Towards a spray UAV for precision silviculture

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EXECUTIVE SUMMARY

The problem

For a UAV spray application to be successful, the craft needs to be able to accurately deliver the precise amount of spray onto the target.

This project aimed to evaluate SPS Automation's custom Aeronavics Icon spray craft whilst operating in the continuous flight intermittent spray mode. Four UAV operating configurations were evaluated: two release heights [2m & 3m] and two nozzle configurations, delivering either very coarse [404-502 microns] or medium [236-340 microns] VMD droplet spectrums. The methodology of the project assessed:

1. Swath width
2. Spray deposition pattern
3. Dose and spray coverage delivered to a 1.5 x 1.5 m nominal target area.

Key results

Whilst promising, this trial demonstrated that the prototype craft is currently not operationally ready, and identified many areas where gains could, and should be, made to improve operational readiness.

The craft operating, with the specified nozzle configurations (producing fine-medium 219-micron VMD and very-extremely coarse 508-micron VMD droplet spectrums) and release heights (3 m and 2 m), was producing a swath adequate to release a 1.5 m wide area in a single bout. However due to many factors, some easily remedied, the targeting was poor despite relatively straightforward conditions. Moreover, the craft could not deliver the work-rate identified to be important for cost effective operation.

Impediments to full operational readiness include: The craft could not deliver the requisite volumes at the flight speed presumed necessary for optimal work-rates > 2m/s. The third-party waypoint navigation control system was not fit for purpose limiting the continuity of flight and speed of operation. The GPS locations could not be preassigned (as most operational situations would require) and there was an easily rectified offset in the sprayed and surveyed locations. The craft was beset by a number of technical glitches which limited the reproducibility of the spray delivery.

Further improvements to the spray system and set up, including redesigning the nozzle actuation mechanism so that the forward and aft nozzles operate independently, are recommended to improve spray precision.

Implications of results for the client

This trial was an important step to test the prototype craft and identify where improvement is required. With this knowledge informing further development of the craft systems, it is expected a much more operationally ready prototype could be produced.

Further work

Once SPS Automation has addressed and reengineered elements of the craft, it is recommended that the UAV spray systems are first properly calibrated, then tested, in a similar trial methodology used here to characterise and quantify the spray delivery output and targeting methodology, before progressing to simulating a field trial and determining actual releasing efficacy. Further trial work could be conducted to profile the degree of wind displacement of the spray to determine the optimal operational windows for accurate spray delivery from the craft and/or identify any strategies to extend that window.

1.0 INTRODUCTION

Managing non-crop vegetation (weeds) in radiata pine plantations is critical for ensuring planted tree survival and for achieving rapid early growth [1]. The most cost-effective method for managing vegetation in New Zealand (NZ) forestry is through the use of herbicide either prior to planting or for “release spraying” seedlings after planting [2]. The timing of control is important to ensure that release is done prior to the growth season when the surrounding weeds can smother the trees, making them harder to find and, also, impacting on their survival and growth. Spot spraying, where weeds are controlled around individual crop trees, has the advantage of using less herbicide than broadcast treatments [3, 4]. However, current labour shortages are making it difficult to find suitably skilled and qualified workers to perform manual silvicultural operations, such as spot release spraying [5].

Multi-rotor uncrewed aerial vehicles (UAVs) for pesticide spray application offer niche opportunities for overcoming labour shortages for manual releasing and, at the same time, improved precision compared with alternatives [6, 7]. While a number of studies have been published on the spray application efficiency of UAVs configured for conventional swath spraying [8-12], there is little information on the targeting efficiency of UAVs configured for spot treatment of individual plants, especially while in continuous flight and for scenarios typical for forestry. Using a UAV for spraying is potentially one way to reduce reliance on labour to undertake spot spraying of weeds pre- or post-planting and also offers a pathway to both reduce the amount of herbicide used during spraying as well as exposure of operators to the spray mix.

Effective spot spraying from a UAV requires accurate positioning above the spray target (i.e. the tree) and the correct dose of herbicide distributed evenly over the target area. On pasture sites being converted to forestry, spot spraying is sometimes used pre-planting to mark planting spots and provide initial weed control. More commonly, however, spot spraying is a post-plant operation applied in early to late spring (depending on pre-plant treatments and the level of weed competition at any particular site). In either situation, overdosing reduces the cost effectiveness of the operation and might negatively impact seedling pine growth depending on the tolerance of the crop to the applied chemical. Underdosing also wastes resources through poor and short-lived weed control. In the pre-plant spot spraying scenario, inaccurate application or overly large spot sizes makes it difficult to maintain consistent planting spacing. Inaccurate application in post plant situations means that the required level of weed control in the neighbourhood of a crop tree may not be achieved.

Spot spraying in continuous flight, termed intermittent swath spraying to distinguish from stop and hover spot spraying, will provide significant gains in productivity (work rate) while reducing the energy demands incurred by stop and hover spot spraying. In a collaboration between Scion, SPS Automation, FGR and Pan Pac, a study was carried out in spring 2022 to develop and test a prototype automated, unmanned aerial platform for release spraying of radiata pine in NZ [13]. This study represented the first known spot release spraying trial using a UAV in forestry globally, progressing spot spraying using the intermittent swath technique from concept towards reality! Numerous challenges were encountered in this study, highlighting that UAV-based spraying technology was not yet ready for operational application. Challenges included:

- reliably identifying and then re-locating individual trees;
- accurately positioning the craft above these positions during spraying;
- navigating safely at low altitude (2-3 m) over complex terrain;
- effectively activating nozzle on/off timing to deliver the target dose at the ideal craft forward speed (e.g. at a 2 ms^{-1} forward speed, a timing of 0.5 s would be required to deliver a 1 m square spot) and;
- weather, wind and rain, potentially affecting the location and efficacy of the herbicide dose which was used to determine the UAV targeting accuracy through browning of the weed canopy.

Further, prior to this study, no calibration of the deposition pattern produced by the craft was undertaken, making it difficult to properly evaluate the spraying system and its suitability for delivering a spot treatment of approximately 1.5 m diameter to meet weed control specifications.

The purpose of the trial in the current study was to work with SPS Automation to assess the operational readiness of their custom Aeronavics Icon spray craft for spot spraying individual trees when operating in a continuous flight mode. Specific objectives were to:

(i) quantify the deposit pattern delivered during spot spraying;
(ii) quantify the accuracy of spot treatment delivery; and
(iii) identify improvements needed to operationalise spot spraying.

Two approaches were used to deliver these objectives. The first involved testing the effect of two droplet size classes and spray release heights on the swath pattern produced by the craft and the second evaluating the targeting efficiency of the craft by measuring spray deposition around pre-determined locations to simulate actual spot spraying.

2.0 METHODS

The aim of the trial was to test the effect of two droplet size classes (medium or very coarse) in combination with two spray release heights (2 or 3 m) on the accuracy and uniformity of spot delivery. For each of the four treatments, the UAV sprayer was tasked with delivering 45 ml of liquid to 2.25 m^2 (1.5 m by 1.5 m square), equivalent to an application rate of 200 L/ha. The effectiveness of spot delivery was assessed using two approaches:

1. Measuring the cross-sectional swath pattern produced whilst flying and continuously spraying along a pre-determined flight line. This approach will provide useful data on the width and cross-sectional shape of the deposit pattern, which in turn will define the width (diameter) of spot weed control (based on the threshold dose for effective weed control).
2. Defining the swath pattern (1) will not provide information on the shape of the deposit pattern in the direction of flight. Hence, the second test was designed to measure the two-dimension deposit pattern and to evaluate the overall targeting efficiency or accuracy. Targeting efficiency is defined as the proportion of applied material that is deposited in the target zone (the 'spot' in this case).

2.1 UAV specifications

The trial was conducted with a new Aeronavics ICON heavy-lift multirotor UAV with eight rotors in a co-axial quad configuration fully battery powered (Figure 1). The craft has an open-source Pixhawk Cube Orange flight controller (CubePilot Pty. Ltd., Geelong, VIC, Australia), and was controlled by the ArduCopter version 4.1.5 flight control software (ArduPilot Copter Project, https://ardupilot. org/copter/) employing a RTK base station (Aeronavics ground station, Aeronavics 26 Kennels Road, Timaru 7975 New Zealand) and commercially available GPS unit and software (u-blox ZED-F9P Multi-band GNSS receiver) [14], The spray system had two 4 L tanks and a maximum tank carrying capacity of 8 L. This craft was analogous to the petrol generator-battery powered craft flown in a previous trial at Glenlyon station [13]. To maintain continuity, the craft was loaded with additional weight to account for the petrol generator system which would be used in standard operations.

Figure 1. Aeronavics ICON heavy-lift multirotor UAV with four CDA micromiser nozzles.

Operationally, it is important that the craft provides details of how much spray was applied to each tree (with tree location defined as a waypoint) along with other important operational details such as time stamp, droplet size, nozzle flow rate and disc RPM, release height and flight speed. It is most useful when this information is delivered using point data based on the GPS update frequency. This information, coupled with high resolution site-specific meteorological conditions recorded at the time of spraying, can then be used for quality control and to drive models to quantify spray deposition (efficacy) and spray drift (environmental impacts). For this study, the SPS Automation craft recorded for each assigned target waypoint:

- pump flow rate;
- duration of spray release;
- latitude and longitude;
- spray release height (based to the range finder);
- barometer altitude;
- time and the flight mode.

2.2 Nozzle system specifications

Unlike the craft used in the previous trial [13], the spray system used the Micromiser CDA spinning disc nozzles which provided a better droplet size control, than hydraulic nozzles, and can provide variable droplet sizes with minor adjustments to the spinning disc rotational speed (and flow rate), rather than having to replace hardware to adjust the required droplet size range. The craft was fitted with four Micromiser M10 controlled droplet application (CDA) nozzles, with one mounted under each of the four co-axial rotors (Figure 1), each individually supplied by peristaltic pumps with the capacity to deliver 100-400+ ml/min flow rate. Each pump was controlled by the same central driver so were not individually tuned or modulated.

Unlike normal operational circumstances, where a craft would employ a single set up optimised for the task at hand, this trial required the craft to produce two droplet sizes, medium and very coarse. This would allow the operational merits of droplet size to be evaluated. Recent experimentation with the M10 nozzles, demonstrated that medium droplet sizes ~250-350 μm could be achieved at 300 ml/min flow rate and disc speeds < 3000 revolutions per minute (RPM). Coarser droplets would be achieved by increasing the flow rate and/or reducing the spinning disc RPM. However, with this disc design the maximum flow rate that did not cause overloading (or flooding) of the disc, leading to excessive droplet sizes, was also 300 ml/min. With this flow rate limitation, the only option to produce the larger (coarse) droplet size class was to reduce disc rpm and to maintain a flow rate of 300 ml/min. Unfortunately, this maximum flow rate limited the total aircraft output i.e. this flow rate gives a collective output (for the four nozzles) of 1,200 ml/min or 20 ml/s. Hence, a flying speed of 0.67 m/s would be required to deliver the prescribed 45 ml per 1.5 x 1.5 m target.

This speed does not meet the target application speed of 2 m/s, selected to achieve a reasonable aircraft productivity/work rate. At the target speed, an output of 3,600 ml/min would be required from the four nozzles. So, for the purposes of this trial, a decision was made to accept the lower flow rate and application rate of 66.6 L/ha (assuming all applied spray lands withing the 1.5 x 1.5 m target area). From a scientific perspective, droplet size is the key variable that would influence spray pattern/deposit pattern and not spray volume *per se*, so the data from this study will still be relevant even with an application rate below what was specified. A future design iteration of the SPS spraying UAV is expected to meet the specifications for the target droplet size and flow rates.

