Precision Silviculture Programme

TECHNICAL REPORT

UAV Release Spraying : Results from operational UAV trials

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Precision Silviculture Partnership

Report information sheet

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Executive summary

The problem

Establishment is one of the most critical times of the forest growing process. To ensure the seedlings have the best chance of survival and optimal growth in their first 1-2 years, competition from neighbouring plants must be minimised. A best practice, and lower-herbicide input option, is to spot release the vegetation surrounding the seedlings with a knapsack sprayer in the spring, shortly after planting. However, labour shortages are making it increasingly difficult to guarantee that spot release spraying can be done on time and to specification, therefore alternate solutions are being sought. Unmanned aerial vehicles (UAVs) offer an opportunity to automate the spot release spraying process and relieve the pressure of sourcing labour. The majority of off-the-shelf UAV platforms, however, do not have the capability of spot spraying and can only be programmed to spray strips. There is also a deficit of research and available information to foresters on the spot-spraying methodology using an UAV. The objective of this study was to apply a spec-built UAV to spot release seedlings in a recently established forest to assess performance of the system and its suitability to the environment.

Client initiatives

Scion has been working with Pan Pac for the past year on a project to operationalise spray UAVs for forest establishment. This work has included developing methods for detecting young seedlings (6 months after establishment) using remote sensing techniques, creating spatial layers for individual tree locations and trialling a number of different commercially available UAVs and contractors. In addition, Scion have also worked with a number of UAVs and commercial contractors over the past 6 years to assess their suitability for spot spraying operations.

This project

The purpose of the Automated Release Spraying project was to progress towards an individual tree management approach for silvicultural operations at an operational level. Critical to success was the harnessing of new technologies to carry out these tasks, in this case, an operational UAV platform able to carry out automated individual spot-spraying of planted trees.

The project represented a collaboration between Scion, Pan Pac, Forest Growers Research, and SPS Automation. This project built on previous work and involved locating seedlings immediately after establishment, utilising ultra-high resolution airborne remote sensing and deep learning seedling detection. Seedling locations were then provided to a spray craft, which carried out release spraying operations. The scope of this project did not extend to carrying out any form of tree health or planting quality control (QC), or indeed the planting of the trees themselves and is limited to two trial areas. The first, a ~25 ha ex-paddock that was planted and release-sprayed in 2021 and has had subsequent weed growth into the spot; the second, a similarly-sized ex-paddock that was not pre-sprayed prior to planting. Measures for success included follow-up remote sensing to assess the accuracy of the spray locations and the efficacy of spray deposition.

Key results

- This study potentially presents one of the first operational spot-spraying trials with an UAV in forestry globally and has developed the new concept of intermittent swath spraying.
- This study has proven the concept of using waypoints derived from aerial imagery to direct an UAV spray craft to apply prescribed herbicides to individual trees.
- A novel method for assessing the area of spray efficacy is also presented, which can be used to scale up the assessment of spot-spraying trials to areas much larger than previously possible.
- The study found that waypoints could be navigated to on foot with a real time kinematic (RTK) global navigation satellite system (GNSS) with a root-mean-square error (RMSE) of 0.36 m.
- The craft was able to navigate to the individual seedling waypoints and deliver an effective dose of herbicide with a RMSE of 0.71 m, calculated from the centroid of the sprayed spots to the target waypoints.
- The area of efficacy was found to be ~47% on target for a 1 m diameter prescribed spot area, and ~40% on target for a 1.5 m diameter prescribed area.

- Work rates were calculated and found that, in its current form UAV spot releasing is nearly tenfold the cost of manual releasing. However, with more work on the system and other efficiency gains, cost is predicted to reduce to potentially double manual releasing, or perhaps less if swarm technology can be implemented.
- Potential benefits of bringing new labour to the industry and reducing chemical usage, compared with blanket releasing from a helicopter, could make this technology an attractive option for forestry, despite the potential increase in cost.

Implications of results for the client

The results of this study indicate that spot releasing from a UAV is a very real possibility with multiple benefits, including health and safety, introducing new workers to the industry, and potentially time and cost savings (when swarm technology can be implemented). The development of this system could also enable other opportunities, including precision nutrition, precision planting, by pre-spraying planting locations, and chemical thinning. These benefits will only be realised with significant investment in the technology and a commitment from industry to develop this new method.

Further work

Our results indicate that further work on developing the system is required until its full potential can be assessed. The conditions of the trial were less than optimal, and future study that separates out variables, such as slope and wind would be beneficial. Due to the missed opportunity of calibrating the spray craft deposition and characterising the spray deposition pattern prior to the trial, a calibration study is still required to gain a fuller understanding of spray pattern produced by the craft and how this correlates with area of efficacy under field conditions.

UAV Release Spraying

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Introduction

Having high costs, with no immediate returns, establishment is one of the most critical times of the forest growing process (Montagnini, et al., 1995) with vegetation management a critical component of this phase. Vegetation management ensures that there is minimal competition for limited resources thereby optimising survival and early growth (Richardson, 1993; Wagner, et al., 2006). One of the most effective methods for improving productivity is the management of the surrounding weeds (Nambiar, et al., 1993). The most cost-effective method for managing vegetation in New Zealand (NZ) forestry is through the use of herbicide either prior to planting or “releasing” seedlings after planting (Rolando, et al., 2011). Release spraying generally uses herbicides to which the crop species is tolerant with spot spraying comprising ~60% of the total area release sprayed each year (Rolando, et al., 2013). Spot spraying is largely carried out in NZ by contractors walking the establishment site with knapsack sprayer (Richardson, 1993). Releasing is generally in the spring after planting, between the months of September and December (Rolando, et al., 2013). The timing is important to ensure that the trees are released prior to the growth season when the surrounding weeds can smother the trees, making them harder to find and impacting on their growth.

Current labour shortages are making it difficult for foresters to find suitably skilled and qualified workers to perform silvicultural operations, such as release spraying (Baker, 2018). To overcome labour shortages, some foresters are having to rely on aerial spraying as a means of ensuring timeframes are met. Broadcast spraying from manned aircraft is roughly equivalent to the cost of spot spraying, however, it is not practical on all site and terrain types. It also increases the environmental impact, due to the higher amount of chemical that is applied to sites, and increases the risk of spray drift (Richardson, 1993). There is also increasing public concern around the use of herbicides in forestry (Deighton, et al., 2021), with foresters meeting some resistance to aerial spraying of herbicides (Dare, et al., 2011; Mason, et al., 2022), impacting on social license to operate. Unmanned aerial vehicle (UAV) spraying is an emerging technology that could resolve some of these issues.

UAV spraying was first developed in Japan in the 1980’s (Sylvester, 2018) and was quickly adopted and developed in other countries. “Plant protection UAVs” first appeared in China in 2014 and have seen a rapid growth in their use from less than 4000 nationwide in 2016 to more than 160,000 machines in 2021 (Hu, et al., 2022). In China, plant protection UAVs have proven popular due to their operational efficiencies in helping to combat labour shortages caused by an ageing population and urbanisation (Lan, et al., 2018). An additional benefit of UAV spraying over knapsack spraying, is that it reduces exposure of the operator to harmful chemicals (OECD, 2021).

Developed for agricultural applications, most current spray systems are designed to carry out broadcast (swath spraying) applications (Hunter III, et al., 2020), in which the craft is programmed to autonomously fly up and down the field of interest spraying continuously. The majority of research to date has been focused on this broadcast, or swath spraying, application and development has been largely focused on this area (Wang, et al., 2022).

Spot spraying is another method of application, in which the craft is tasked with applying a targeted spot, alternating the application of chemical based upon a timer or a GNSS location. Very little research to date has been focused on spot spraying (Richardson, et al., 2020), and to the best of our knowledge no operational trials in forestry have been reported in the literature. Plant protection UAV manufacturers have recently developed an “orchard mode” to enhance the usability of these craft for fruit tree growers (Guo, et al., 2022). This mode enables craft to spot spray trees based on a pre-determined route that is calculated from a prior photogrammetry flight that identifies the locations of the trees and the optimal, three dimensional flight path to avoid hazards (Guo, et al., 2022). While effective, these commercial UAV platforms capable of spot spraying generally have a wide swath width to cover fruit tree canopies. For example, the DJI Agras MG-1 has a minimum spray width of 4 m at a flight height of 1.5 m above ground level (AGL) (DJI Ltd, 2023). As best practice for spot releasing in forestry is confined to a 1.8 m (or less) diameter spot , around each tree (Richardson, et al., 1996), the spots produced by the current off-the-shelf UAVs are generally too large for forestry applications.

In addition to the issues identified above, many off-the-shelf systems are unable to be programmed to perform spot spraying flights. Craft that are configured for spot spraying, such as the more recent XAG and DJI models, generally have a pre-programmed spot spray mode which follows the “stop and rotate” method of application. For example, the DJI T20 has a spot spray mode in which the UAV flies to a series of pre-determined waypoints, hovering over each waypoint, turning on its nozzles and rotating 360° about the central axis of the fuselage (Guo, et al., 2022).

An example of this motion can be found in Figure 7b in the Flight planning and spray methods section. This method is beneficial for orchard work as it ensures even coverage of the tree canopy, but for spot releasing seedlings in a forestry setting it is too time consuming. Flight controllers for off-the-shelf UAVs are generally “locked” by the manufacturers, meaning that swath spraying systems cannot be modified to carry out bespoke spot spraying, and spot spraying craft cannot be reconfigured to create smaller spot sizes. A number of flight controllers do exist that can be programmed to carry out automated flight to suit forestry applications, provided they are integrated with a suitable craft. Spec-built crafts enable the combination of a purpose-built spray unit with a programmable flight controller and the ability to create a bespoke spot spraying UAV for forestry.

For this study, Scion, Pan Pac and FGR, collaborated with a NZ-owned and operated automation specialist, SPS Automation, to build a UAV system to the required specifications for spot spraying in forestry. Previous work had already determined the feasibility of locating seedling at approximately six months after planting using imagery from a manned aircraft and deep learning detection algorithms (Hartley, et al., 2022). The ability to detect significantly smaller and more difficult to identify seedlings was an unknown yet critical factor for spot spraying, given that the window for release spraying is generally one to four months after planting.

This study had the following aims:

1. To quantify tree location shortly after planting using existing remote sensing technologies and determine the accuracy of different technologies in identifying precise tree location.
2. To evaluate the targeting accuracy of a bespoke UAV release spot spraying trees using pre-determined remotely sensed tree locations.

The second aim was broken down into further objectives to:

1. Evaluate the optimum system approach to achieve efficient delivery of the targeted spot.
2. Quantify the shape of the spot delivered.
3. Determine the accuracy of tree location identified from aerial imagery and UAV remote sensing technologies.
4. Quantify the potential work rate of the UAV and the costs and efficiencies required to make operations cost-effective.

This report details the research methodology and field trial outcomes.

Materials and methods

Study site

The spray trials were conducted at Pan Pac's Glenlyon Forest in Hawke's Bay (Figure 1). The forest ranges from flats, bordering stream beds, to steep terrain. The stand selected for the trial is rolling to steep with an average gradient of 8.85° and a maximum gradient of 43.54°. A stand was chosen that was representative of the typical terrain conditions when establishing forests in the region. The site was formerly utilised for rearing dry stock, and was rich in nitrogen and calcium (Hartley, et al., 2022). The predominant vegetation was grass and scattered pastoral weed species with shelter trees (predominantly *Populus* and *Eucalyptus spp.*) planted strategically across the site. The site is at an average elevation of 377 m above mean sea level and is therefore quite exposed to the Foehn winds that frequently affect the region in the spring (McGlone, 2002). Rainfall in the region is low (average) and generally associated with easterly winds, with droughts common between November and May (McGlone, 2002). The annual rainfall normal for the Forest Headquarters weather station in Gwavas, located ~5km to the SW of the trial site, is 998 mm, with the monthly rainfall normal for September being 76 mm (Chappell, 2013).

