provide a more optimized, effective, and accurate unmanned aerial spray system.

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