Calibration of the flow rate at each nozzle showed, for the control setting used during this trial, each peristaltic pump delivered a different flow rate to the nozzle as follows:

- 400 mL/min to left rear;
- 300mL/min to left front;
- 248mL/min to right rear (there were air bubbles in the line which could not be purged), and;
- 348mL/min to right front (this nozzle had a leak and would drip when not pressurised).

Hence, the total flow rate was 1296 mL/min giving a theoretical application rate of 72 L/ha if all other specifications were met. The medium droplet spectrum was delivered by supplying 248-400 mL/min to each of the four nozzles operating at 3000 RPM and the very coarse droplet spectrum was delivered by supplying 248-400mL/min at 1800 RPM. The variance in flow rate to each nozzle will also contribute to a wider droplet size spectrum than if the flow rates were consistent. Spray was collected on cast-coated white cards placed under the swath for selected replicates to assess the actual droplet size delivered for each treatment.

Key learning/outcome: As a result of this trial SPS Automation are developing higher flow rate pumps and improved CDA nozzle technology that can accommodate higher flow rates while maintaining droplet size control. SPS Automation are also developing direct pump speed control methods (stepper motor based peristaltic pump control) for better flow control and monitoring flow rates. Ideally the spraying system will record actual flow rates and disc rpm achieved with each nozzle during the application.

2.3 Trial location, flight path set-up and meteorological details

The trial was conducted at Te Papa Tipu Innovation Park in the Scion nursery (Figure 2). The meteorological station (Gill Windsonic WS60, Scottech 1/4 Timothy Pl, Christchurch 804, NZ) was positioned roughly 30 m south of the spray areas, far enough to avoid being compromised by the wake of the craft but close enough to measure the prevailing wind and site conditions.

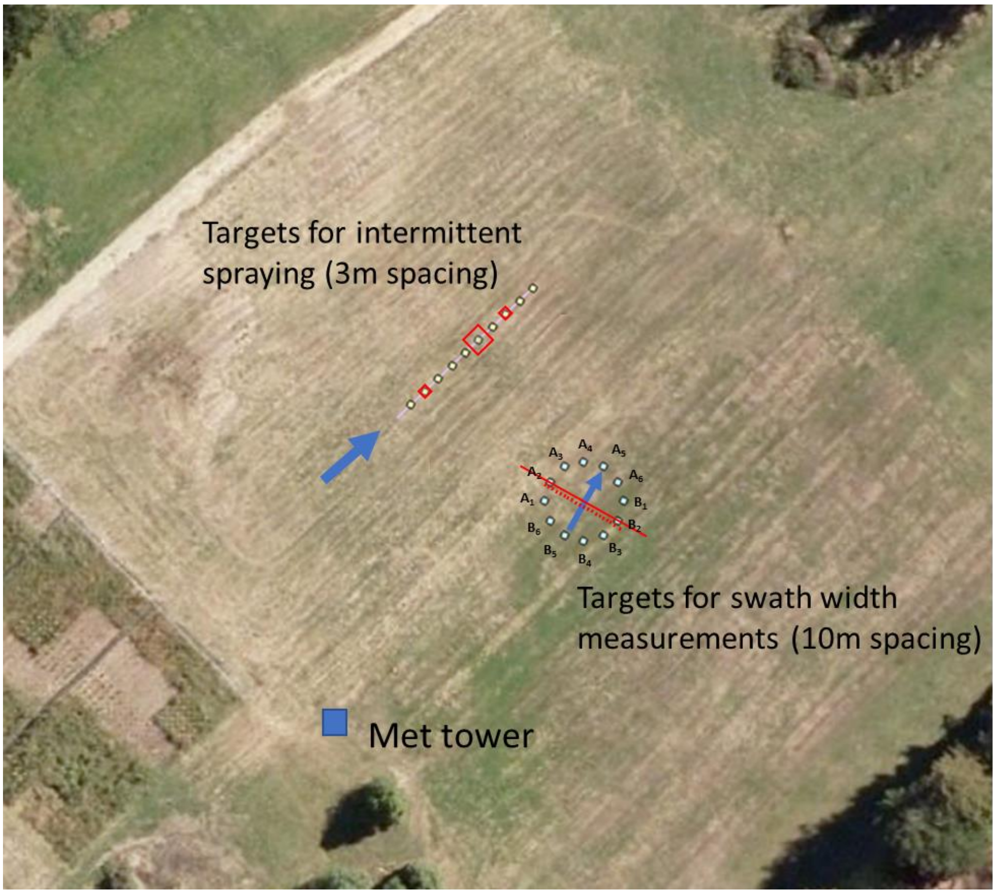

Figure 2. Trial site at Scion Rotorua. White circles indicate the GPS targets/waypoints provided. Blue arrows indicate flight paths taken for each operation. Red boxes and lines indicate sampling locations for those flightlines.

Swath pattern analysis: For the swath width distribution phase of the trial , a south to north flight line (A-B on Figure 2) was established and surveyed. Wind conditions were relatively stable throughout the trial, so the orientation of this line (roughly parallel to the wind) was not changed. A sampling line for measuring the swath pattern was set up perpendicular to the centre of the flight line.

Intermittent swath spraying in continuous flight: For testing the targeting efficiency of spraying simulated individual tree targets, 10 individual spots were surveyed and marked at 3 m spacing along a single line, thereby mimicking the spacing of individual trees in a single row (see Figure 2).

For an actual spot spraying operation, individual tree (post-plant spray) or spot (pre-plant treatment) locations would be needed to guide the aircraft. It is expected that these locations would be taken from a geo-referenced image or using existing data for situations where tree locations were recorded at planting. Hence, for each of these experiments the target locations were first pre-assigned using ARCGIS (Software version:3.1.2. Coordinate system: WGS 1984 Web Mercator (auxiliary sphere)) and then located at the trial site using an Arrow Gold GPS unit (model: Arrow

Gold®. supplier: EOS positioning systems inc). These coordinates were then provided to the spraying UAV. However, it became apparent that there was a scale error in the arrow Gold located GPS positions and those specified through ARCGIS, and the decision was made to manually record the previously marked target locations using the aircraft so that GIS/GPS mapping errors would not compromise the experimental data.

Key learning/outcome: A failsafe protocol should be developed to ensure positional information is consistently interpreted by different systems (GIS/GPS).

2.4 Characterising the swath width and distribution pattern

The effect of spray height (2 m and 3 m above the target) and droplet size (medium and very coarse) on the distribution of spray deposits across the swath delivered by the UAV was assessed by flying over a 15 m long 1.1 mm diameter cotton string collector (supplier: WRK of Arkansas) placed 50 cm above ground level and at 90 degrees to the flight direction (Table 1; Figure 3). For three replicates of each treatment, a line of 21 steel plate collectors were placed at 0.5 m spacing under the central 10 m of the string collector (Figure 3). The purpose of the steel plates was to provide quantitative data on spray deposits to calibrate the string data where the relationship between fluorescence (deposition) and collected spray volume can be influenced by droplet size [15] . Five secured cast-coated cards spaced 1 metre apart, were placed on wooden blocks under the string for droplet-size analysis. A spray dye tracer (2g/L pyranine, Ravenswood Australia) was used to detect spray deposits on the string (WRK string spectrometer, WRK of Oklahoma, Stillwater, OK, USA) and plates.

For each treatment, the craft flew south to north at 2 m/s spraying continuously for 10 m with an output of 16.2 mL per 1.5 m of forward flight (the nominal spot length). If this spray was all deposited within a swath width of 1.5 m the application rate within the swath would be 72 L/ha.

Table 1. Treatments for swath flights continuously spraying 10 m.

Treatment	Droplet size	Release height	Replicate flights
1	Medium	2 m	6
2	Medium	3 m	6
3	Very coarse	2 m	5
4	Very coarse	3 m	5

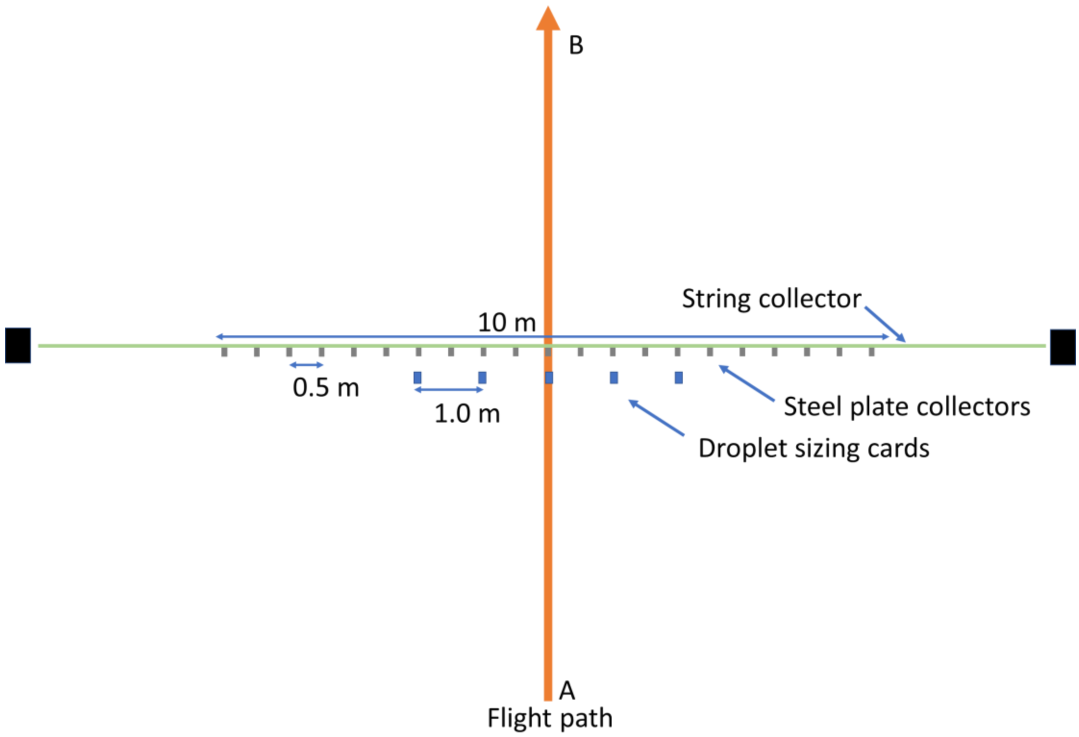

Figure 3. Sampling layout for swath patterning. Blue squares represent droplet size cards, orange squares represent stainless steel collector plates.

2.5 Characterising the intermittent swath spray targeting accuracy and deposit pattern

This experiment was originally designed to determine the accuracy and precision with which the UAV spray craft could apply a prescribed dose of spray to a series of ten pre-defined targets (1.5 x 1.5 m) representing young radiata pine with a typical spacing of 3 m within the planted row. Accuracy was defined by the proportion of total applied spray delivered within the target (spot treatment) area. Precision is the reproducibility of that dose application irrespective of accuracy. To test the precision and accuracy of the SPS spot spraying system, three sampling locations were selected out of the 10 target locations. To quantify spray deposition, an array of 17 steel plates at 0.5 x 0.5 m spacing, giving a sample area of 1.5 x 1.5 m, was established at two locations. A larger array of 81 plates, also at 0.5 x 0,5 m spacing, was established at one location giving a sampling area of 4 x 4 m area (Figure 4). For these spot spraying flights over the ground plate arrays, a 10 g/L tartrazine dye (Hawkins Watts Ltd. Penrose, Auckland 1642, NZ) solution was sprayed so that collected spray volumes could be determined by colorimetric analysis.

For this trial, only one treatment was applied, medium drops and a 2 m release height. This treatment was replicated 6 times. However, during the trial an extra treatment (Flight 4) was attempted to probe the optimal trigger point distance switching the sprayer on and off before and after the GPS waypoint (Table 2, see Section 3.6.4).