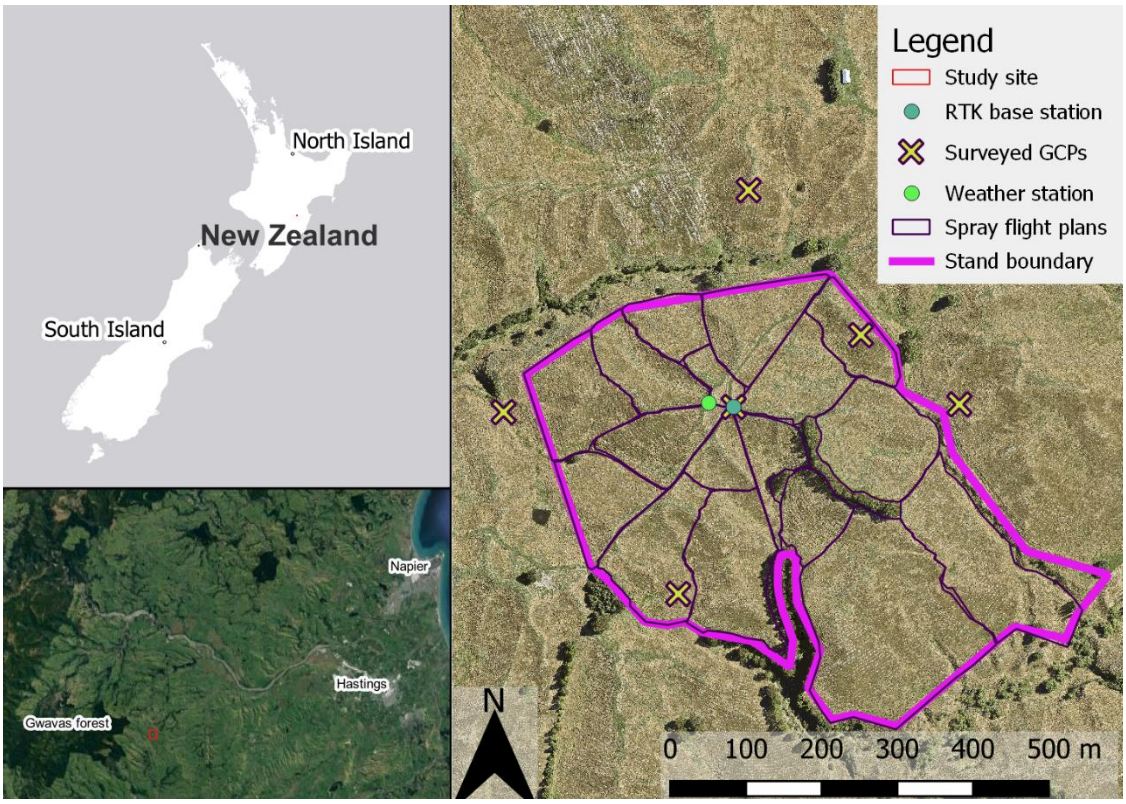

Figure 1. Map of the study site showing location within the wider region and within New Zealand. Ground control points used for pre- and post-survey UAV flights are marked, along with the met station location and the location for the UAV RTK antenna.

The majority of the 596 ha site was planted in July 2021 using traditional manual planting techniques and received a preliminary spot release spray in October 2021. The remainder of the site, approximately 80 ha, was planted in July 2022. The site was grazed until planting, with no additional vegetation control or site preparation carried out prior to planting. Within the forest, two stands were selected for the trial from the two different age classes: the first stand, established in 2021, was fourteen months old when the spray trial was conducted; the second was approximately one month old during the seedling detection trials.

Seedling detection methodology

UAV seedling detection

To assess the first aim of the trial, SPS Automation were contracted to carry out trials to assess the feasibility of seedling detection in a recently afforested site using a range of sensors. Sensors trialled included a high resolution standard visual light (RGB) camera, a multispectral camera and a UAV laser scanner (ULS). RGB data were captured with a 24 megapixel (MP) Sony Alpha 6000 (Sony, Tokyo, Japan) with a 16mm SEL16F28 lens. Multispectral data were captured with a MicaSense RedEdge-M (MicaSense Inc., Seattle, WA, USA) multispectral sensor, providing five narrow bands of imagery (blue = 455–495 nm, green = 540–580 nm, red = 658–678 nm, red edge = 707–727 nm and near-infrared (NIR) = 800–880 nm). Multispectral and RGB sensors were both mounted to an Aeronavics Navi UAV (Aeronavics, Timaru, NZ). ULS data were collected with an Ouster OS0-32 laser scanner (Ouster, San Francisco, CA, USA) that was integrated onto a customised UAV by SPS Automation. Flights were conducted at a range of heights below 50 m AGL to assess the impact of ground sample distance (GSD)[1] on accuracy of detections and to find an optimal flight height. Optimal RGB data were captured at a height of 13 m above ground level (AGL) to produce a GSD of ~0.3 cm. Optimal multispectral data were collected at a height of 15 m AGL to produce a GSD of 1.03 cm. The data collected were found to be insufficient for seedling detection and so the additional flight parameters, including the ULS flight parameters, are not presented here.

The results of the seedling detection study concluded that the recently planted seedlings were too small and covered by grass to be detected at approximately one month after planting (Figure 2). It was therefore decided that the stand established in 2022 should be removed from the spray trials and the focus solely shifted to stand established in 2021. The results of the seedling detection study can be found in SPS Automation's report "Precision Forestry With Drones", in Appendix A.

Figure 2. Aerial RGB image from the trial site established in 2022 (left) and a terrestrial image (Right) to demonstrate the small size of the seedlings compared to the grass. Imagery from SPS Automation's report "Precision Forestry With Drones", Appendix A.

Aerial seedling detection

As the UAV seedling detection was not able to detect trees to the required accuracy, it was decided to fall back on data captured at the site in a prior trial. Airborne imagery of the site was captured utilising dual PhaseOne, 100 MP cameras providing RGB and infrared imagery (RGBi). The sensors were combined with a PhaseOne iX controller and an Applanix AVX210 global navigation satellite system-inertial measurement unit (GNSS-IMU) and this sensor suite was flown with a Cessna 180K fixed wing aircraft (Figure 3) at a height of ~460 m AGL to achieve a GSD of 2.5 cm. Imagery was then processed into an orthomosaic by the contractor, using ground control points (GCPs) from the site. The GCP network was set up on a grid of approximately 300 m x 300 m across the entirety of Glenlyon Forest and professionally surveyed to give optimal accuracy.

[1] Ground sample distance (GSD) is the distance between the centre of two neighbouring pixels in an aerial photo or orthomosaic, which represents a measured distance on the ground. For example, a 1 cm GSD means that one pixel represents a 1 cm x 1 cm area on the ground. GSD can also be referred to as the spatial resolution or, in more basic terms, "pixel size".

The resulting orthomosaic image was passed on to Indufor who used their commercial deep learning solution to identify seedlings across the site. Imagery was captured on 16th February 2022, seven months after establishment and seven months prior to the spot-spraying trial. Analysis of a subset of 90 points found that the seedling detections had an RMSE of 0.21 m from the centre of the tree crowns. This analysis was completed by comparing the detected seedling location to the location of the centre of the seedling crown in the same orthomosaic. For the purposes of this study, we assume that the detections represent the actual tree location.

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Figure 3. SkyVUW's Cessna 180K aircraft (Right) used for the aerial seedling detection flight.

Accuracy of navigating to aerial detections

To assess the accuracy of using a GNSS to navigate to waypoints derived from aerial seedling detections, a subsample of 90 seedling locations were selected and tested in the field using mobile GIS. The subsample of points were selected from the site by manually assessing the aerial imagery to find points which had a variety of weed species and slope classes to get a more representative sample of the area. The locations were input into mobile GIS, comprised of ArcGIS Field Maps (ESRI, Redlands, CA, USA) on an apple iPad Mini (Apple Inc., Cupertino, CA, USA) tablet using an Arrow Gold (EOS Positioning System, Terrebonne, QC, Canada) real-time kinematic (RTK) GNSS; Figure 4a).

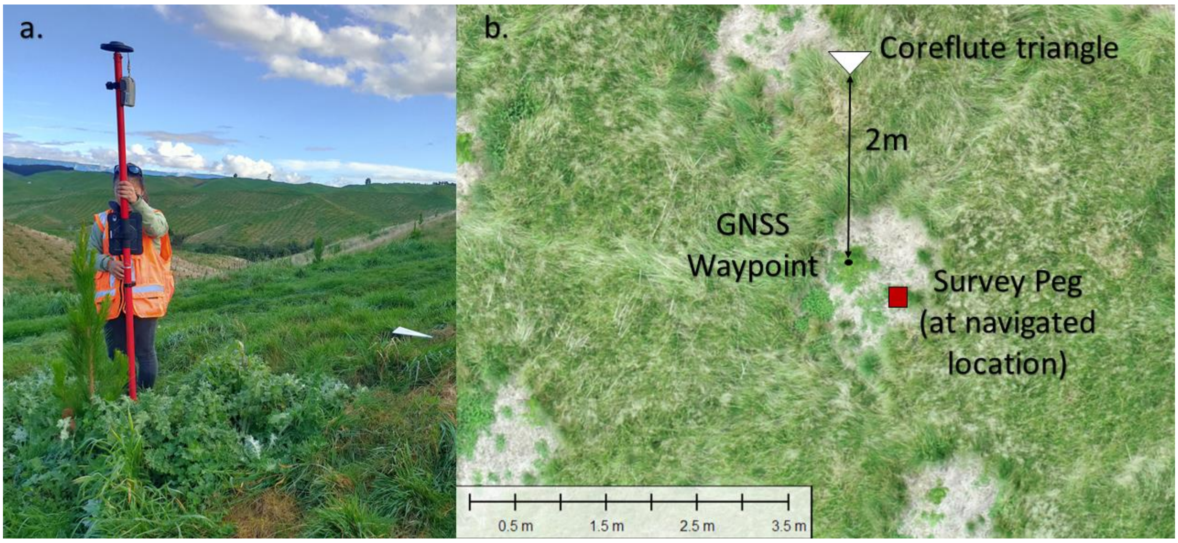

Figure 4. (a) Using mobile mapping system to navigate to the detected seedling waypoint in the field, with coreflute plastic marker in the right-hand side of the image; (b) diagram of the experimental layout, with the GNSS waypoint of the detected tree derived from the aerial imagery (black spot), the coreflute marker (white triangle; to aid in locating seedlings in aerial imagery) and the survey peg of where the mobile GIS navigated to (red square).

Due to the enhanced accuracy of the technology for navigation, a RTK GNSS was selected to test the accuracy of the seedling detection locations, as well as the accuracy of a GNSS in its ability to navigate to these locations. It was considered that simply navigating to these locations and taking another reading with the RTK GNSS would potentially confound the results with additional positional errors, such as ephemeris error or atmospheric interference, associated with GNSS positioning. To remove these errors, a novel approach was devised in which physical markers were placed on the site at the location navigated to with the RTK GNSS (Figure 4). The site was then flown and georeferenced using the same ground control as the aerial imagery, from which the seedling locations were detected. This co-registered UAV imagery, which was precisely aligned with the original aerial imagery, was then used to measure the distance between the physical markers placed in the field and the seedling detection points in a GIS.