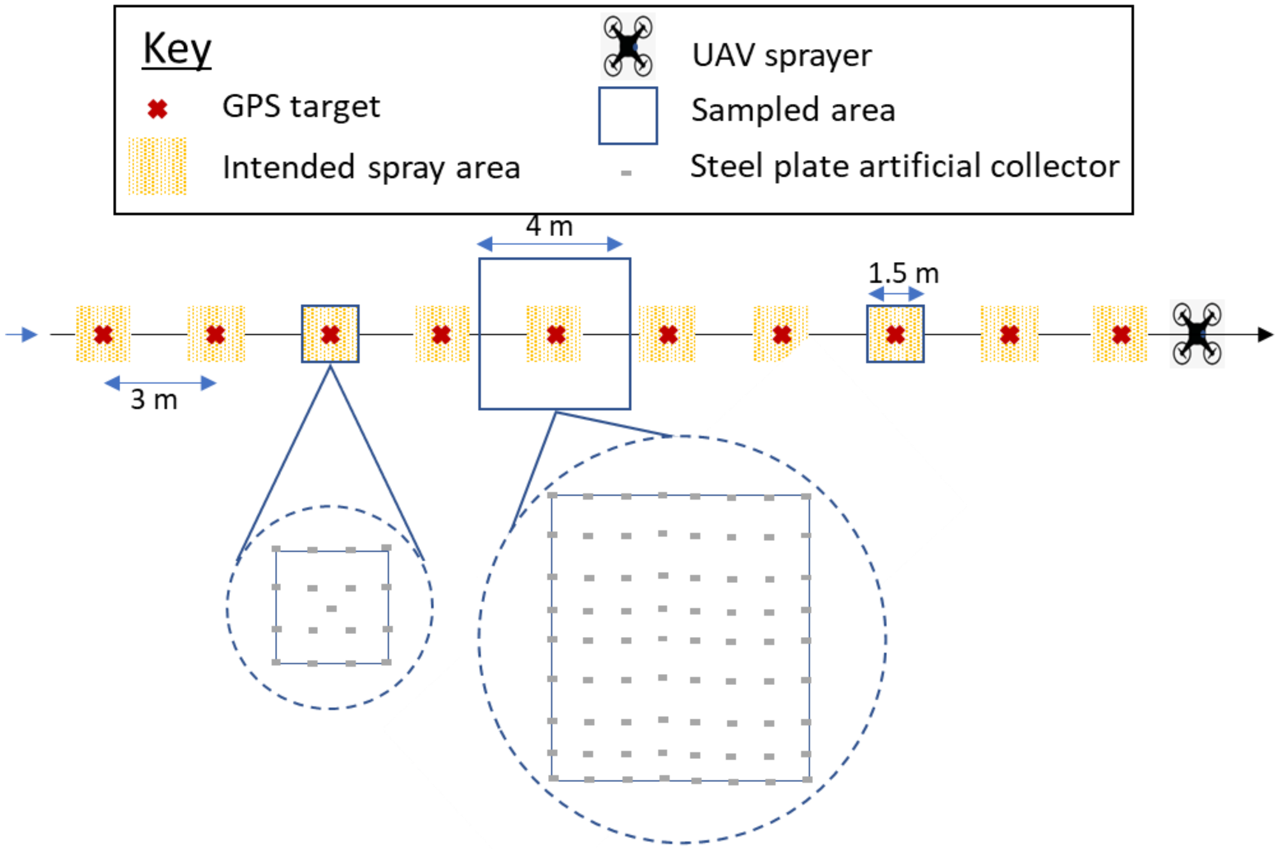

Figure 4. Sampling layout for the intermittent swath spraying patterning featuring 10 GPS assigned targets with two smaller 17 plate sampling arrays and a larger 81 plate sampling array.

Table 2. Treatments for intermittent swath spraying targets in continuous flight 10m

Treatment	Droplet size	Release height	Replicate flights	Trigger point on/off
1	medium	2 m	6	-0.75m/0.75m
2	medium	2 m	1	-0.5m/0.25m[ǂ]

ǂ estimated values.

2.6 Spray dye tracer quantification

For the swath width flights over the string collection system, and the plate lines, a 2 g/L pyranine solution was sprayed. To quantify spray deposition, 50 cm lengths of string were washed with 10 mL of 0.025% DuWett water, 125 µL of wash was buffered with 75 µL of Tris buffer. The sprayed steel plates were washed with 25 mL of 0.025% DuWett water, 160 µL of wash was buffered with 40 µL of Tris buffer. The Tris buffer (required for accurate quantification of pyranine (see [16]) was made by adding 0.1 M hydrochloric acid (36%, Ajax Chemicals) to 0.1 M Tris (hydroxymethyl)-methylamine (AnalaR Biochemical, BDH Chemicals Ltd) until a pH > 8.5 was achieved. The fluorescence of the buffered pyranine solutions was measured using a Varioskan LUX (Make: Varioskan LUX model: VLB00D0 supplier Thermo scientific) at 515 nm excitation and 460 nm emission wavelengths.

For the interment swath spraying flights, the plates were washed with 25 mL of 0.025% DuWett water and, the concentration of tartrazine dye determined by spectroscopic absorbance at 427 nm quantified using a Varioskan LUX (Varioskan LUX VLB00D0, Thermo scientific).

2.7 Data analysis

2.7.1 Quantifying the volume of spray delivered

Knowing the volume of spray delivered during an application is fundamental to estimating spray application efficiency (the proportion of applied spray landing in the target zone). Multiple methods were used to quantify the amount of spray delivered and the resulting distribution of spray deposits across the swath and within the spot from each flight.

1. During the flight the UAV recorded the flow rate through the pumps with impeller-based flow sensors as well as the duration of spray; total spray volume released is the product of these factors. **No calibration was undertaken to quantify the accuracy of these records, But SPS acknowledged that they will be working to improve these systems.**
2. Before and after each flight the craft was weighed to determine the total mass lost during the flight. The scale used was accurate to ± 0.02 kg or the equivalent of 20 mL.
3. The nozzle flow rates were manually calibrated prior to spraying and this data coupled with the target flight speed and spray line length or time sprayed can be used to estimate a theoretical application volume.

2.7.2 Swath pattern analysis

The volume of spray received by the plates (with dimensions of 0.152 m in the direction of flight and 0.076 m across the swath) during the swath pattern analysis experiments was assumed to be representative of deposition of the sampling area covered by each plate. Once deposition per unit area on each plate had been scaled to a sampling length of 0.5 m, total deposition across the swath was the sum of all interpolated plate values. Similarly, the volume of spray received by the string (with dimensions of 0.0011 m, or 1.1mm, in the direction of flight and continuous sampling across the swath divided into 0.5 m increments) was assumed to be representative of deposition of the sampling area covered by the string.

Because of potential collection efficiency issues, the relationship between string fluorescence and plate deposition data (amount per unit area) was calculated using linear regression. Using this relationship an estimate of total deposition was made by integrating estimated deposition data along each string line.

With deposition data from both of the above methodologies, spray deposit patterns across the swath were calculated and the following parameters estimated:

- Position of peak deposition relative to the flight line (aircraft centreline).
- Value of peak deposition (maximum dose delivered).
- Lane separation (or effective swath width / bout width) was calculated by overlapping the measured swath pattern with itself using different distances between overlaps, summing total deposition and calculating the coefficient of variation (CV) of summed deposition [17]. Lane separation was defined as the maximum lane separation producing a CV of 30% or less.
- Application efficiency, the total deposition integrated across the swath pattern compared to amount of spray released. Several different values of application efficiency were calculated based on:
    - total deposition across the swath;
    - deposition integrated across a width of 1.5 m centred on the location of peak deposition; and
    - deposition across a width of 1.5 m centred on the aircraft flight line.

Analysis of variance was used to test for treatment effects on these parameters.

2.7.3 Intermittent swath application

Spray deposition per unit area on steel plates was calculated for each array configuration (Figure 4). The amount of spray collected by each plate was interpolated to estimate spray deposition over the area (0.25m^2) represented by each plate. Application efficiency was calculated as total deposition within the target zone (i.e. the spot treatment area) as a proportion of the total amount of spray captured on the grid. It is more conventional and appropriate to define application efficiency as the total amount captured in the target zone as a proportion of the amount of spray released, but in this trial the actual amount released was unclear due to factors discussed later.

3.0 RESULTS

3.1 GPS target designation and navigation

Precision spraying using GPS positioning ideally requires sub-10 cm geo-positional accuracy. With its RTK base station the SPS Automation UAV should, in theory, have highly accurate and precise positioning. However, the observed flight lines for both experiments appeared ~-0.5 m west of the marked waypoint location(s). This observation is supported by the spray volume data where the centre of the spray distribution also appears to be offset by an average of about -0.5 m (west) from the nominal centreline (see Sections 3.5.3 and 3.6.4). For the swath pattern trial, the expected flight line was determined by the handheld Arrow Gold GPS Unit, which may have its own positional inaccuracies. However, for the intermittent swath spray line trial the points were marked manually on the ground and then identified and uploaded to the flight control computer by placing the craft at each target location. The flight control mode used has an acceptable positional error when flying to waypoints and in this trial the error is likely to be low due to the straight-line flight path. Observed flight line displacement (i.e. where the craft deviates to the right or left of the target waypoint or flight line) was attributed to an operation error where the RTK base station was calibrated after the GPS locations had been uploaded causing an approximate 0.5 m surveyed displacement from the initial data capture GPS calibration. According to the GNSS receiver catalogue [14], centimetre accuracy is expected should the target locations and the UAV position both be determined using properly calibrated RTK base stations.

Key learning/outcome: The true targeting accuracy cannot be determined from this trial, however, reproducible precision can be determined. Ensure time is taken to fully calibrate all GPS equipment before any operation preferably taking advantage of the recently launched SouthPan Network.

3.2 Droplet size

Cast-coated cards placed under the swath of the craft show that at 1800 RPM the volume median diameter (VMD) of droplets impacting the card averaged 508 μm with a relative span (RS) of 0.91, which is on the cusp of the extremely coarse size class droplets according to the American Society of Agricultural and Biological Engineers (ASABE) standard S572.1 [18] . The 3000 RMP treatment produced an average VMD of 219 μm with a RS of 1.1, within the threshold of being categorised as fine size class droplets ASABE standard S572.1 [18]. The smaller than expected smaller droplet size class may have resulted from flow rates lower than the requested value of 300 mL/min. Despite being fractional out of the size class intended these treatments will continue to be referred to by the target designation medium and very coarse throughout the remainder of this document.

3.3 Telemetry and communication

Due to internal communication errors between the micro-controller (performing the real time motor control for pumps etc) and the spray control computer, of the 29 missions flown, 22 swath and 7 intermittent spray missions, nine missions recorded no data (see (Appendix Tables A2 and A3).

Key learning/outcome: An explanation for the communication errors was not provided however SPS Automation will develop a more robust data logging system. Better sensors for determining flow rates are required.

3.4 Flow rate and volume delivered

During the flight the UAV recorded the flow rate through the pumps with impeller-based flow sensors (Appendix Tables A2 and A3). These flow sensors were not calibrated prior to the trial and SPS Automation do not know the relative sensitivity of the device. The volume sprayed provided in the flight log seems to be a multiplication from the duration of the spray (sec) and twice the flow rate (ml/sec). However, this is not an exact match, so the volume sprayed is not determined from one, or both, of these metrics but through some other method. Moreover, the flowrate should be multiplied by 4 to reflect the 4 nozzles hence the volume sprayed in the flight log is significantly different (paired t-test $P < 0.05$), roughly half that measured, compared to the mass lost or a quarter of the estimated volume sampled in the target zone by each of the sampling methods (Tables 6 and 8 below).

Key learning/outcome: Knowing the volume of spray delivered during the application is fundamental to estimating spray application efficiency. The craft flow rates sensors need to be improved and properly calibrated to give accurate information about volume released. For calibration trials a more accurate scale and weighting methodology would be preferable. SPS Automation are investigating direct pump speed control methods to determine flow rates.

3.5 Swath pattern experiment

3.5.1 Meteorological conditions

There were no significant differences ($P > 0.05$) in meteorological conditions experienced by any of the treatments (Table 3; also see Appendix 1 Table A1 for more details). Temperatures were very cool (7 to 8°C) and relative humidity remained moderate (72-73%), so evaporation rates would have been minimal for droplets released from the aircraft. Wind speeds were generally low and reasonably consistent with treatment means varying from 1.4 to 2.2 m/s and maximum gusts ranging from 1.8 to 2.8 m/s. Wind direction was also reasonably consistent with means ranging from southerly to south-westerly.

Table 3. Mean and standard deviation (in parentheses) for meteorological conditions experienced during spraying each of the four treatments.

Trt[1]	Release height (m)	Drop class	Wind speed (m/s)	Max wind speed (m/s)	Wind dirn[4]. (°)	RH[5] (%)	Temperature (°C)
1	2	Med[2]	1.4 (0.9)	1.8 (1.1)	177 (49)	73 (7)	8.4 (1.5)
2	3	Med	1.6 (0.7)	2.0 (0.8)	184 (75)	72 (7)	8.4 (1.3)
3	2	VC[3]	1.8 (0.8)	2.3 (1.1)	227 (68)	73 (6)	7.4 (0.7)
4	3	VC	2.2 (1.7)	2.8 (2.2)	177 (85)	72 (6)	7.6 (0.9)
		P-value:	0.66	0.60	0.63	0.99	0.40

Trt[1] = Treatment; Med[2] = Medium; VC[3]= Very Coarse; dirn[4] = direction; RH[5] = relative humidity

3.5.2 Flight log telemetry captured by the craft

Flight data were only recorded for 17 out of the 22 flights. From the recorded data, there were no treatment differences ($P > 0.05$) for the total spray volume applied, the duration of the application, the recorded altitude and the estimate of height above the ground from the range finder (Table 4; also see Appendix 1 Table A2 for more details). According to the spray system output, the mean spray volume released during each flight was consistent (47 – 50.3 mL) as was the duration of spraying (4.7 to 5.0 s). However, there was no independent measure to verify these numbers. Both the altitude above sea level (302-303 m) and the laser range finder data (2.6 m to 3.6 m) are measures of spray release height. With release height being one of the treatments, it was expected that the system would record a treatment difference for these variables. Given the variance in recorded measurements (Table 4), it is unclear whether the system was unable to maintain a consistent release height or whether the error in the instruments was simply larger than the requested accuracy for discriminating between these two treatments (2.0 vs 3.0 m). If the latter, it is of some concern given that these flights were over a flat grass surface, very different from the terrain challenges that will be faced during operational spot spraying in many forest environments.

Key learning/outcome: Further work and improved systems are needed to have confidence in aircraft output data and/or improve consistency of the flight/application.

Table 4. Mean and standard deviation (in parentheses) flight data recorded by the aircraft during spraying.

Trt[1]	Release height (m)	Drop class	Volume (ml)	Duration (s)	Altitude (m)	Height (m)	Flow rate (ml/min)
1	2	Med[2]	47.5 (1.5)	4.7 (0.1)	302.9 (1.3)	3.1 (0.3)	308 (6)
2	3	Med	48.1 (1.0)	4.7 (0.1)	303.1 (1.1)	2.9 (2.1)	320 (6)
3	2	VC[3]	50.3 (6.4)	5.0 (0.7)	302.0 (1.1)	2.6 (1.5)	297 (20)
4	3	VC	47.0 (1.0)	4.7 (0.1)	303.0 (1.1)	3.6 (2.0)	304 (20)
		P-value:	0.53	0.65	0.46	0.84	0.26

Trt[1] = Treatment; Med[2] = Medium; VC[3]= Very Coarse.

3.5.3 Swath patterns

Analysis to determine the relationship between plate deposition and string data to estimate total deposition is shown in Appendix 2.

Swath patterns were characterised in a range of ways including the position of peak deposition, the amount of recovered spray deposited within the +/- 0.75 m of the nominal centre line, and +/- 0.75 m of the position of peak deposition (see Appendix 1, Figures A1, A2 and A3 for plots of all swath patterns).

Position of Peak deposition (where 0 m is equal to the centre of the nominal flight line and displacements are represented by offsets in metres to east (+) or west (-)) was significantly influenced by the maximum crosswind vector (downwind displacement) ($P = 0.017$) and by drop size ($P = 0.039$), but not release height ($P > 0.05$) as follows:

For the Medium drop size: Peak position (m) = -1.122 + 0.255 x Maximum wind vector (m/s)
For the Very Coarse drop size: Peak position (m) = -0.494 + 0.255 x Maximum wind vector (m/s)

As expected, swath displacement is greater with the smaller droplet size. Assuming a very low wind speed and using a larger droplet size (less prone to displacement), swath displacement (off-set off nominal flight line) was still approximately 0.5 m indicating an offset of about -0.5 m in the nominal flight line position as discussed previously (Section 3.1).

The proportion of total deposition within a 1.5 m strip centred on the nominal flight line was relatively low (Table 5) for three of the four treatments ranging from 26 to 44%. However, there was significantly higher deposition (68%) with the larger droplet size and lower release height. This result probably reflects the expected reduced swath displacement with this latter treatment. There was no treatment effect on the proportion of total deposition within a 1.5 m strip centred on peak deposition (range from 62 to 70%) **indicating that if we could account for or reduce swath displacement, we would probably achieve a reasonable result for spot diameter. Nevertheless, it would be useful to evaluate whether different nozzles could tighten up the swath even more.**

Table 5. The proportion of deposited spray within a 1.5 m strip centred on either the nominal flight line or the position of peak deposition.

Trt[1]	Drop VMD (µm)	Height (m)	% Deposition within:	
			+/- 0.75 m from centreline	+/- 0.75 m from peak
1	220	2	25.9 (b)	65.8 (a)
2	220	3	30.3 (b)	62.1 (a)
3	500	2	68.1 (a)	70.2 (a)
4	500	3	44.0 (ab)	62.0 (a)

Means sharing common postscripts are not significantly different (LSD test, P >0.05)

3.5.4 Volumetric measurements

The mission parameters, 2 m/s flight speed and 10 m target zone, and the pre-flight flow rate calibration of 1296 mL/min (Section 2.2), predicts 108 mL should be delivered for each swath flight. Unfortunately, using a range of standard methods to measure and estimate the volume released by the craft during the mission/flight produced a wide variation in these estimates (Table 6). With such a variation and uncertainty over some of the values to use in the calculation, there is no basis for calculating true spray efficiency i.e. the amount of spray deposited in the target area as a proportion of the total amount of spray applied (as opposed to a proportion of the amount of spray deposited in the swath). **This result again highlights the need for better and/or more reliable output data for quality control purposes.**

Table 6. Volumetric assessments made by various assessment methods.

Trt[1]	Release height (m)	Drop size	Flight #	Vol by mass lost (± 20ml)ǂ	Telemetry data vol (ml)*	Vol estimated from string data (ml/15m)	Vol estimated from plate data (ml/10m)
1	2	Med[2]	10	120	49	215	213
			12	100		223	176
			14	120	47.5	219	
			16	120		137	
			18	500	46	75	
			22	100		143	125
2	3	Med	9	100		160	151
			11	100	49	233	112
			13	120	47	200	
			15	100		207	
			17	80	47.5	177	
			21	120	49	267	145
3	2	VC[3]	1	100	61.5	153	
			3	340	46.5	150	138
			5	100	48	140	127
			7	120	46.5	152	
			19	180	49	192	162
4	3	VC	2	140	47.5	151	196
			4	-100	46.5	163	
			6	40	46	185	139
			8	140	46.5	211	
			20	300	48.5	234	115

Trt[1] = Treatment; Med[2] = Medium; VC[3]= Very Coarse. ǂ Volume by mass lost estimated assuming 1 ml/g liquid density. Volumes in red are suspected errors in measurement or compromised spray runs. * telemetry data from Table A2, Appendix 1.

3.6 Intermittent swath spot spraying experiment

3.6.1 Meteorological conditions

Seven flights were completed, all using the medium drop size class and 2 m release height (note Flight 4 was conducted with different mission parameters to the other 6 replicate flights, see Section 2.5). Average wind speed during these flights ranged from 0.5 to 2.1 m/s with maximum wind speed showing a larger range from 0.7 to 4.0 m/s (Table 7). For most flights the wind direction was consistently blowing from south-western quadrant. However, the wind dropped significantly for the last 2 flights with the direction shifting to the north-eastern quadrant. Relative humidity remained high and temperature low during the application meaning than droplet evaporation would have been insignificant.

Table 7. Wind conditions for each swath flight. All flights conducted with medium droplet size class

Trt[1]	Height (m)	Drop size	Ft#[3]	Ave. wind speed (m/s)	Max wind speed (m/s)	Bearing		Humid. (%)	Temp. (°C)
						(°)	direction		
1	2	Med[2]	1	2.1	4.0	221	SW	83	5.4
			2	1.2	2.0	260	W	75	5.9
			3	1.6	2.6	241	WSW	73	6.3
			5	1.5	2.1	203	SSW	71	7.4
			6	0.5	0.7	32	NNE	88	5.2
			7	0.9	1.4	106	ESE	79	7.1
2	2	Med	4	0.9	1.4	292	WNW	70	7.2

3.6.2 Flight log telemetry captured by the craft

Flight log telemetry captured over the 7 flights again highlighted challenges with the instrumentation including no readings recorded for height from the range finder (see Appendix, Table A3).

3.6.3 Volumetric measurements

The mission parameters, 2m/s flight speed and ten 1.5 m target zones, and the pre-flight flow rate calibration, 1296 mL/min (section 2.1), predicts 16.2 mL should have been delivered to each target and 162 mL over flight spraying ten locations. Table 8 presents the results of various methods used to measure and estimate the volume released by the craft during the intermittent swath spraying mission/flight (Section 2.7.1). Two of the six replicate flights appear to be compromised. Flight 7 explicably had a much higher volume delivered across the flight (560 mL by weighing method). Flight 1 had a slightly lower volume 340 ml by mass lost. The telemetry data for flight 1 was highly unusual with only 5 waypoints recorded each with variable long spray durations and high volumes delivered (Appendix Table A4). Spluttering of the spray delivery was observed during flight 7 but not during flight 1. With such wide variation in estimates, there are no reliable figures for the total volume applied, so true application efficiency cannot be calculated.

Table 8. Volumetric measurements

Trt[1]	Height (m)	Drop size	Flight #	Vol by mass lost (± 20ml)ᵻ	Telemetry data vol (ml)*	Vol estimated from large plate array (ml)ɨ
1	2	Medium	1	340	192	333
			2	380		283
			3	380	133	373
			5	400	137	290
			6	400	127	330
			7	560		587
2	2	Medium	4	400		335

Trt[1] = Treatment. ᵻ Volume by mass lost estimated assuming 1 ml/g liquid density. Volumes in red are suspected errors in measurement or compromised spray runs. * Summation of telemetry data from table 8. ɨ Interpolated spray volume for measured at one location extrapolated for the 10 spot applications.