A mobile GIS was used to navigate to each waypoint and then a brightly painted wooden stake was placed in the ground at the point navigated to (Figure 4b). A 20 cm white coreflute plastic arrow was then mounted on another peg which was placed 2 m due North of each tree navigated to, making the trees easier to locate in aerial imagery (Figure 4b). The site was then flown with high resolution (~ 0.5cm) RGB UAV imagery, from which the brightly painted navigation pegs could be manually annotated within a GIS. For UAV flight parameters, please refer to UAV remote sensing to determine spray efficacy.

Spray Trial Methodology

UAV remote sensing to determine spray efficacy

UAV remote sensing was utilised to assess the targeting efficiency of the spray system. The site was mapped prior to spraying, and once again after the area of spray efficacy was clearly defined by dead vegetation. Mapping was conducted with a DJI P1 (DJI Shenzhen, China) 45 MP full-frame RGB camera mounted on a DJI Matrice 300 (DJI Shenzhen, China) quadcopter UAV (Figure 5). Flights were conducted at a height of 70 m AGL, a flight speed of 5 m/s, and a forward and side overlap between images of 80% and 70% respectively. The resulting orthomosaics had a GSD of 0.66 cm and 0.76 cm for the pre- and post-spray flight respectively. Flight planning was conducted in the DJI Pilot 2 software (DJI Shenzhen, China) utilising its inbuilt terrain following functionality, to ensure an even GSD across the area of interest.

Figure 5. DJI Matrice 300 UAV with mounted DJI P1 camera ready to take-off for mapping the site prior to spraying

The resulting imagery was processed into orthomosaic maps using the Pi4DMapper (Pix4D) software (Pix4D, Lausanne, Switzerland). The orthomosaics were processed using GCPs from the Glenlyon GCP network, so that they tied in seamlessly to the aerial imagery, enabling comparisons between the data sets with minimal spatial errors.

UAV spray trials

Spray Craft

Spray trials were carried out with an Aeronavics ICON heavy-lift multirotor UAV with eight rotors in a co-axial quad configuration (Figure 6).

Figure 6. SPS Automation's custom Aeronavics Icon spray craft set up for work at the trial. The location nozzles can be seen attached to the legs, approximately under the propellors.

The craft has a maximum take-off weight of 50 kg and was fitted with a custom spray system by SPS. The spray system has two 4 L tanks, a maximum tank carrying capacity of 8 L and uses four AITX8001VK, hollow cone, air induction, low flow rate nozzles (TeeJet Technologies, IL, USA), which are attached with one on each leg of the craft, approximately under the propellors (see Figure 6). According to the manufacturer's specifications, the minimum pressure (4 bar) for the AITX8001VK nozzles should produce extremely coarse (XC) droplets; that is, droplets with a volume median diameter (VMD) of 503-665 microns. However, laboratory testing of the UAV spray system indicated spray pressure at the nozzles was approximately 1.5-2.0 bar. A lower spraying pressure makes it likely that droplet sizes were larger than the targeted range. The system was retrofit by SPS with a hybrid petrol-electric motor, enabling longer flight times and more efficient ground control operations (i.e., no battery management). The craft is capable of flying with a full load for ~16 minutes, and for ~31 minutes with a half load. 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/). This enabled maximum customisation of the flight path and the ability to programme different spray methods. Additional information on the craft can be found in the SPS Automation report in Appendix B.

UAV Spray system

In the project proposal, a rudimentary evaluation of the UAV spray system was planned prior to the spray trial. Due to poor weather and technical issues during the window when Scion staff were working with SPS Automation on this, the assessment did not take place. In order to meet the deadlines for the project, SPS Automation tested and finalised the spray system without Scion staff physical involvement. The workplan for the calibration can be found in Appendix B.

Flight planning and spray methods

The trial site was divided into 17 smaller flight areas based on their terrain and aspect (Figure 1) and then flight paths were created within each one. Flight paths needed to be approximately linear to minimise movement of the craft disrupting smooth flight. Each flight area was, therefore, broken down further into individual flight lines. There are arguably three main methods for spot application when spraying from a UAV: stop and spray (Figure 7a), in which the craft flies to a waypoint and deposits the prescribed dosage; stop and rotate (Figure 7b), in which the craft flies to a waypoint, and applies the spray whilst rotating; and intermittent swath spraying

(Figure 7c), in which the craft flies continuously, starts spraying when it reaches a waypoint immediately prior to the target. The craft then ceases to spray when it reaches a second waypoint immediately after the target, or when the craft has flown for a given amount of time at a given speed to deliver the required dose. Spot spraying without movement is likely to produce an uneven coverage of spray volume within the target zone as the hollow cone nozzles each produce a doughnut pattern. Rotation (Richardson, et al., 2020) or linear movement along the length of the static "doughnut" radius will produce a continuous deposit pattern across the swath. Another benefit of the intermittent swath method is that the craft doesn't stop to apply the chemical, possibly gaining some time efficiency. As the stop and rotate method would reduce time efficiency, and there was such a small amount of chemical prescribed that only a partial rotation would be completed, this study focused on assessing the stop and spray and intermittent swath methods.

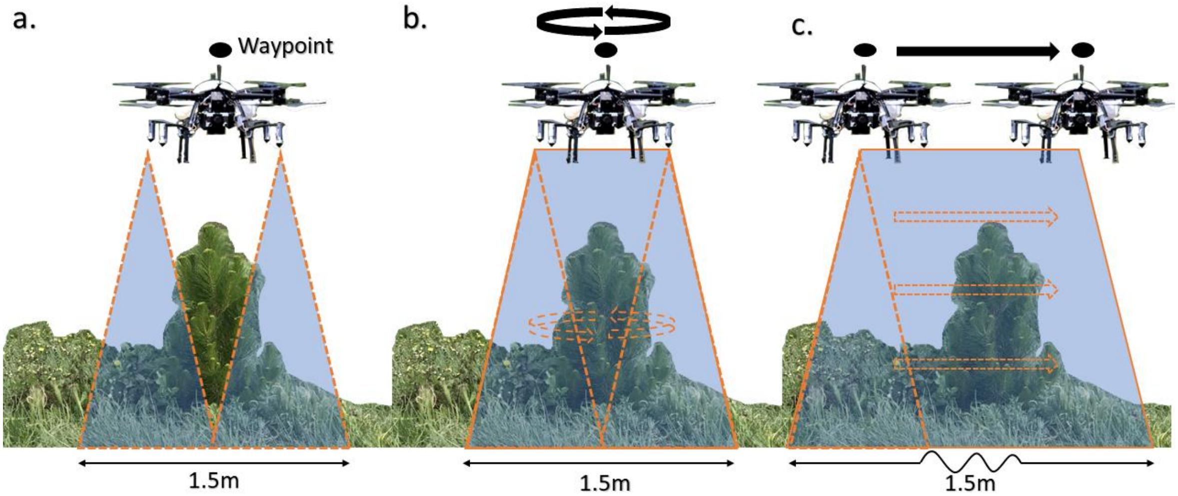

Figure 7. Spray deposit methods that can be used for spot application from a UAV: (a) stop and spray; (b) stop and rotate; (c) intermittent swath spray with waypoints before and after the target tree to turn on and off the flow. Note: spray deposits are for demonstration purposes and diagrams not to scale.

Chemical Prescription

The prescription from the forester was for a 1.3 m diameter circle around each tree, however, when auditing a 1 m diameter is an acceptable result. Best practice in NZ is for a 1.8 m diameter spot around each seedling (Richardson, et al., 1996). As the craft would be carrying out some intermittent swath spraying (Figure 7c), the forward motion of the craft would be more likely to create a square-sided spray pattern. It was decided, therefore, to calculate rates of spray for a square. The spray system was planned to deliver 45 mL of spray mix to an area of 2.25 m^2 (a 1.5 m x 1.5 m square), with the spray mix composed of Valzine 500 (AGPRO NZ, Auckland, NZ) at 10%, with BeenThere marker dye (FIL, Mt Maunganui, NZ) at 0.2%. This meant the application rate of product was 2.0 mL per square metre or 0.85 g/m^2 terbuthylazine and 0.15 g/m^2 hexazinone; the upper limit of the manufacturer's specifications.

Meteorological equipment

To monitor the potential impact of weather on the experiment, a meteorological station was established on top of the hill in the centre of the area of interest (Figure 1 and Figure 8). A CSAT3 sonic anemometer and CR6 datalogger (Campbell Scientific, Logan, UT, USA) mounted on a 2.5 m mast measured wind speed and direction every second for the duration of the spraying. Ambient temperature and relative humidity were measured every minute with a EE181 sensor (Campbell Scientific, Logan, UT, USA) connected to the same CR6 datalogger. In addition to this, rain data was collected from the Gwavas Forest Headquarters weather station, which is administered by Hawke's Bay Regional Council. The Gwavas Forest Headquarters station is ~5km to the SW of the study site (Figure 8b).

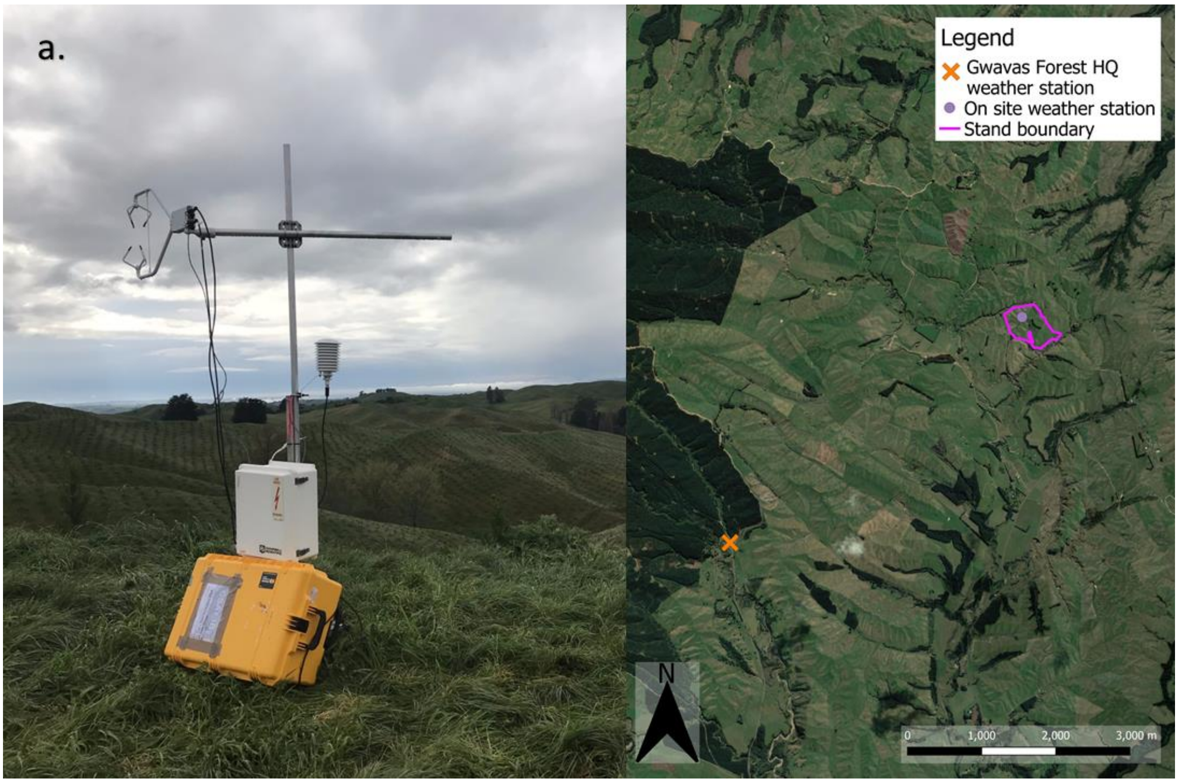

Figure 8. Weather station set up on the study site (a) and location of the Gwavas Forest HQ weather station in relation to the study site (b).