3.6.4 Intermittent swath spot pattern

There was variable deposition within the 1.5. m x 1.5 m target area ranging from 10 to 31% of the total spray captured (Table 9; Appendix 3, Figure A4 and A5). As noted previously, this percentage is not a true measure of application efficiency because there is not a reliable estimate of the actual amount of spray applied at each location. There was a significant increase in deposition in the 1.5. m x 1.5 m area centred – 0.5 m west of the target under the observed flight path of the craft (paired *t*–test P = 0.006, Table 9 vs 10). However, the average target deposition as a proportion of grid deposit was only 33.1%, well below what would be needed for an acceptable 'precision' application. While accuracy was poor, there was reasonable consistency in the results with a coefficient of variation (CV) of 30%. Reducing the spray on/off triggering points (treatment 2) appears to improve the precision to a more acceptable 57% (Table 10) although this is a single replicate. The spray captured by each 4 x 4 m sampling grid includes spray from adjacent target locations (see below) inflating the total volume captured and reducing the relative % of total spray captured by the target area. Therefore, treatment 2's reduced swath length will also reduce the spray captured from the adjacent target applications improving the relative % of total spray captured by the target area. The smaller 1.5 m x 1.5 m sampling grid data (Figure 4, section 2.5) received similar absolute volumes 15 mL (26% CV), however, there is no way to determine the relative percentage volume deposited without a reliable estimate of the volume applied.

If the target grid is extended to 2.5 m (Table 9 and 10), the proportion of deposited spray captured in this area increased, as expected and ranges from 37 to 63%. If this area was centred under the flight path of the craft these values increase a small but significant 2.5% (paired *t*–test P = 0.03, table 9 vs 10). However, 43% of the spray received by the 2.5 m x 2.5 m area is outside the 1.5 m x 1.5 m targeted area. This 2.5 m x 2.5 m area is 1 m from the adjacent spray areas, hence should be less compromised by overspray from the adjacent applications. Clearly further work is needed to improve the accuracy of targeting.

Table 9. Summary statistics for deposition on 4 x 4 m grids (centred on grid centre)

Trt[1]	**Flight #**	**Grid total deposit (ml)**	**Volume deposited in 1.5 x 1.5 m spot**		**Volume deposited in 2.5 x 2.5 m spot**	
			mL	**% of grid total**	**mL**	**% of grid total**
2	*4*	*33.5*	*11.0*	*32.8*	*26.4*	*78.8*
1	1	33.3	3.4	10.1	12.2	36.5
	2	28.3	6.5	23.0	14.5	51.1
	3	37.3	11.7	31.4	22.8	61.2
	5	29.0	7.4	25.4	18.2	62.7
	6	33.0	6.4	19.4	19.6	59.6
	7	58.7	14.0	23.9	36.2	61.7
			Mean*	**22.2**		**55.5**
			SD	**7.1**		**10.2**
			CV (%)	**32.0**		**18.4**

Trt[1] = Treatment. * Summary statistics exclude treatment 2.

Table 10. Summary statistics for deposition on 4 x 4 m grids (centred on flight path)

Trt[1]	Flight #	Grid total deposit (ml)	Volume deposited in 1.5 x 1.5 m spot centred on flight path (-0.5 m west)		Volume deposited in 2.5 x 2.5 m spot centred on flight path (-0.5 m west)	
			mL	**% of grid total**	**mL**	**% of grid total**
2	*4*	*33.5*	19.1	56.9	26.8	79.9
1	1	33.3	4.5	13.6	13.1	39.3
	2	28.3	9.2	32.5	16.2	57.2
	3	37.3	14.5	38.9	22.6	60.6
	5	29.0	11.0	37.8	18.6	64.1
	6	33.0	11.9	36.0	20.3	61.5
	7	58.7	23.4	40.0	38.3	65.3
			Mean*	**33.1**		**58.0**
			SD	**9.9**		**9.6**
			CV (%)	**29.9**		**16.5**

Trt[1] = Treatment. * Summary statistics exclude treatment 2.

Data from the large sampling grid showed clear evidence of overspray from adjacent plots caused by the large craft footprint and the spray triggering system (Appendix 3). The larger than desired footprint (zone of spray deposition) is a result of the lack of independent control for rear and front nozzles. All nozzles are triggered when the front nozzles reach the edge of the target zone. At this point, the rear nozzles are still ~1 m away from the target zone (Figure 5). Similarly, the front nozzles continue to spray beyond the target area until the GPS unit reaches the off waypoint. Spray is deposited the entire 4 m length of the sampled area with peaks, apparently from adjacent targets, at the beginning at end of the sampling zones (Figure 6). The adjacent target areas are only 0.25 m from the edge of the 4 m by 4 m sampling area. This means the total spray captured metric used to assess the targeting accuracy was compromised. The effect of reducing the distance of the triggering waypoints to the GPS target was to reduce the encroachment of spray from the adjacent plots (Flight 4, Appendix 3, Figure A4). This also increased the volume of spray delivered to the target area, due to the lower flight speed and tightening of the longitudinal deposition profile (Tables 9 and 10).

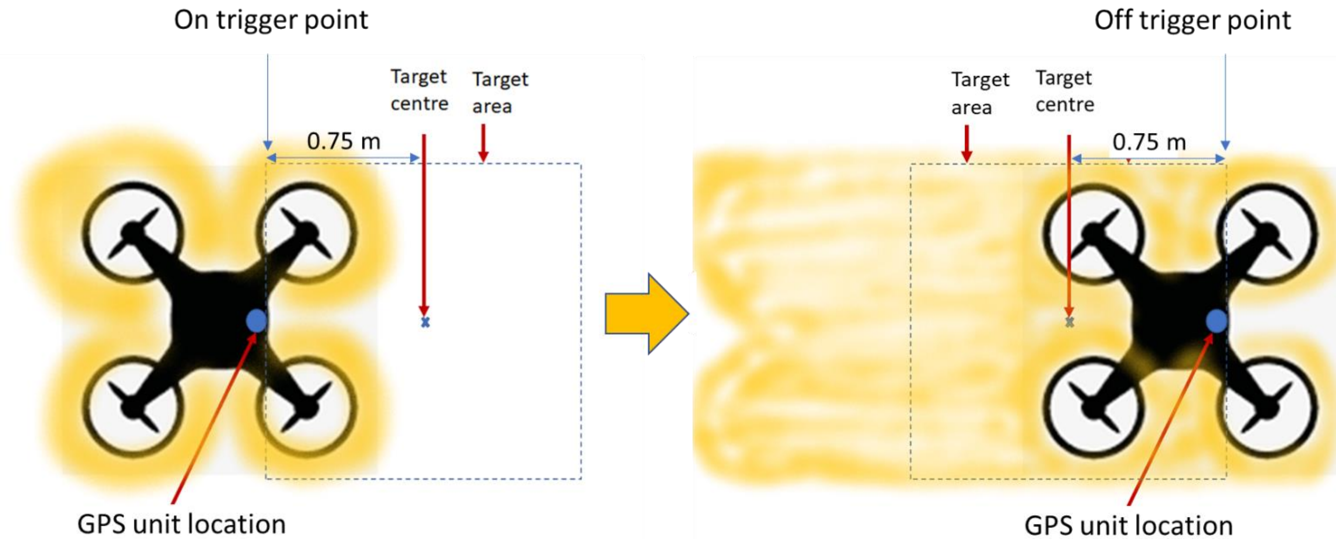

Figure 5. Depiction of the off-target spray caused by the footprint of the UAV and the location of the GPS unit relative to the trigger waypoint

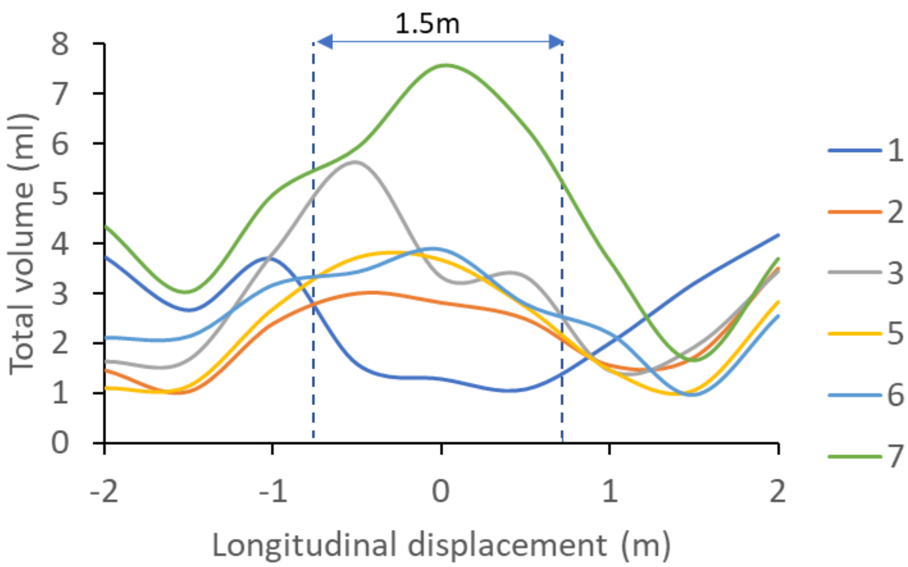

Figure 6. Average volume delivered across the full width (4 m) of the large plate array in the longitudinal direction parallel to the direction of flight. The dotted lines indicate the 1.5 m target length (vertical lines).

Key learning/outcome: Independent control of the rear and front nozzle is ideal in a future system to enable higher precision application of spray to the target zone.

The craft produced a clear bimodal pattern in the horizonal direction perpendicular to the line of flight, presumably under each line of nozzles (Figure 7), which was not as apparent from the string collector swath data. The calculated centre of spray mass (data not shown) averaged over all flights and sample zones is displaced 0.5m west, at the coordinates (0, -0.5). It is possible that the bimodal distribution is because the deposit pattern does not have time to develop fully with the rapid switching of spray on and off.

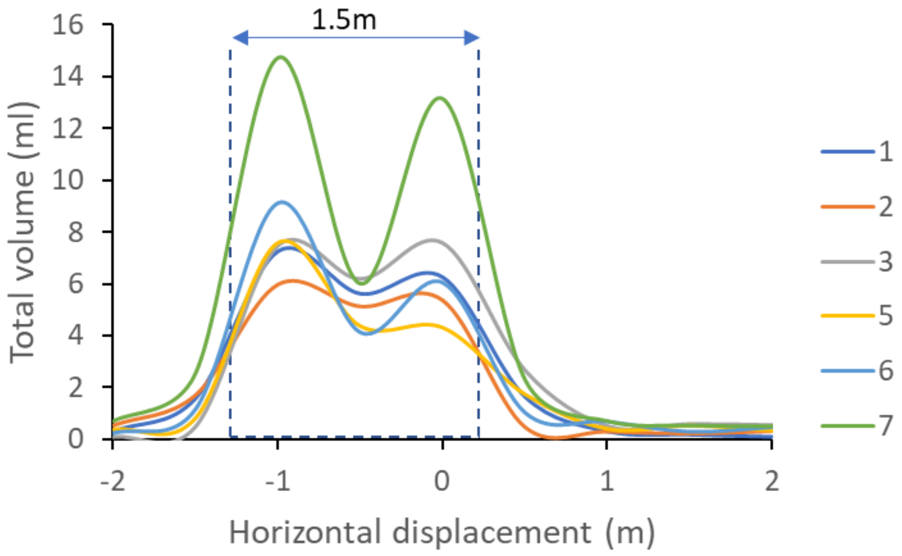

Figure 7. Average volume delivered across the full length (4m) of the large plate array in the horizontal direction perpendicular to the direction of flight. The dotted lines indicate the 1.5m target width (vertical lines).

Key learning/outcome: Sprayer set up could be improved to produce a more uniform spray deposition across the target area.

4.0 DISCUSSION

4.1 Waypoint navigation and flight speed

To achieve a commercially viable UAV-based spot spraying platform, there is a need to ensure the system operates with the maximum practical forward speed that allows accurate targeting of the application. As a starting point, the goal is to achieve accurate targeting with a ground speed of 2 m/s. One challenge is that all standard UAV flight control waypoint navigation systems require a craft to slow at a waypoint. In this case each target tree, and then accelerate to the determined operational speed between waypoints. Due to the proximity of the on-off waypoints in an intermittent swath spraying situation, as tested here, the UAV did not have time to accelerate to spraying speed before reaching the off-waypoint. Hence, the plots were flown with variable speed and less than the prescribed 2 m/s. Constant acceleration and deceleration significantly increases operational energy demands, reducing flight time, increasing fuel consumption. Moreover, when the acceleration and deceleration occur during spraying, the deposit pattern in the direction of flight is a gradient reflecting the variable flying speed, unless the flow rate could be adjusted to match the speed. While this is technically possible, and many helicopter spraying systems already adjust output to match flying speed, adjusting the flow rate of hydraulic and CDA nozzles will alter the droplet size produced. Any future systems will need to have well developed relationships between flow rate and droplet size, as well as reliable independent systems and software for measuring flow rate to make adjustments to achieve a constant application rate unless a constant flying speed can be confidently achieved. There are technologies that enable modification of flow rate without altering droplet size, but a simpler solution is to fly at a reliably constant speed.

Key learning/outcome: As a result of this trial SPS Automation are developing trajectory-based navigation control anticipated to be more flexible, accurate and suited to NZ's unique terrain and intended usage. Future systems require the ability to adjust flow rate and maintain droplet size in situations where flight speed may vary.

4.2 Altitude control

The craft has three methods to determine altitude, an internal thermally stabilised barometer, a laser range finder and the GPS unit. During these flights the barometer was used to control the height. This method of control provides a steady release height however does not track the contours of the terrain. For this trial, over flat terrain there would, in theory, be minimal difference between the two methods, however, most forestry scenarios have undulating terrain where the craft must be flown with a range finder height control. Range finder height control failed over steep terrain and with the craft pitching forward in flight during the previous trial at Glenlyon station (Hartley et al., 2023). In the current trial there was little agreement in height estimates between the various systems so further work is needed to ensure the functionality and accuracy of whatever height measurement system is finally adopted for the production craft.

Key learning/outcome: The altitude control must be fit for purpose to accurately maintain the release height over flat or undulating terrain. To allow proper accountancy of the spray operation the flight logs must accurately record the height above ground/target.

4.3 Swath pattern experiment

4.3.1 Peak deposition and effective swath width

An ideal precision spray would deliver an even volume/dose of product over the target area with minimal off target spray. The proportion of applied spray deposited within +/- 0.75 m of the peak demonstrates the potential efficiency of a spray application if any swath displacements effects can either be accounted for or eliminated. All the treatments produced a very similar average spray pattern, spray distribution and peak deposition, when each replicate distribution is centred on the peak i.e. representing the optimal application efficiency achievable (Figure 8). The current spray craft and spray system configuration therefore has the potential to deliver ~69% of the total applied spray into the target zone (1.5 m wide area) with 85% depositing in a 3-4 m span (average of all treatments). In reality, there was significant swath displacement due to both a crosswind component and an error in flight line positioning. While the latter can be 'easily' corrected, the former can be minimised by factors such as reducing flying height (2 m rather than 3 m) and considering larger droplet sizes. With the herbicide mixes used for spot treatments, it is unlikely that efficacy would be significantly reduced by using larger droplet sizes especially if taking that path increased total deposition within the target zone. While it may be possible to account for swath displacement by offsetting the aircraft position as a function of meteorological measurements in real time, the first step should be to get a basic system functioning and operationalised.

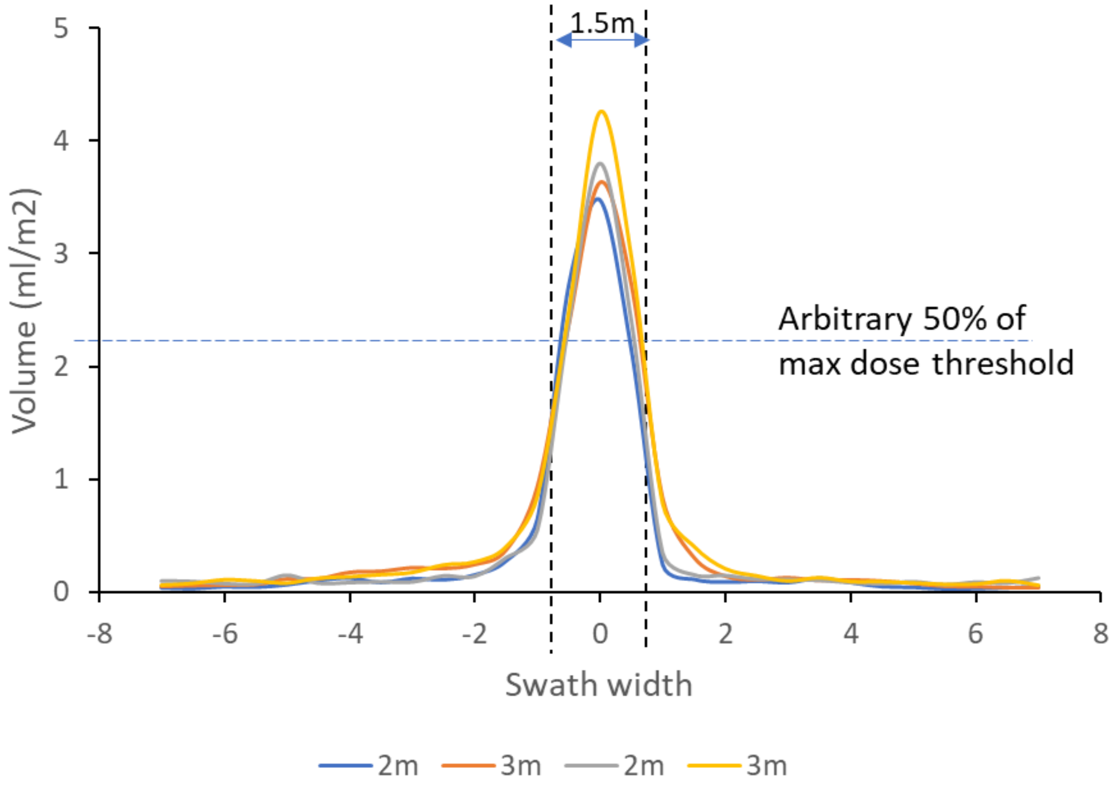

Figure 8. Average swath pattern produced by each treatment (Experiment 1). The dotted lines indicate the 1.5 m target width (vertical lines) and the arbitrary 50% threshold of the maximum dose (horizontal line) where the efficacy is deemed to be too low.

Key learning/outcome: Methods to deliver a narrower more uniform swath and to minimise swath displacement effects need to be investigated. Options for achieving this aim include modifying the nozzle type (droplet size), nozzle placement, or factors such as release height.

4.4 Intermittent swath spray targeting accuracy and deposit pattern

4.4.1 Spray triggering points and spray craft footprint

For this experiment the mission had a line of ten spray targets at 3 m spacing with a desired release area of 1.5 m by 1.5 m around each target. This leaves a 1.5 m "unsprayed" non target gap between the target areas. The width of the area released is determined by the swath width, as measured and described in the swath experiment, and the length of the area released is a function of nozzle on and off points, the aircraft speed, meteorological conditions and factors such as spray release height. The length of the applied spray area was determined by waypoints programmed at a set distance before and after the target GPS to trigger the spray unit on and off. Other methods could be used, for example spray for a fixed duration after triggering. For six of the seven intermittent swath flights the craft was set to turn spray on 0.75 m before the target and off 0.75 m after (Table 2) which should deliver a 1.5 m long swath. However, it was observed that, due to the large footprint of the craft, the nozzles at the rear of the craft are triggered ~1 m before the target area as the craft triggers when the GPS unit reaches the on waypoint. Similarly, the front nozzles continue to spray beyond the target area until the GPS unit reaches the off waypoint (Figure 6). This approach results in the applied dose being spread of a much larger area than the actual 1.5 x 1.5 m target zone. For even coverage the UAV needs independent control of the front and rear nozzles, with each pair switching on and off as they pass into or exit from the target zone.

Key learning/outcome: Waypoint navigation needs to be adapted so that the flight speed remains consistent irrespective of waypoint spacing or location. Independent control of front and rear nozzles is needed so that spray is only released within the target zone.

5.0 CONCLUSION AND RECOMENDATIONS

This trial tested the operational readiness of the SPS Automation developed Aeronavics ICON heavy-lift multirotor spray craft. Even under the relatively simplistic conditions trialled, light wind and flat terrain, the craft did not perform to the standard required for operational spot spraying. Nevertheless, the challenges identified should be relatively straightforward to overcome with appropriate modifications and testing. A high number of replicate flights were compromised by inaccurate flying and uncertainty over some of the key variables such as spray output. The spray pattern produced by the craft was too broad (> 1.5 m), reducing the effective dose achieved in the target area.

This trial has identified a number of areas that could be, or should be, improved including; better integration of externally supplied GPS locations, improved spray system reliability, developing waypoint navigation systems capable of maintaining a consistent flight speed >2m/s, engineering higher flow rate pumps and nozzle systems calibrated to deliver prescribed droplet size, modifying the spray system rand/or application method to produce a boarder more uniform swath spray distribution, engineering the spray system to actuate forward and aft nozzles independently, employ terrain tracking height control systems, improve telemetry data capture and recording/communication reliability, develop more accurate calibrated flow sensors, and instigating operational protocols to calibrate the craft and RTK base station. To allow adequate auditing of the spray operation the flight logs should record accurate telemetry for each spray location that includes ~10 cm accurate GPS location of spray target, current time, flow rate and spraying duration (volume delivered), release height and flight speed. All of this could be part of a fit for purpose forestry centric software platform aligned with the UAV system.

Specific learnings and outcomes from the trial are summarised below.

- Higher flow rate pumps and improved CDA (or other) nozzle technology are needed to achieve the target application rate while maintaining droplet size control. Ideally the spraying system will reliably record actual flow rates and disc rpm achieved with each nozzle during the application, as well as all other telemetry data.

- Systems for spray release height control must be fit for purpose and accurately maintain release height even over undulating terrain. To allow proper accountancy of the spray operation the flight logs must accurately record the height above ground/target.

- Improved protocols are needed to ensure GPS waypoints and navigation systems are aligned and that the aircraft systems will actually navigate to the required points with a high level of accuracy. Taking advantage of the recently launched SouthPan Network should improve GPS accuracy.

- As a result of this trial SPS Automation is developing trajectory-based navigation that should maintain a steady ground speed between. Future systems require the ability to adjust flow rate and disc rpm to maintain droplet size in situations where flight speed may vary.

- Knowing the volume of spray delivered during the application is fundamental to estimating spray application efficiency. The craft flow rates sensors need to be improved and properly calibrated to give accurate information about volume released. SPS Automation are investigating direct pump speed control methods to determine flow rates.

- Alternative droplet sizes and possibly nozzle spacing / release height combinations need to be investigated with the aim of increasing the proportion of applied spray delivered within the 1.5 m x 1.5 m target zone.

- The spray on/off system would be redesigned with independent control for the front and rear nozzles. This approach would allow the front and rear nozzles to turn on and off at the same location (rather than the same time).