Spray efficacy analysis

Post-spraying, target waypoints from the aerial seedling detection were loaded into a GIS, along with the orthomosaics of the site, and the sprayed points were manually annotated. The area around each waypoint that was visually assessed as having been killed by the spray was digitised, creating a polygon for each spot. A range of spatial metrics were calculated on the resulting polygons and these were split into two categories: metrics that influenced the shape of the area of spray efficacy, and metrics that represent the effect of the spray treatment. A list of the metrics utilised can be found in Table 1. Spray targeting accuracy, or how much herbicide was applied over the target zone, cannot be determined from this data. The spray efficacy metrics can only be used to determine the effective targeting efficiency, i.e., the proportion of vegetation in the nominal treatment area, centred on the GNSS waypoint, that was actually killed.

Table 1. Table showing the factors/metrics that influenced the area of spray efficacy along with metrics calculated to evaluate the shape of that area, with a description for each metric and the method used to derive it.

Metrics that influenced area of spray efficacy	**Description**	**Method**
Aspect	The predominant direction that the slope faces (°)	ArcPro 3.0 (ESRI Inc., Redlands, CA, USA) – Slope tool in 3D Analyst extension
Intended Rangefinder	Height that the craft was intended to fly when spraying (m AGL)	From the flight logs
Actual Rangefinder	Height that the craft actually flew at (m AGL)	From the flight logs
Time to rain	Amount of between time sprayed and the next rainfall (seconds)	From HBRC rain gauge
Slope Max	The maximum slope within the area of spray efficacy (°)	ArcPro 3.0 – Slope tool in 3D Analyst extension
Slope Min	The minimum slope within the area of spray efficacy (°)	ArcPro 3.0 – Slope tool in 3D Analyst extension
Slope Mean	The mean slope within the area of spray efficacy (°)	ArcPro 3.0 – Slope tool in 3D Analyst extension
Spray Method	Whether the craft was programmed to spray with the stop and spray or intermittent swath method	NA
Wind direction	Direction of the wind (°)	From Met Station
Wind speed	Wind speed (m/s)	From Met Station
Area of spray efficacy metrics	**Description**	**Method**
Area	Area of spray efficacy enclosed within annotated polygon (m^2)	ArcPro 3.0 – feature geometry
Perimeter	Length of the perimeter of the area of spray efficacy (m)	ArcPro 3.0 – feature geometry
Shape index	Simple ratio of perimeter divided by area. This metric is useful for comparing objects with the same area to determine how regular their shape is i.e., the less regular, the higher the perimeter and shape index will be.	ArcPro 3.0 – field calculation using the following equation: $\frac{perimeter}{area}$
Corrected Shape Index	This is a variation on the traditional shape index (perimeter/area), which corrects for polygon size by dividing the perimeter of a polygon by the square root of the area x 4pi. This has the effect of comparing the polygon perimeter to the polygon of a circle, which is deemed to be a regular shape. The result is an index in which a score of 1 is highly regular or a circle, and the higher the number, the less regular it is.	Calculated in R statistical programming language (R Core Team, 2020) using the following equation: $shape\ index = \frac{perimeter}{\sqrt{4\pi \times area}}$

Roundness	Roundness was calculated using the Polsby-Popper test. This measures the roundness of a shape and outputs an index in which a circular object has a value of 1, and a highly irregular shape will be close to 0.	Calculates in ArcPro 3.0 using the vector calculation tool and the following equation: $Roundness = \frac{\sqrt{4\pi \times area}}{perimeter}$
Height of polygon	The maximum length of the polygon in line with the direction of the craft's orientation (m)	Calculated by fitting a bounding box to the annotated spray spots and applying a bounding box in QGIS (QGIS Development Team, 2023), then calculating the height of the bounding box.
Width of polygon	The maximum length of the polygon perpendicular to the direction of the craft's orientation (m)	Calculated by fitting a bounding box to the annotated spray spots and applying a bounding box in QGIS, then calculating the height of the bounding box.
Percentage prescription released	The percentage of the prescribed area that was effectively released.	Calculated using the st_intersection function within the sf package (Pebesma, 2018). This function calculates the intersection between two overlapping areas, or in this case the overlap between the prescribed area and the area effectively released.
IoU	Intersection over Union is a metric normally used to assess the accuracy of object detection polygons in imagery. The metric expresses the ratio of the intersection and union between the predicted and ground truth areas on an image, with the resulting number fitting on a scale of 0 (no overlap) to 1 (perfect overlap). In this study, we applied the metric to the overlapping area between the prescribed area for release, with the actual area released.	Calculated in R using the following equation: $IoU = \frac{area\ of\ overlap}{area\ of\ union}$

Metrics for slope and aspect were derived from a 1 m lidar DTM provided by the forest manager using ArcPro. The metrics were then analysed to derive statistics around the consistency and accuracy of the targeting efficiency and to look for correlation between the spray efficacy and the metrics that influenced the area of spray efficacy. It should be noted that, although the chemical prescription was calculated for a square, the analysis was focused on the area released as being circular. Two sizes of circle were used to represent the optimal spot in our analyses: a 1 m and a 1.5 m diameter circle, referred to as the prescribed areas. This analysis was implemented because the acceptable result for the forester's standard prescription was for a minimum 1 m diameter circle released around each tree. A second, larger circle with a 1.5 m diameter was also used as our chemical prescription for this trial was for a square with 1.5 m sides. The key point of the shape analysis was to assess the regularity of the area of spray efficacy shape.

Statistical analysis

The accuracy of the GNSS waypoints and the area of efficacy centroids was determined using the route mean square error, and was calculated using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}}$$

where y_i represents the measured variable, $\hat{y}_i$ represents predicted measurement, navigated to, or the centre of the area of spray efficacy, and n represents the sample size.

Correlation between environmental and operational variables with the area of spray efficacy metrics was calculated using the coefficient of determination (R^2) using the following equations:

$$R^2 = \frac{\sum_i (\hat{y}_i - \bar{y})^2}{\sum_i (y_i - \bar{y})^2}$$

where y_i represents the target waypoint, $\hat{y}_i$ represents the actual waypoint navigated to, and $\bar{y}$ represents the average of observed values.

Results and discussion

RTK GNSS navigation accuracy

Of the subset of 90 seedling locations that were selected for assessment, three of the points were not assessed due to time constraints. Of the remaining 87 points the RMSE was 0.36 m (Table 2), with only 3 of the points falling outside 1 m from the target waypoints (Figure 9). When these points are removed the RMSE improves to 0.20 m. The mean distance between the point navigated to and the waypoint for the detected seedling was 0.22 m, with a minimum distance of ~0 m, and a maximum distance of 2.16 m.

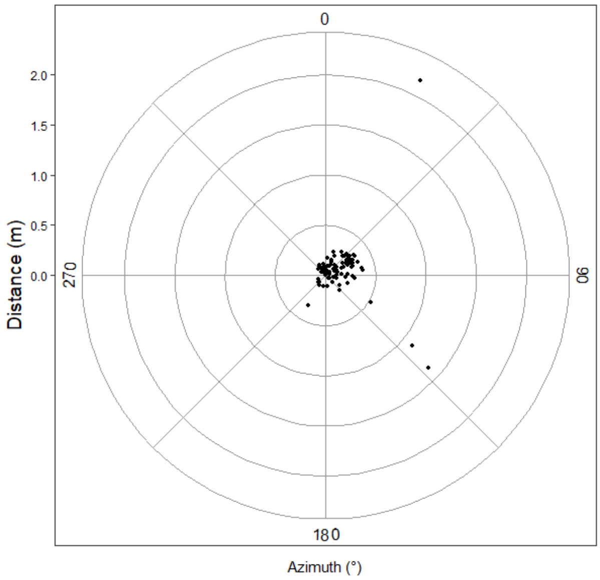

Figure 9. Plot showing the distance and bearing of the point that was navigated to in the field and the target waypoints, derived from the aerial imagery seedling detections.

Table 2. Minimum, maximum and mean error between the target waypoint and the point that was navigated to in the field with an RTK GNSS.

	Min.	Max.	Mean	RMSE
Distance between detected seedling waypoint and navigated point	0.00	2.16	0.22	0.36

UAV Spray Trial: Meteorological and Operational variables

During the time of spraying, the average wind direction was from the West on the first day and then East and Southeast on the second and third days (Table 3). Average wind speed, temperature and relative humidity recorded per day ranged from 3.5 m/s to 6.7 m/s, 9.7 °c to 17.5 °c and 65.1% to 95.6% respectively (Table 3). The daily figures for these variables, along with the craft flight parameters can be found in Table 3. Wind direction for each day is also represented in Figure 10. Note that the reported average temperature for 22.09.2022 is lower as the system was decommissioned earlier in the day than on previous days due to inclement weather.

Table 3. Mean daily meteorological conditions over the duration of the spray period, spray method and spray release height.

Date of trial	Wind Speed (m/s)	Wind Direction (°)	Temperature (°c)	Relative humidity (%)	Spray Method	Release Height (m AGL)
20.09.2022	6.7	287.6	17.5	65.1	Spot	2
21.09.2022	3.5	117.6	14.4	78.1	Intermittent swath	3
22.09.2022	4.3	131.8	9.7	95.6	Intermittent Swath	3

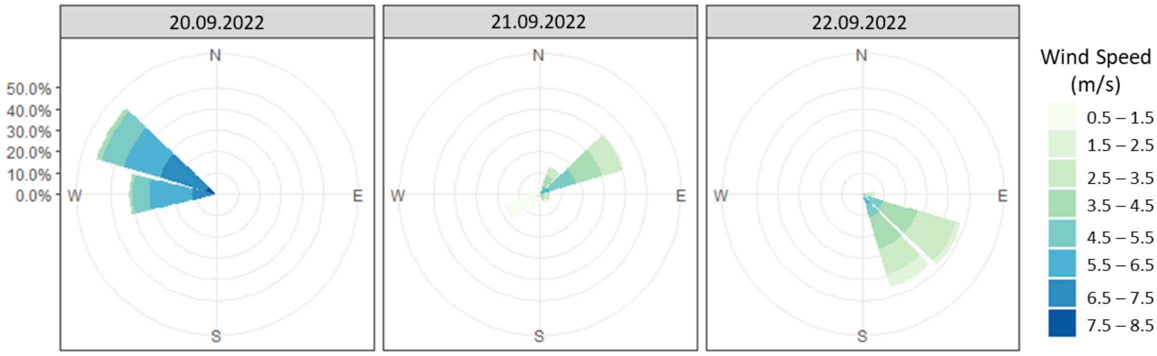

Figure 10. Mean wind direction at the time each sprayed spot was sprayed, grouped in 40° bins, and coloured by wind speed in 1m/s bins.

UAV Spray Accuracy

Due to technical issues and poor weather during the trial period, only two of the seventeen flight areas were used for the spray trial. Within these two trial areas, a total of 425 spots were sprayed across a period of 4 days. The annotated spots can be seen in Figure 11. Of these 425, 31 spots were not recorded by the flight controller system. When the centroid of each area of spray efficacy is compared to the waypoint location that the craft flew to, the mean distance between the two points was 0.61 m, with a minimum and maximum distance of 0.03 m and 3.04 m respectively (**Table 4**; visual representation in **Figure 12**). The RMSE of the accuracy of the area of efficacy centre to the target was 0.71 m. Annotated spots represent the area which has received an effective dose of herbicide sufficient to kill the local plants. This is an indirect assessment of the positional accuracy of the craft. Once the spray is released complicating factors such as prevailing wind, ground slope and subsequent rain fall etc may displace the spray from its initial release location. However, these are factors that an UAV must contend with in order to deliver a targeted dose to properly release a seedling. The results of the area of spray efficacy annotations are displayed in Figure 11.