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APPENDICES

Appendix 1: Additional Data

Table A1. Wind conditions for each swath flight

Release ht (m)	Drop size	Flt #	Plate line	Ave. wind speed (m/s)	Max wind speed (m/s)	Bearing (°)	Direction	Humid. (%)	Temp. (°C)
2	Very coarse	1	N	1.3	1.5	201	SSW	69	7.5
		3	Y	2.2	3.2	271	W	71	7.6
		5	Y	2.4	2.9	295	WNW	71	7.7
		7	N	2.6	3.2	243	SW	69	8.2
		19	Y	0.7	0.9	123	ESE	83	6.2
3	Very coarse	2	Y	0.6	0.9	135	SE	69	7.7
		4	N	2.4	3.0	244	WSW	71	7.7
		6	Y	4.3	5.9	226	SW	68	8.0
		8	N	3.3	3.8	234	SW	69	8.3
		20	Y	0.4	0.6	47	NE	83	6.1
2	Medium	10	Y	1.3	2.1	177	S	68	8.9
		12	Y	2.4	2.6	209	SSW	69	9.1
		14	N	2.3	3.1	211	SSW	69	9.2
		16	N	1.8	1.9	229	SW	70	8.8
		18	N	0.4	0.6	132	SE	72	8.7
		22	Y	0.2	0.3	106	E	87	5.4
3	Medium	9	Y	2.5	2.7	229	SW	69	8.7
		11	Y	1.7	2.3	237	SW	68	9.0
		13	N	2.3	2.9	218	SSW	69	9.2
		15	N	1.6	1.9	192	SW	70	9.0
		17	N	1.0	1.5	193	S	72	8.8
		21	Y	0.7	0.9	35	NE	86	5.7

Table A2. Telemetry from the swath pattern flights where records were saved (17 out of 22)

Ft#	Trt id	Vol. (ml)	Duration (sec)	Latitude	Longitude	Altitude	Range finder (m)	Time m/s/ms	Flow rate (ml/min)
1	56	61.5	6.19	-38.1571	176.2707	303.03	3.59	23:58.8	302
2	57	47.5	4.75	-38.1571	176.2707	303.09	4.42	39:44.2	309
3	58	46.5	4.66	-38.1571	176.2707	301.51	3.57	52:31.4	286
4	59	46.5	4.68	-38.1571	176.2707	302.82	4.77	07:05.0	273
5	60	48	4.76	-38.1571	176.2707	301.91	3.28	16:38.8	268
6	61	46	4.64	-38.1571	176.2707	303.47	4.51	32:10.0	296
7	62	46.5	4.67	-38.1571	176.2707	303.2	2.67	47:57.3	319
8	63	46.5	4.78	-38.1571	176.2707	304.41	4.29	54:15.1	323
10	64	49	4.79	-38.1571	176.2707	302.14	3.21	37:21.4	303
11	65	49	4.80	-38.1571	176.2707	303.61	4.41	51:24.8	327
13	68	47	4.69	-38.1571	176.2707	303.64	2.54	15:33.3	313
14	69	47.5	4.76	-38.1571	176.2707	304.42	2.83	25:29.4	315

17	70	47.5	4.77	-38.1571	176.2707	303.65	4.54	01:02.5	320
18	75	46	4.65	-38.1571	176.2707	302.06	3.4	10:24.5	305
19	129	49	4.63	-38.1571	176.2707	300.33	0	56:43.2	309
20	130	48.5	4.71	-38.1571	176.2707	301.39	0	07:27.1	319
21	140	49	4.63	-38.1571	176.2707	301.44	0	21:50.6	319

Note: Fields provided in the data log, but not presented in this table, include Automated (flight: true or false), Mission note, Active note, Spray note, and Drone armed (true or false). Flight number was not part of the flight log but could be manually imputed into mission or active note.

All swath pattern data

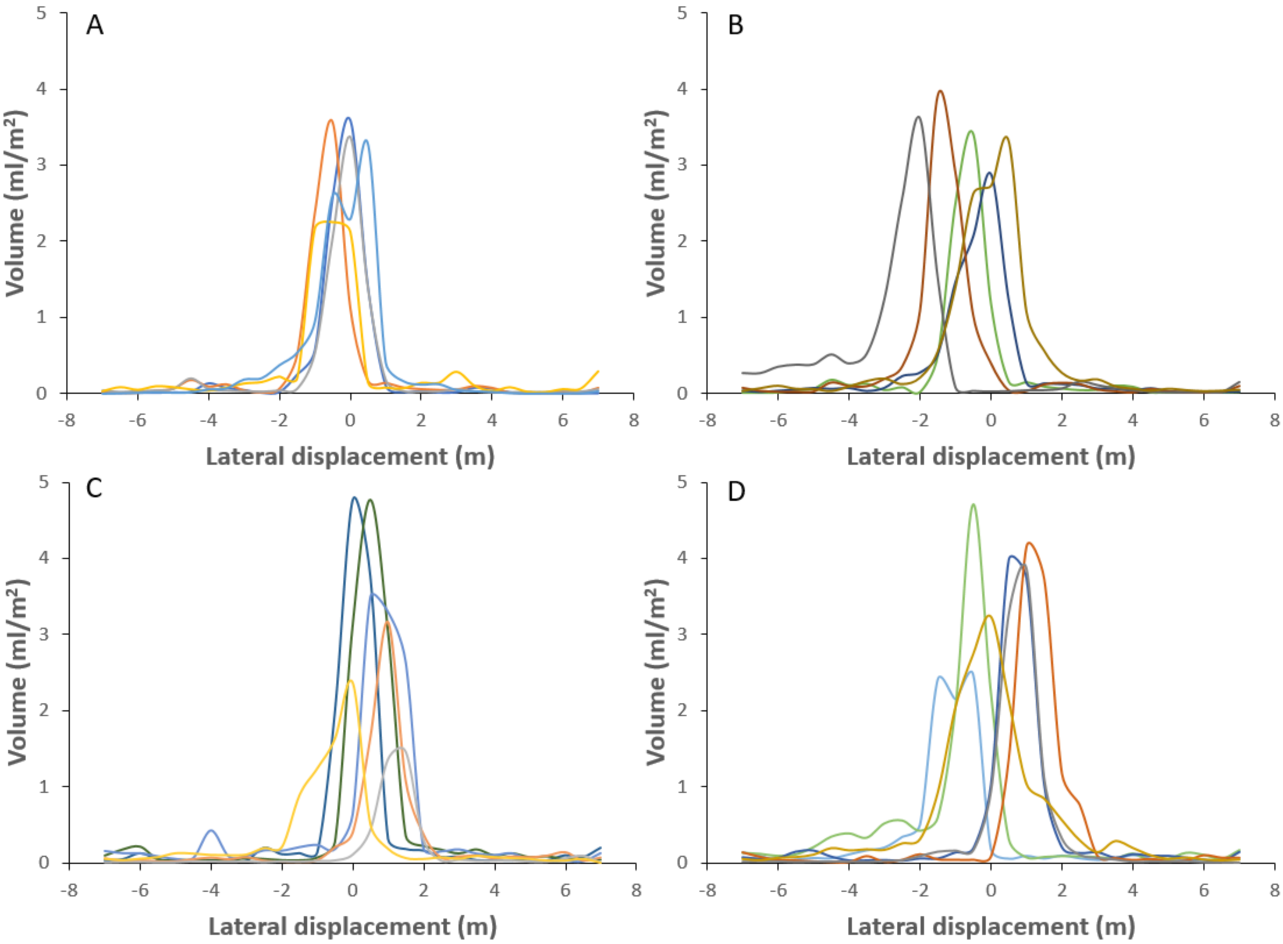

Figure A1. Overlayed spray swath displacement of each flight replicate for each treatment; A) Very coarse droplets at 2m release height B) Very coarse droplets at 3m release height, B) Medium droplets at 2m release height and D) Medium droplets at 3m release height.

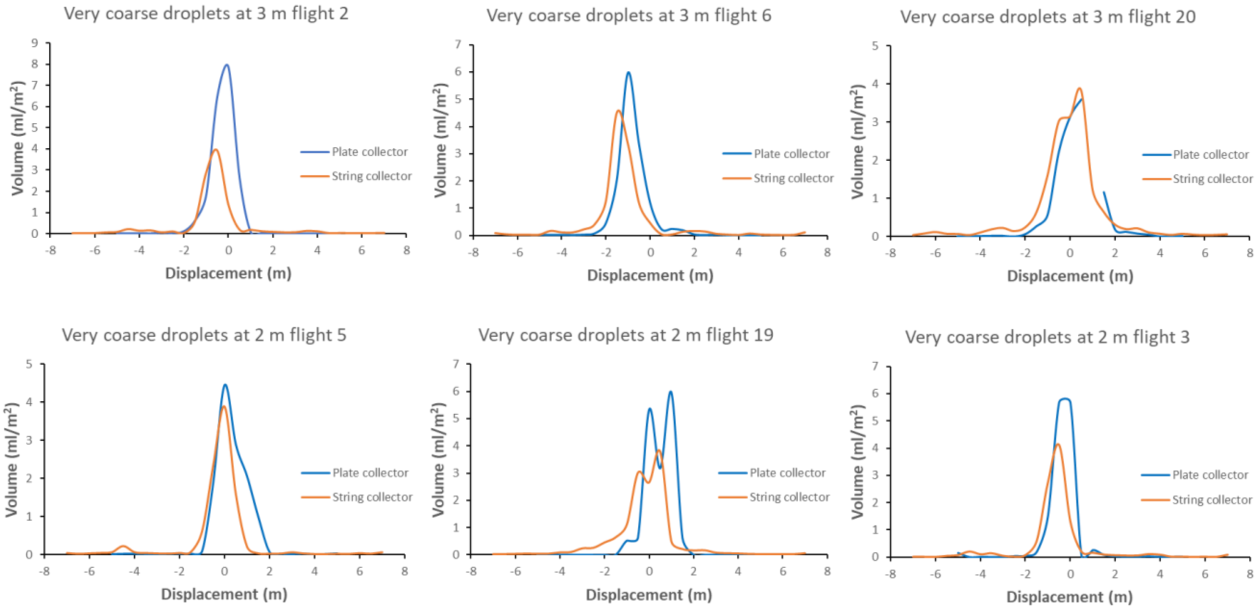

Figure A2. Plate and string swath deposition patterns for the very coarse droplet spectrum of each flight replicate at 2m and 3m release height.

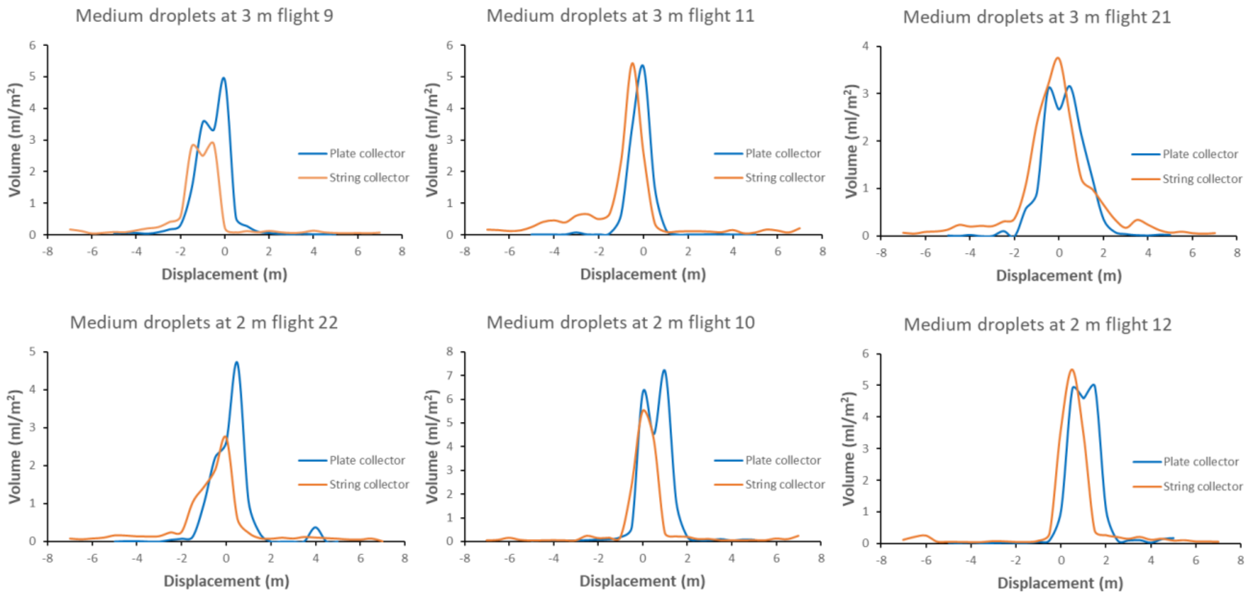

Figure A3. Plate and string swath deposition patterns for the medium droplet spectrum at 2m and 3m release height of each flight replicate at 2m and 3m release height