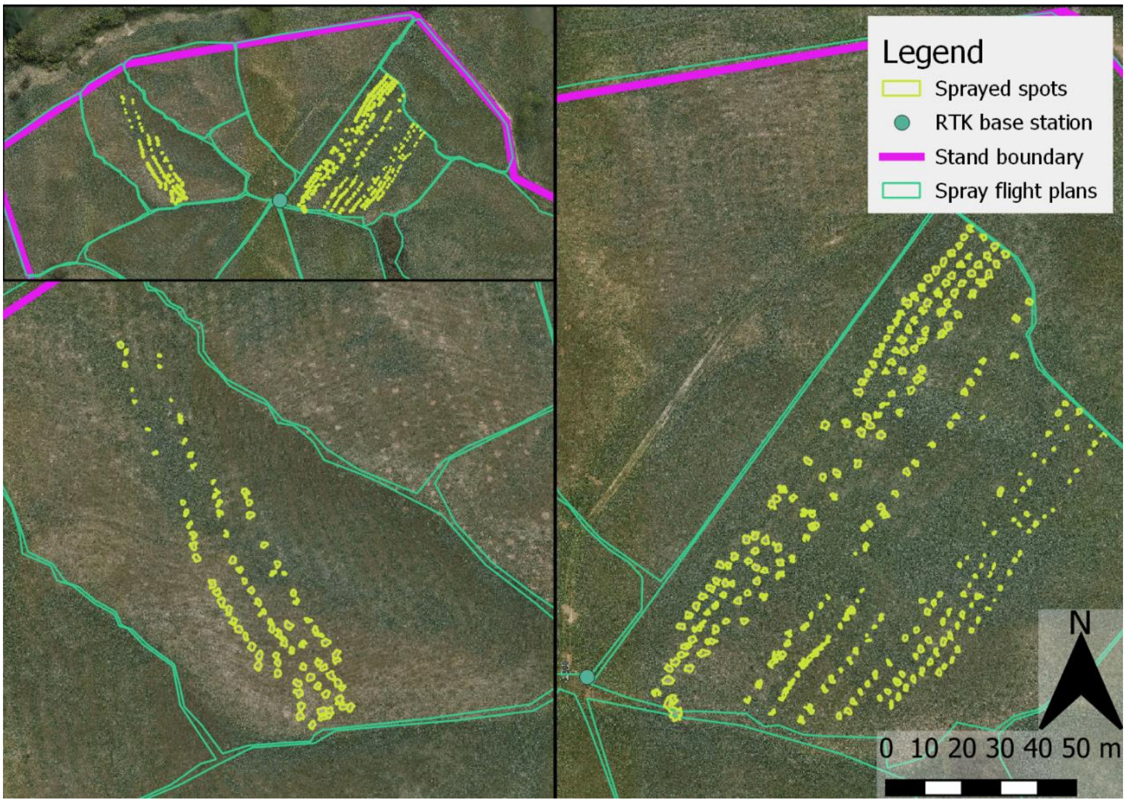

Figure 11. Map of annotated spray spots (yellow polygons) in flight area 15 (left) and 6 (right). Inset shows the location of these two flight areas within the wider context of the trial site.

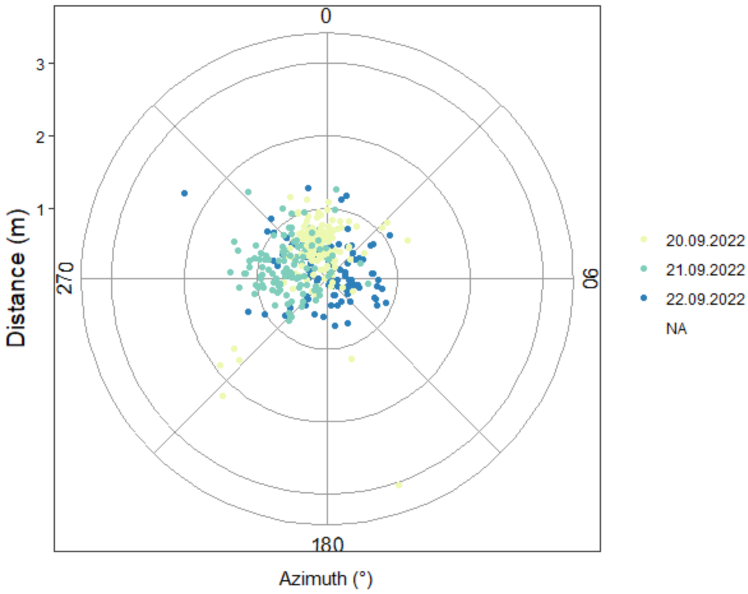

Figure 12. Plot showing the distance and bearing of the area of spray efficacy centroids from the target waypoints. Data points coloured by day of trial.

Table 4. Minimum, maximum and mean error between the target waypoint and the centroid of the sprayed area of efficacy for each spot.

	Min.	**Max.**	**Mean**	**RMSE**
Distance between detected seedling waypoint and centre of area of spray efficacy	0.03	3.04	0.61	0.71

The average area of spray efficacy size was approximately to prescription, with an average area of 1.64 m². Analysis of the area of spray efficacy shapes showed a mean roundness index of 0.51, with a minimum of 0.14 and a maximum of 0.92 (Table 5). The mean area for the area of spray efficacy represents 208.39% of the prescribed area for a 1 m diameter target (0.79 m² area) and 92.62% of the prescribed area for a 1.5 m diameter target (1.77 m² area). Areas for 1 m and 1.5 m prescribed targets were taken from shapefiles and used in calculations for percentage of vegetation killed within the target area. The shape index of each area of spray efficacy was also very varied, with a mean of 4.76 and minimum and maximum of 1.92 and 17.8 respectively (Table 5). Examples of what the areas of efficacy within the lower, upper and mean range for shape index can be found in Figure 13.

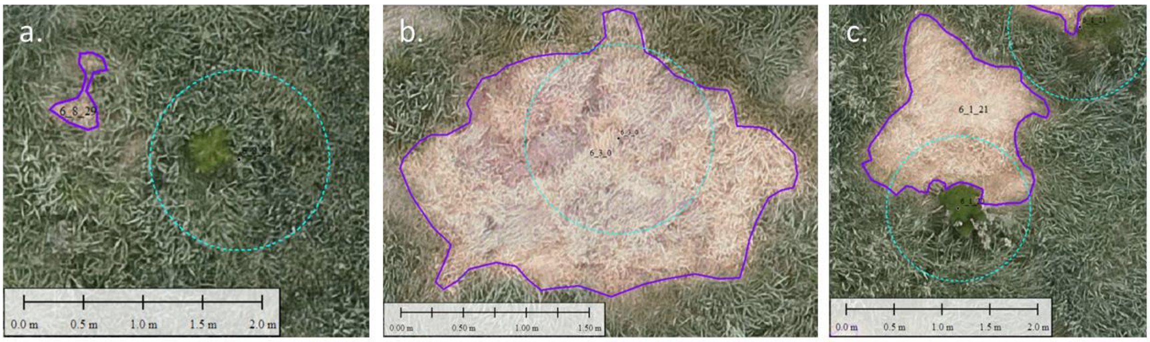

Figure 13. Examples of areas of spray efficacy (purple polygon) in the upper (a; 17.8), lower (b; 2.11) and mean (c; 5.04) range for shape index within the study population. Prescribed 1.5 m diameter spots (blue dotted circles) shown for reference.

When the area of spray efficacy was compared to the prescribed circular target area around each target waypoint, the mean percentage of each target that was covered was 48.6%, with coverage range from 0% (a complete miss) to 100% for a 1 m diameter target (Table 5), and a mean coverage of 41.6%, with a range of 0% to 98.6% for a 1.5 m diameter target (Table 5). 100 of the treatments, representing 22.9% of the total, were completely off-target for a 1 m prescribed target area, and 80 (18.3%) of the treatments missed for a 1.5 m prescribed target area. The Incident over Union (IoU) ratio to assess the accuracy of the area of spray efficacy covering the target area was, overall, poor for both the 1 m target (0.19) and 1.5 m target (0.28; Table 5), with the maximum values for each target area being 0.51 (1 m) and 0.75 (1.5 m; Table 5). To evaluate the consistency of the area released by the UAV, ignoring targeting accuracy, the target area can be assumed to be at the geometric centre of the area of spray efficacy. This shows that the UAV would have effectively released (killed) 79.4% of the vegetation, within a 1 m diameter prescribed target, with minimum and maximum values of 7.8% and 100% (Table 5). Likewise, for a 1.5 m diameter target area the mean percentage of vegetation killed was 65.8%, with minimum and maximum values of 4.9% and 100% (Table 5), IoU values between the area of spray efficacy and a 1 m diameter prescribed target around the geometric centre of the area of spray efficacy gave mean, minimum and maximum values of 0.38, 0.07, and 0.81 respectively. For a diameter of 1.5 m from the centroid of the area of spray efficacy, IoU values showed a mean of 0.52, a minimum of 0.05 and a maximum of 0.83.

Table 5. Metrics derived from sprayed areas of efficacy per spot including minimum, maximum and mean values.

Metric (unit of measurement)	Min.	Max.	Mean
Spot area (m²)	0.09	11.90	1.64
Shape index of the area of spray efficacy	1.92	17.80	4.76
Corrected shape index of the area of spray efficacy	0.14	0.92	0.51
Average slope value within the area of spray efficacy (°)	0	35.30	18.66
Max slope value within the area of spray efficacy (°)	0	30.90	16.01

Percentage of vegetation killed within 0.5 m radius of the target waypoint	0.00	100	48.57
Percentage of vegetation killed within 0.75 m radius of the target waypoint	0.00	98.60	41.62
Incident over union between area of spray efficacy and 0.5 m radius of target	0	0.51	0.19
Incident over union between area of spray efficacy and 0.75 m radius of target	0	0.75	0.28
Percentage of vegetation killed within 0.5 m radius of the centre of the area of efficacy	7.76	100.00	79.41
Percentage of vegetation killed within 0.75 m radius of the centre of the area of efficacy	4.85	100.00	65.77
Incident over union between area of spray efficacy and 0.5 m radius of the centre of the area of efficacy	0.07	0.81	0.38
Incident over union between area of spray efficacy and 0.75 m radius of the centre of the area of efficacy	0.05	0.83	0.52

The resulting metrics for the shape and size of the area of spray efficacy (spot roundness, area, shape index and corrected shape index) were correlated against factors that might influence the area of spray efficacy and inferred targeting efficiency. Information on these factors, including aspect, slope, spray height, wind direction and speed, is presented in Table 1. Correlations were generally weak at best and are not reported in this paper. The only correlation of note was a modest correlation between shape index and max slope ($R^2 = 0.25$).

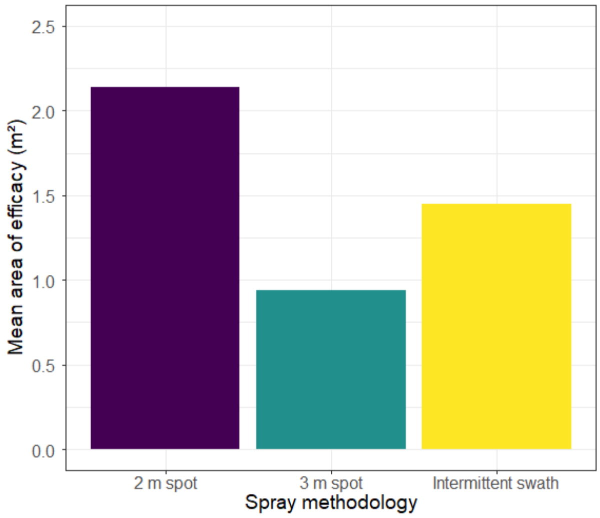

Figure 14. Bar plot showing the mean area of spray efficacy for 2 m AGL and 3 m AGL spot and intermittent swath methodologies.

The mean area of the area of spray efficacy was affected by the height of the craft. When the different methods were compared, the spot spraying method at 2 m AGL produced a mean area of spray efficacy of 2.14 m^2, spot spraying at 3 m AGL produced a mean area of spray efficacy 0.94 m^2 and the intermittent swath method produced a mean area of spray efficacy of 1.39 m^2. Flights for the intermittent swath methodology were only conducted at a height of 3 m AGL.

Discussion

Key points:

Accuracy of GNSS for navigating to waypoints

Analysis of the subset of points found that it was possible to navigate on foot to the waypoints of the seedlings detected from aerial imagery using an RTK-enable mobile GIS with a high level of accuracy. The mean navigational error was 0.22 m, with an RMSE of 0.36 m and only 4 of the points falling more than 0.5 m from the target. This proves that the use of RTK GNSS makes it possible to navigate to a feature of interest to within a threshold that would be suitable for precision spraying. Since the date of the trial, Australia and New Zealand's partnership have implemented the Southern Positioning Augmentation Network (SouthPAN). SouthPAN, which became operational on September 26th 2022, is a satellite-based augmentation system (SBAS) which will increase GNSS accuracy and could have a significant positive impact on the accuracy of UAV operation and general navigation.

Targeting efficiency of the spray craft

The areas of spray efficacy were not as accurate as the GNSS trials, with the mean distance between the centre of the areas of spray efficacy and the target waypoint being 0.61 m, an RMSE of 0.71 m and the minimum and maximum distance of ~0 m and ~3 m. These figures do not necessarily indicate that the spray was missing the targets, it simply indicates that the centre of the area of spray efficacy was overall off target. The centre of the area of spray efficacy is not only influenced by the location of craft at time of spray release, but also all the factors that influence the spray droplet trajectories from their point of release to deposition. The resulting deposit pattern influences the dose per unit ground area and consequent efficacy. If the area of spray efficacy was on target, but elongated in a particular direction, then the centroid will move in that direction (Figure 15). It should also be noted that, due to time constraints, SPS Automation were unable to programme the craft to record all of the data that would have been useful for analysis. One such metric that was overlooked was the GNSS location of the craft when spray was released. Due to this, we are not able to assess whether the offset between the area of efficacy centroids and the target waypoint was caused by the crafts physical location being off target. This data should be recorded for future study to ensure that this variable can be accounted for.

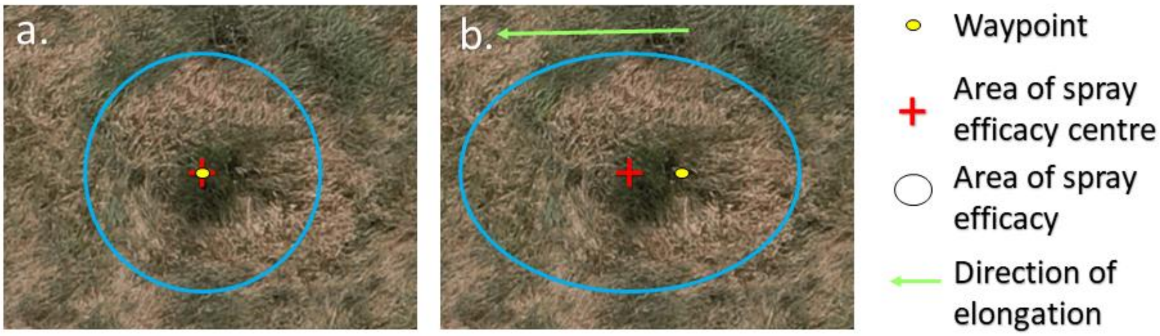

Figure 15. Diagram demonstrating how the centroid of a spot can be influenced by the elongation of the area of spray efficacy, moving the centroid further from the target waypoint.

Our results show a moderate level of accuracy when all of the different sources of error, such as the weather conditions, the complexity of the terrain, and the lack of recorded information about the positioning and targeting accuracy of the craft are taken into consideration. The method for annotating the extent of the spots is relatively subjective, which could be influencing the results. As the spots had been sprayed previously, and there were some areas of browned grass in the pre-sprayed imagery, it was difficult to get certainty on the actual area that had been killed by the chemical. Future research should be carried out on a site with even, green vegetation surrounding the trees, such as a recently planted paddock, or setting up targets as artificial targets on a plain background. This method was used in a previous study, where artificial trees were set up on a surveyed grid of locations, and collector plates were set up on each "tree" to assess the accuracy and efficacy of the deposition (Richardson, et al., 2020). Additionally, our annotations did not include the seedling itself within each of the area, which would have biased the area of efficacy calculations to some extent due to the variation in tree size (Figure 16).

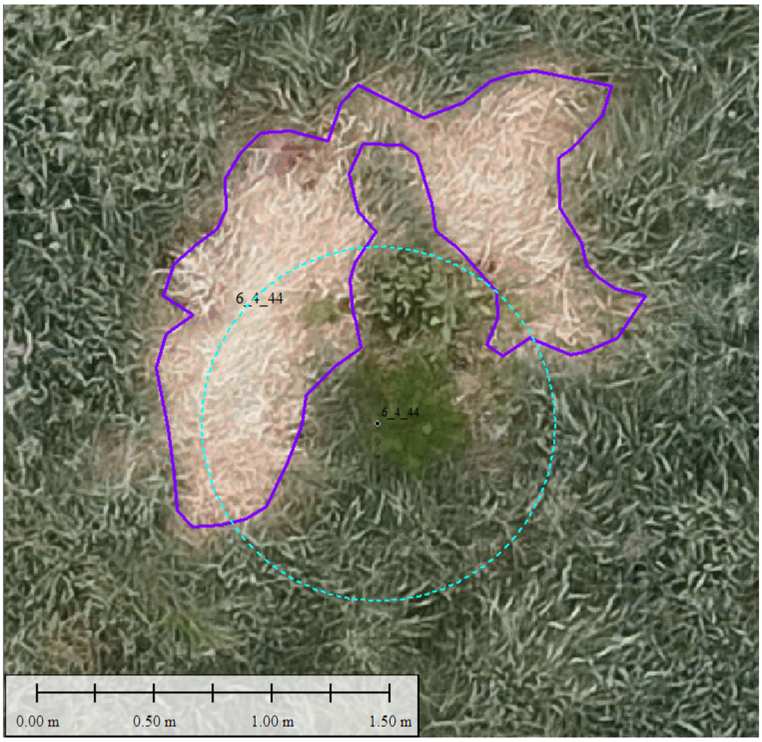

Figure 16. Example of spot annotation (purple polygon) showing the seedling crown is left out of the annotation, whereas the prescribed area (blue dashed circle) takes into account the seedling crown.

Future research should aim to take factor this into account. Deep learning algorithms have been successfully trained in detecting young *P. radiata* trees (Pearse, et al., 2020). This would be an effective method for detecting the seedling crowns, for which a crown area could then be calculated and removed from the prescribed area calculations. With enough training data, deep learning algorithms could also be trained to automate annotation of the area of spray efficacy too, which would reduce the subjectivity of the exercise.

Spray efficacy

Our results indicate that the shape of the areas of spray efficacy was not regular. The minimum and maximum areas for the areas of spray efficacy was 0.09 m^2 and 11.9 m^2 respectively, with a mean area of 1.64 m^2. This is approximately what was prescribed to release the trees with a circular spot with a diameter between 1-1.5 m (0.79 - 1.77 m^2). The nominal shape for spot release would be a circle. The Polsby-Popper test assesses the roundness of a shape and expresses it as an index in which a circle would have a value of 1 and a random shape with no circularity would have a value of 0. Our results overall showed that the areas of spray efficacy were not round or regular, with a mean roundness of 0.51, with a minimum of 0.14 and a maximum of 0.92. Whether the area of spray efficacy is round, square, or another shape, the importance of shape assessment is that the area has a regular, continuous size and shape. Ideally, the seedling should be located in the centre of the area of spray efficacy, and a consistent distance from the target seedling to the shape perimeter. In future studies, the spray deposition of the craft should be assessed in controlled conditions so that a baseline of the spot shape and spray pattern can be measured. In practice, the seedling would shade the direct deposition area, which affects the annotation methods that we have used in this study.

When comparing the nominal area to be released around each tree with the actual area of spray efficacy, there was only an average overlap of 41.62% and 48.57% between the required area to release and the actual area released for a 1.5 m and a 1 m diameter target prescribed target area respectively. This tells us that the spray deposited was ~40% to 45% on target. When assessing the overall accuracy of the area of efficacy between the prescribed area to be released and the actual area released, the mean IoU was 0.28 for a 1.5 m target and 0.19 for a 1 m target. This measure takes into account the area of both the prescribed and actual spots and the overlapping area between the two. These results also show that, overall, the spray efficacy was moderate in its ability to kill the prescribed area for both a 1 m and a 1.5 m prescribed diameter target, however, the relatively poor IoU values indicate that there was a reasonable amount of spray that was off target.

To assess whether the area of spray efficacy would have effectively released a 1 m or 1.5 diameter prescribed target, we also compared the area of spray efficacy to an artificial prescribed area around the centroid derived from each area. These results reported much higher mean values for percentage of spray on target (79.41% and 65.77% for a 1 m diameter and 1.5 m diameter prescription respectively; Table 5), and higher mean values of IoU (0.38 and 0.52 for a 1 m diameter and 1.5 m diameter prescription respectively; Table 5). This indicates that the craft can produce a spot that is on average capable of releasing areas of the prescribed size the majority of the time. Without any information on the location of the craft at the time of deposition, it is not possible to comment as to whether this offset was caused by the locational accuracy of the craft, or other factors such as spray system configuration or environmental factors,

Overall, our results show that the SPS-customised Aeronavics Icon was moderately accurate in its ability to fly to the spot locations, however, the spray only effectively released ~20% to 30% of the prescribed area for a 1 m or 1.5 m diameter circular control area. As our results only show the area of effective vegetation control and not the area that the spray was actually deposited, it is difficult to assess whether the irregular shape of the areas of spray efficacy and off-set is due to the deposition of the herbicide, or an exterior influence, such as rain, slope or wind. When the results of the areas of spray efficacy were assessed against the environmental and operational metrics that could have influenced the deposition, no obvious correlations were observed. The most notable correlation was a moderate correlation between maximum slope and shape index (R^2 = 0.25). Shape index is not the most intuitive metric for comparing shapes as it is influenced by size, i.e. two shapes with the same shape but different area would give two different results (Bhardwaj, et al., 2019). We also compared other metrics that are not constrained by size (roundness and corrected shape index), however, these only returned weak correlations (R^2 = <0.2). It should also be noted that, while wind data was collected at the trial, the location of the weather station was chosen to be central to the wider trial area and is possibly not representative of wind speed near the craft. Due to adverse wind conditions, sites were chosen that were in the lee of hills to reduce the impact of wind, and the wind speed monitored on a handheld anemometer were significantly less than those recorded by the met station. Future study should look to have more localised wind monitoring. It would also be interesting to assess the areas of spray efficacy with the distance from the top of the slope for any correlation.