Table A3. Telemetry from the 7 intermittent swath application flights each targeting 10 waypoints

Ft#	Trt id	Vol. (ml)	Duration (sec)	Latitude	Longitude	Altitude	Range finder (m)	Time m/s/ms	Flow rate (ml/min)
1	-64	56.5	5.525266	-38.1572	176.2704	301.06	0	11:35.9	351
1	-65	36.5	3.194196	-38.1572	176.2704	300.72	0	11:49.3	347
1	-66	50	4.264428	-38.1572	176.2704	300.54	0	11:59.1	357
1	-67	23.5	2.152001	-38.1572	176.2704	300.75	0	12:41.5	328
1	-68	25.5	2.437805	-38.1572	176.2704	300.8	0	12:45.2	342
3	-69	13	1.450199	-38.1571	176.2705	299.81	0	22:52.7	306
3	-70	13.5	1.429811	-38.1571	176.2705	299.8	0	22:56.0	359
3	-71	13.5	1.429801	-38.1571	176.2706	299.8	0	22:59.0	324
3	-72	13.5	1.42928	-38.1571	176.2706	299.8	0	23:02.2	333
3	-73	13	1.44983	-38.157	176.2706	299.8	0	23:05.4	345
3	-74	13	1.410139	-38.157	176.2706	299.79	0	23:08.6	326
3	-75	13	1.429462	-38.157	176.2706	299.81	0	23:11.8	330
3	-76	13	1.449934	-38.157	176.2707	299.81	0	23:14.9	322
3	-77	14	1.449475	-38.157	176.2707	299.8	0	23:18.1	333
3	-78	13	1.429442	-38.1569	176.2707	299.85	0	23:21.4	345
5	-79	20.5	2.035667	-38.1572	176.2704	297.85	0	12:54.6	337
5	-80	13.5	1.451285	-38.1571	176.2705	299.8	0	13:29.1	293
5	-81	13	1.430652	-38.1571	176.2705	299.82	0	13:32.3	320
5	-82	14	1.431441	-38.1571	176.2706	299.81	0	13:35.4	341
5	-83	13.5	1.431534	-38.1571	176.2706	299.82	0	13:38.4	333
5	-84	14	1.431247	-38.157	176.2706	299.83	0	13:41.8	318
5	-85	13.5	1.451803	-38.157	176.2706	299.83	0	13:45.0	337
5	-86	14	1.431339	-38.157	176.2706	299.82	0	13:48.1	322
5	-87	13.5	1.430881	-38.157	176.2707	299.83	0	13:51.4	346
5	-88	14	1.430024	-38.157	176.2707	299.81	0	13:54.6	332
5	-89	14	1.4507	-38.1569	176.2707	299.88	0	13:57.8	313
6	-90	12.5	1.440069	-38.1571	176.2705	299.88	0	37:44.5	314
6	-91	12.5	1.408378	-38.1571	176.2705	299.86	0	37:48.1	311
6	-92	12	1.341285	-38.1571	176.2706	299.87	0	37:51.2	326
6	-93	12	1.335115	-38.1571	176.2706	299.88	0	37:54.4	325
6	-94	13.5	1.319487	-38.157	176.2706	299.87	0	37:57.6	341
6	-95	13	1.299409	-38.157	176.2706	299.88	0	38:00.8	323
6	-96	13	1.318882	-38.157	176.2706	299.88	0	38:04.0	329
6	-97	13	1.299242	-38.157	176.2707	299.87	0	38:07.2	315
6	k-98	13	1.299145	-38.157	176.2707	299.88	0	38:10.4	337
6	-99	12.5	1.28459	-38.1569	176.2707	300.01	0	38:13.6	320

Note: Flight number was not part of the flight log but could be manually imputed into mission or active note.

Appendix 2- Estimation of total deposition for swath pattern analysis

Correlating deposition data from plates, expressed as deposition per unit area, with string fluorescence values enables conversion of the string data into similar units. As expected, there was a strong, linear correlation between string fluorescence values and plate data, but the relationship changed slightly with treatment factors. There was a significant effect of height ($P = 0.009$) and interactions between height x fluorescence ($P = 0.002$) and height x drop size ($P = 0.008$) with an overall adjusted-R^2 of 91%. It is expected that any factors that change the average angle of approach to a 3-dimensional collector (string) will also change collection efficiency [19] Based on the regression model, the following models were used to convert fluorescence data to deposition values. The following relationships (Figure 5) were used to convert fluorescence to deposition in mL with both the fluorescence values and deposit data scaled to represent a sampling zone of 0.5 m across the swath and 1 m of forward flight (i.e. 0.5 m^2).

Height = 2 m, Drop = Very Coarse: Deposition (ml/0.5m2) = -0.00820 + 0.000014 x Fluorescence.
Height = 2 m, Drop = Very Coarse: Deposition (ml/0.5m2) = -0.02119 + 0.000013 x Fluorescence.
Height = 3 m, Drop = Medium: Deposition (ml/0.5m2) = -0.04186 + 0.000012 x Fluorescence.
Height = 3 m, Drop = Medium: Deposition (ml/0.5m2) = -0.01012 + 0.000011 x Fluorescence.

Appendix 3 - Intermittent swath spraying

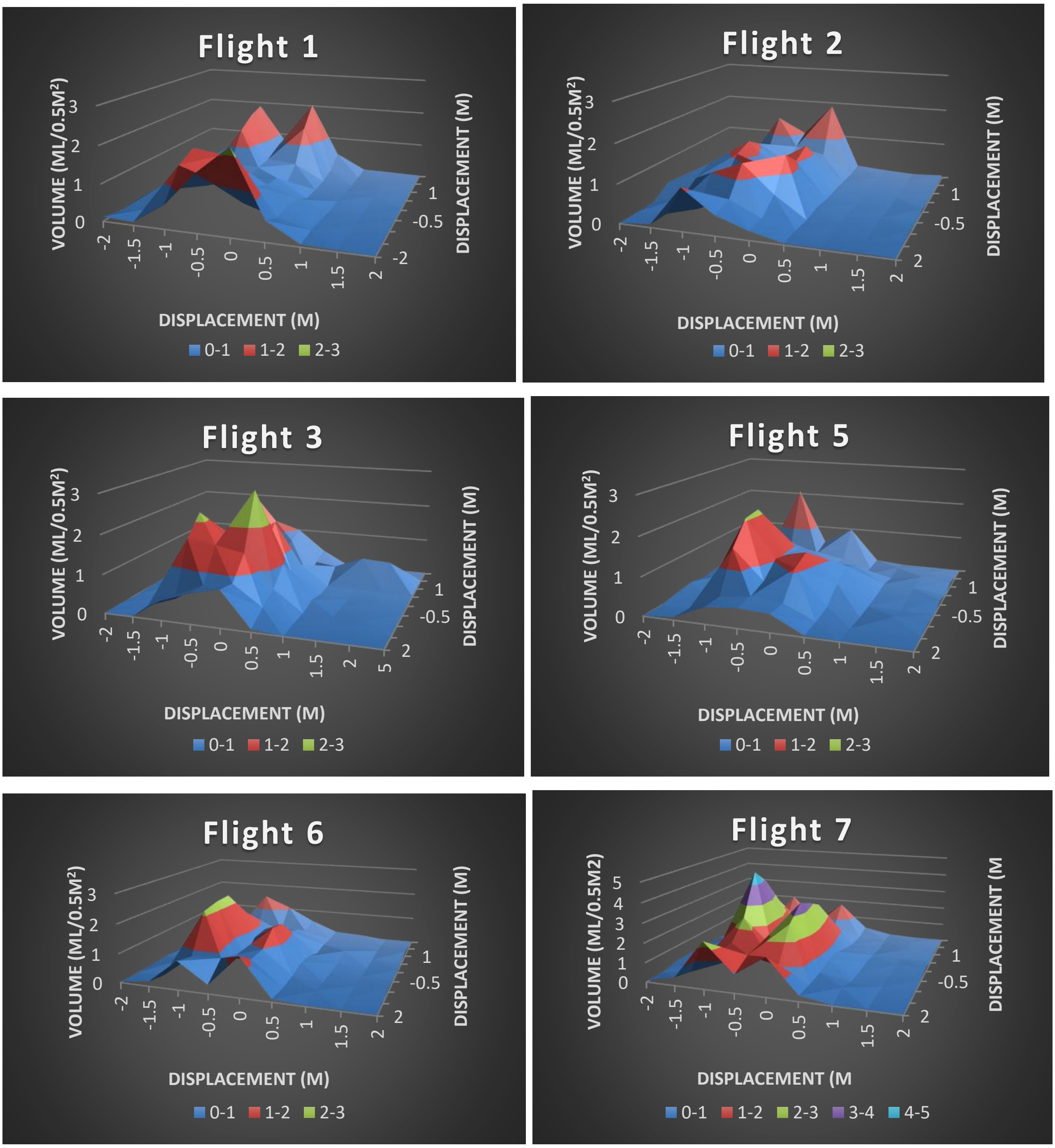

Figure A4. Deposition patterns for each 6 identical flights in the large 4m by 4m array.

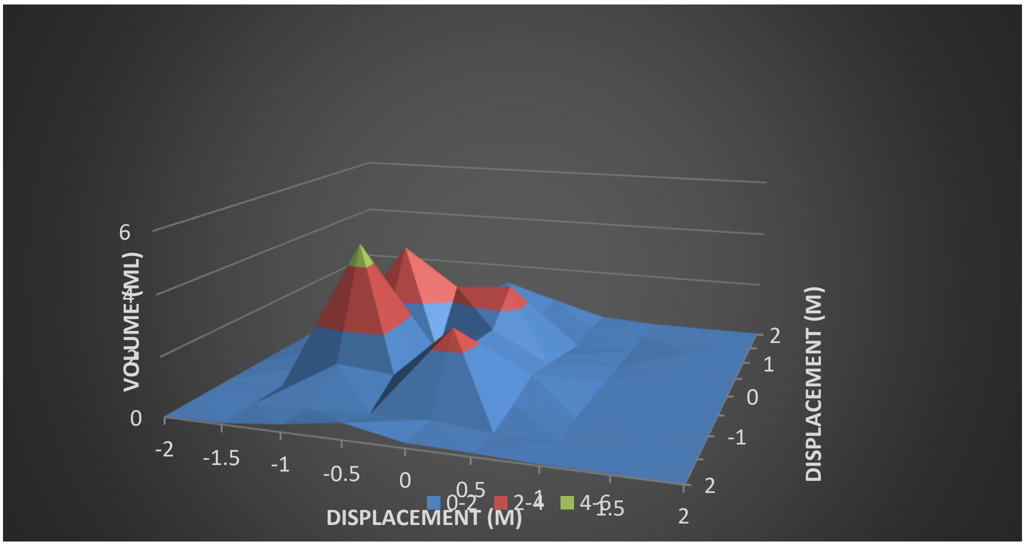

Figure A5. Deposition pattern of the sole flight with narrower on/off trigger points in the large 4m by 4m array.