One notable trend was between flight altitude and area of spray efficacy (Figure 14). The different spraying methodologies produced different mean areas of efficacy (i.e., spot sizes), with the intermittent swath method producing a larger area of spray efficacy than the spot spraying method conducted at the same height (Figure 14). When analysing the effect of height against the area of efficacy for the spot spraying results alone, the higher altitude flights produced a smaller area of efficacy (Figure 14). Without more data it is impossible to attribute the smaller area of efficacy at higher altitudes of release to any particular mechanism. It may be due to a reduced area of spray deposition possibly due to reduced wake deflection from the ground at the higher flight height. Conversely, the spray deposition area may actually be increased, due to a wider swath width and increase ambient wind dispersal having longer to act upon the falling droplets yet giving a reduced area of efficacy due to a smaller area receiving a dose that exceeds the efficacy threshold concentration. Previous research has found that as the spray release height increases, the percentage of spray drifting off target also increases (Ahmad, et al., 2020). There is a known interaction between wake, droplet trajectory, release height and wind speed. Many studies measuring swath patterns and spray drift have been conducted in controlled conditions over flat surfaces, but few have characterised drift and deposition when spraying over vegetation canopies. To this end, we can only speculate whether the minor increase in spray release height in our study is significantly influencing the amount or pattern of spray deposition and consequently the resulting area of spray efficacy.

Modelling the effect of variables such as wind speed and direction, slope, and flight altitude is highly complex and our results have not highlighted any trends. Future study on a range of slope gradients, and a range of wind conditions, with repetitions of different flight altitudes across each variable would enable more rigorous analysis and a better understanding of the crafts performance in each of these varied parameters. In addition, SPS Automation did not have adequate time to fully programme the system to record information, such as flow metre recordings, to assess actual chemical volumes applied per spot. With more development of the system, this valuable information could be included in the spot pattern analysis.

Work rate and cost efficiencies

Due to the technical issues and adverse weather conditions that were faced during the trial period, there was not enough data to carry out any time efficiency studies on the craft. We can, however, make some estimates based on the craft specifications and prior knowledge of the working system. The craft has a maximum carrying capacity of 8 L of chemical mixture, and therefore at a rate of 45 mL per spot, the craft can spray ~177 seedlings per tank. For the stop and spray method, with an average application time of 1.3 seconds, and with an average of 5 seconds between each seedling, the craft could spray 177 seedlings in approximately 19 minutes. The craft is able to fly for 16 minutes on a full tank of fuel carrying maximum payload, and 31 minutes carrying half payload, therefore, with the payload reducing throughout the flight, the craft should be able to spray a full tank of herbicide without having to land for a refuel. Pit stop times, to fill up fuel and agri-chemical tanks, are estimated by SPS Automation to be approximately 2 minutes, therefore the total time to fill the tanks and spray 177 trees is 21 minutes. When planting at a standard stocking of 833 stems per hectare, it would take approximately 4.71 tanks to release spray 1 hectare, which would indicate a work rate of ~99 minutes per hectare. Extrapolating this to a regular working day, it would be possible to spray ~4.85 ha in an 8-hour period. There would be additional time for setting up and packing down the craft, which would be approximately 0.5 to 1 hour, depending on the complexity of the system and the experience and size of the crew. Currently the system requires three operators: one pilot controlling the UAV, one pilot controlling the software and one ground crew member refilling the tanks. This would mean that it would be ~3 personnel days to release spray 4.85 ha. SPS Automation estimate that this system, when fully developed and tested like their custom system for spraying wilding pines, could be operated by a single pilot, and if fuel and chemical were pre-mixed at the start of each day, the same work rate could be achieved by a single operator, with additional time for setting up and packing down the craft.

For cost efficiency, the daily rate for this trial was $250 per person per hour, therefore, a per hectare rate for spraying with a crew of three operators would be $1237.50. If a day of spraying consisted of eight hours, then the cost to carry out a full working day would be $6000. The reality of a working day for a UAV crew is that there would be time for setting up and packing down, along with a one-hour break for lunch. An additional $750 to $1500 should, therefore, be added for set up and pack down, based on 0.5 to 1 hour at either end of the spraying. These costs would be one third of this total cost when the system is fully developed and operated by a single pilot, with an estimated daily cost of $2250 to $2500. The average hourly rate for a UAV contractor is approximately $99.12[2] per person per hour. This would make costs significantly cheaper, however, these average industry costs take into account all UAV contractors from technical contractors operating large and expensive crafts under CAA part 102 regulations (reference), to a single operator doing aerial photography. SPS Automation are a technical research and development company, and not a typical UAV contractor, and although these costs are indicative, the reality is that for a UAV spraying contractor, who needs higher tier certifications, chemical handling qualifications, and more expensive equipment, the costs will likely be higher. According to the Chair of UAVNZ and Senior Lecturer/RPAS Consultant at Massey University School of Aviation, Dr I. L. Henderson, UAV spray contractors can range from $200 to $500 per hour depending on the size and complexity of the craft being used, although some contractors charge by the job rather than the hour (I. L. Henderson, personal communication, January 27, 2023). Note that none of these costs take into account the cost of the agrichemicals, because it is assumed that the forester would be adding these costs on top regardless of whether using manual or UAV contractors to do the work.

Based on some figures supplied by Pan Pac for carrying out spray operations with manual crews, the approximate daily rate per person for spraying is $450 per day. One person can spot spray one ha in grass in approximately 3 hours, therefore, in a typical day one person can spray ~ 2.7 ha, making a per hectare rate of ~$166.67 (Table 6). When we break this down to a per hectare rate, the UAV is nearly ten times the cost of a manual contractor ($1562.5; Table 6), and even when the system is fully developed and can be operated by a single pilot, the cost per hectare will

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[2] Figures calculated by taking the average turnover of a UAV company in New Zealand ($108,000) from 2018 (Airways NZ, 2018), applying inflation of 23.9% from 2018 rates to 2023 rates, and dividing by the number of chargeable hours per year (1350).

still be will still be nearly 1.5 times the cost (~$520.84; Table 6). If we use the national average UAV contractor rates, the cost improves, but the per hectare rate is still nearly fourfold the cost of a manual release sprayer ($619.5). The cost becomes comparable if the system could be operated by a single operator at the national average rate ($206.50; Table 6).

Table 6. Cost efficiency calculations for UAV-based spot releasing and manual releasing.

Method	Hourly rate	Daily rate (8 hours work)	Daily rate (inc. 1hr set up and 1hr pack down)	Cost per hectare	Number ha per day per person
UAV – based on SPS Automation costs (3-person crew)	$750	$6000	$7500	$1,562.5	1.6 (4.8 for crew)
UAV – based on SPS Automation costs (1-person crew)	$250	$2000	$2500	~$520.84	4.8
UAV – based on national average UAV contractor costs (3-person crew)	$297.36	$2,378.88	$2,973.6	$619.5	1.6 (4.8 for crew)
UAV – based on national average UAV contractor costs (1-person crew)	$99.12	792.96	$991.2	$206.5	4.8
Manual (3-person crew)	$168.75	$1350	NA	~$166.67	8.1
Manual (1-person crew)	$56.25	$450	NA	~$166.67	2.7

These calculations do not take into account the cost of chemical, and the daily rates assume that it is possible to actually spray for eight hours in a day, which at the time of year when these operations are taking place is unlikely. It was noted that the UAV system was able to deposit chemical in wind conditions that would usually not be practical for manual spraying. The downdraft of the UAV could possibly facilitate spraying in stronger winds and even extend the spraying window further than currently possible with manual spraying (Chyrva, et al., 2022; Shi, et al., 2022). In addition to this, it must be taken into consideration that the UAV spraying contractors are a new and different pool of workers to enter into the forest industry, which will alleviate pressure on the labour shortages that exist within the silvicultural workforce and will free up silvicultural workers to work on other tasks, such as pruning or thinning. There are also health and safety benefits to be considered, with UAV operators being able to spray chemicals remotely, compared to operators being exposed to chemicals for long period with the current knapsack spraying methods.

In addition to reducing the number of operators to increase efficiency, there is also potential to increase the number of crafts per operator. Swarm technology allows multiple UAVs to be flown from a single controller. With this technology, the number of hectares per day, per operator could be greatly increased, bringing down the costs still further. This technology is currently in development, so the cost of using a single craft should not be seen as off-putting during these early stages of technological development.

Additionally, even though spot and intermittent swath spray methods were applied in this study, we did not get enough data to full analyse the effects of these two methods on time efficiencies. More development on the craft is required to fully optimise the intermittent swath technique to optimise travel speeds. Future study should build in time efficiency studies to assess the any potential benefits for intermittent swath (continuous flight) over the stop and spray spot methods.

Recommendations and conclusions

This research is, to the best of our knowledge, one of the first operational trials to have been conducted with the UAV spot spraying method on a forestry site. It has given valuable insight into the opportunities that this technology may bring. This research provides evidence that UAVs are able to fly to a given location and apply a prescribed dose of chemical, opening up new opportunities for precision applications for vegetation control, nutrition, and potentially other operations such as chemical thinning. The trial, however, did show that the overlap between the prescribed area to be controlled, and the area released was relatively low. This indicates that more research and development is needed on the system to understand in more detail the impact of environmental and operational variables on the spray deposition and the resulting area of efficacy.

Due to bad weather and some technical difficulties prior to the trial, the planned calibration trials were also cancelled. Calibration of the spray system is critical to optimise the spray pattern and characterise shape of the spot produced at different heights above ground level. It would then be possible to model the effect of slope or wind on the deposition pattern, which can then be tested in field trials. Eventually, with enough understanding, these effects could be compensated for in real time by engineering the system to cope with them (for example, live terrain calculations combined with gimbaled nozzles).

This study has created a novel methodology for assessing the area of efficacy of spot spraying using high resolution UAV remote sensing, which enables the capture and analysis of large areas. This will enable the study of spray patterns over areas much larger than have previously been possible. The methodology, however, does lack a means of assessing the spray deposition compared to the area of spray efficacy. Future studies should assess spray deposition through the integration of capture dishes onto a subset of waypoints across the trial to overcome this shortcoming. Additionally, by using a highly visible dye, it could be possible to carry out a mapping flight shortly after the spray has been deposited to enable the annotation of the sprayed area. This could then be calibrated by the subset of capture dishes, and then compared with the area of efficacy, to gain a more thorough understanding of the influence of environmental and operational variables on deposition and efficacy.

The turnaround time for this project was relatively fast, with only a few months available for SPS Automation to develop and test the spray craft prior to applying it in the field. Future research should build in more time to modify and test the system in an iterative manner, to enhance the performance, and increase the chances of successful capture. The window for the field trials was also in a particularly wet and windy part of the year, and so with a greater window for future studies, adverse weather conditions would not be such a limiting factor.

Although the UAV seedling detection carried out within this project was not successful, we recommend future study in this area try even higher resolution cameras (such as the DJI P1 with a 45 MP camera), which may aid in detection. Additionally, this study only assessed UAV remote sensing in grass and not in cutover, where seedlings would arguably be easier to identify and have less competition from surrounding vegetation. Trials in cutover, especially with greater resolution cameras are, therefore, recommended.

Future studies should also examine spraying pre-planned tree locations prior to planting. If the planting locations are planned, the trees can be planted in pre-determined locations to ensure that the site is stocked optimally. These locations can then be “geo-printed” to the site, using a spray craft. The planters can then plant into these spots, aiding in efficiency by breaking down the vegetation and making identification of planting locations and cultivation easier. The craft then returns to the same locations for release spraying, negating the seedling detection step, which was found to be ineffective by this study. By investing in this technology, it could open up additional operations such as marking trees for pruning, precision nutrition, or chemical thinning of trees, and so there could be real opportunities for developing this as a precision forestry tool. If nutrition could be coupled with release spraying, this could add value to the operation too.

According to our calculations, the cost of UAV release spraying is currently significantly higher than manual spraying. With development and gains in efficiency, this cost is likely to be greatly reduced. It cannot be ignored that, despite the cost increase, the additional labour that can be brought to the industry through adoption of this technology is undoubtably worth exploring further.

Overall, there is a considerable amount of development needed before this technology becomes operational, however, the concept of using UAVs to accurately navigate to seedling locations and spray them has been proved. It is our recommendation that exploring this technology further will be highly beneficial to industry.

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Appendix A

Precision Forestry With Drones

SPS Automation LTD

August 15, 2022

Contents

Introduction

This document contains a review of work conducted by SPS Automation LTD (SAL), as well as a proposal of future works. The sections are:

1. Release Spraying
   - A discussion on the data collection and analysis performed for the purpose of release spraying.
2. Pre-spraying
   - Outline of proposed methods for automated pre-spraying of tree locations for forestry establishment.

1 Release Spraying

This section discusses work that SAL has conducted around the detection of recently planted trees for the purpose of release spraying. Primarily this covers the data collection and analysis work. Aerial imagery was collected by SAL via drone using Lidar, RGB/conventional camera and a MicaSense RedEdge camera.

1.1 RGB/ A6000

1.1.1 *Background and Motivation*

When mapping any area, capturing RGB imagery is typically the default medium for data collection as the end product is versatile (orthophotos, digital terrain maps etc) and intuitive. Drones with high resolution cameras are widely and relatively cheaply available making capturing RGB data more accessible than ever. No discussion on remote sensing methods would be complete without an evaluation of the detection capabilities of RGB. Remote detection using RGB imagery can be done using a wide range of established methods, each with various strengths, weaknesses and use cases. In this section we briefly look over two visual detection methods and discuss how they relate the context of release spraying and respraying.

- A Convolutional Neural Network (CNN) is a type of neural network used to analyse visual data. Most commonly referred to as "Deep Learning", systems based on CNNs have become popular in recent years. The primary drawback of a CNN based detection system is a vast amount of training data required to have a robust system.
- The HSV filter converts a colour image into a binary black and white image. The colour image is broken down into three channels, namely colour (Hue), brightness (Value) and Saturation. A tolerance is specified for each of these channels. All pixels which lie within this tolerance appear white in the black and white image. All pixels which do not lie within this tolerance appear black.
- The watershed algorithm is a classic algorithm used for segmentation and is especially useful when extracting touching or overlapping objects in images.

There are many other computer vision methods that could be evaluated and discussed here, how- ever these have been chosen as they represent very diametrically different methods for approaching a detection problem.

Figures 1 and 2 show some raw imagery taken using the SAL mapping aircraft RGB payload. For the recently planted trees to be release sprayed, data was captured at a height of 13 meters, for a ~0.3 cm ground sampling distance. As a reference, Figure 3 shows a fully planted hill section of small saplings taken from a cell phone camera.

Examples of RGB imagery captured from the RedEdge, which has a lower resolution than the A6000, can be seen in figure 6 (a) and figure 8.

1.1 *RGB/A6000*

Figure 1: RGB imagery from the A6000 of the large trees.

Figure 2: RGB imagery from the A6000 of the small, newly planted trees.

Figure 3: Photo of the small, newly planted trees.

1.1.2 Results

Neural Network Based Detection In SALs other work in wilding pines, CNNs are used for tree detection. However, the CNN models and datasets developed by SAL for wilding pine detection are ill suited for detection of the new seedlings, as they are developed for use on larger trees, which are generally surrounded by non-green vegetation such as tussock. Even manually identifying the trees from the constructed orthophoto proved to be problematic. Additionally, given the limited time available to generate training data for a CNN based detector, this method was considered to be unviable.

HSV Filtering with Watershed Algorithm The use of an RSV filter combined with either a watershed algorithm or blur+blob detection did yield some promising results when the focus was to detect the pre-sprayed areas. These methods, however, were unable to differentiate the small trees for release spraying.

Figure 4 shows the extracted GPS points from an orthophoto supplied by Scion, of a tract of previously release sprayed trees. Without ground truth information about the planted tree locations, it is difficult to analytically evaluate the accuracy of this method but upon initial visual review the results look promising. Similarly, figure 5 shows a zoomed in view with the visual RGB data displayed underneath the GPS points.

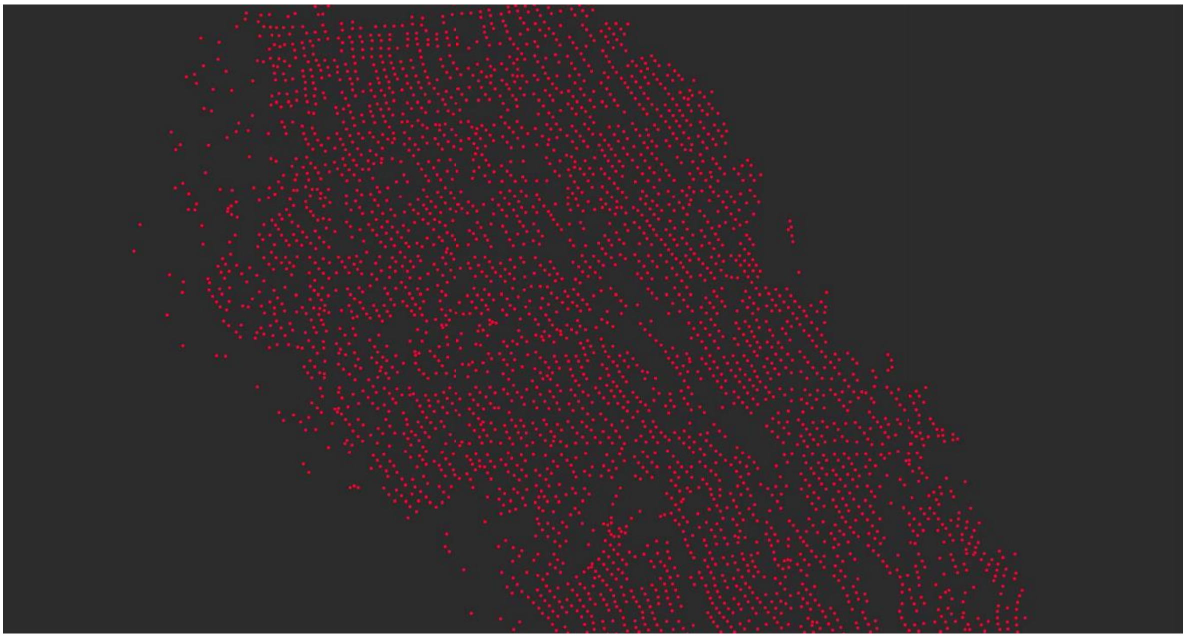


Figure 4: Plotted results of using a RSV colour filter with watershed algorithm for detection of the pre-sprayed tree circles.

Figure 5: HSV colour filter results show over the provided orthophoto.

1.2 RedEdge/NDVI

1.2.1 Background and Motivation

Normalised Difference Vegetation Index (NDVI) is a Vegetation Index (VI) that is often employed in remote sensing to determine things such as crop health and vegetation cover.

The broadband greenness VIs are among the simplest measures of the general quantity and vigour of green vegetation. They are combinations of reflectance measurements that are sensitive to the combined effects of foliage chlorophyll concentration, canopy leaf area, foliage clumping, and canopy architecture. These VIs are designed to provide a measure of the overall amount and quality of photosynthetic material in vegetation, which is essential for understanding the state of vegetation for any purpose. These VIs are an integrative measurement of these factors and are well correlated with the fractional absorption of photosynthetically active radiation (fAPAR) in plant canopies and vegetated pixels. Broadband greenness VIs compare reflectance measurements from the reflectance peak of vegetation in the near-infrared range to another measurement taken in the red range, where chlorophyll absorbs photons to store into energy through photosynthesis. Use of near-infrared measurements, with much greater penetration depth through the canopy than red, allows sounding of the total amount of green vegetation in the column until the signal saturates at very high levels. Because these features are spectrally quite broad, many of the broadband greenness indices can work effectively, even with image data collected from broadband multispectral sensors, such as AVHRR, Landsat TM, and Quick- Bird. Applications include vegetation phenology (growth) studies, land-use and climatological impact assessments, and vegetation productivity modelling. Increases in leaf chlorophyll concentration or leaf area and changes in canopy architecture each can contribute to decreases in the NIR wavelengths and increases in the red wavelengths, thereby causing an increase in the broadband greenness values. With respect to detection of trees for release spraying, the motivation for using NDVI index is that the target conifers will have a different chlorophyll concentration than the surrounding grassy vegetation, which could be detectable using a VI such as NDVI.

The NDVI is calculated using the following formula:

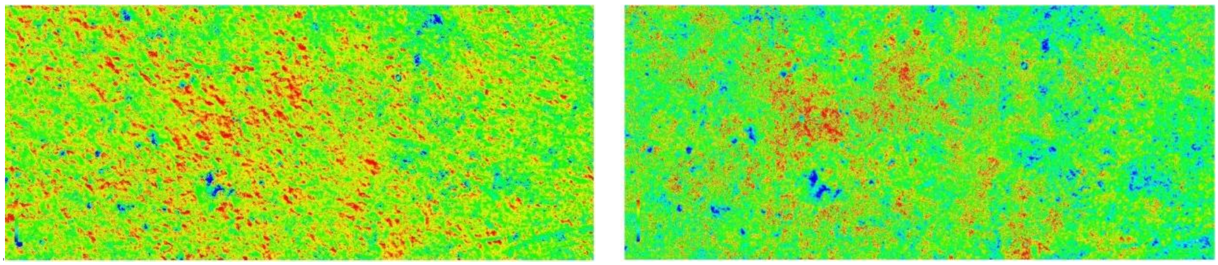
$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

Where NIR is the measured Near Infrared intensity. NDVI is one of the most commonly used.

Table 1: Alternative vegetation index calculations to NDVI.

Index Name	**Formula**	**Advantage over NDVI**
Renormalized Difference Vegetation Index	$RDVI = \frac{NIR - Red}{\sqrt{NIR + Red}}$	It is insensitive to the effects of the soil and sun viewing geometry
Modified Simple Ratio	$MSI = \frac{\frac{NIR}{Red} - 1}{\sqrt{\frac{NIR}{Red} + 1}}$	Increased sensitivity to vegetation biophysical parameters.

(a) RGB (b) NDVI



(c) RDVI (d) MSR

Figure 6: Examples of vegetation index images of the small tree site. It should be noted here that the colour gradients are not consistent between VI images, as they output different ranges.

vegetation indexes as it is simple to calculate and broadly useful for tasks such as land use monitoring and crop monitoring. However, NDVI also has the drawback in that it can saturate in dense vegetation conditions.

There are various other indexes that can be used for evaluating vegetation variation. For this evaluation we have looked into the Vi's described in Table 1.

1.2.2 Results

Small Trees Figure 6 shows various calculated vegetation indices calculated at the small tree site, along with an RGB image of the same area. While the Vi's did successfully discern the areas of high vegetation density, most of these higher density areas corresponded to grassy vegetation rather than the pine saplings. With no discernible pattern detectable within the images, development of an automated detection system was not pursued. The generated orthomosaic has a ground sampling distance (GSD), (the distance between pixels) of 1.02 cm at the high points. This means that the small trees which are approximately 5-10 cm in diameter will appear no larger than 10 pixels across in the VI images. Furthermore, the low foliage density of the young trees means that often the grassy vegetation below each tree saturates the VI image around the tree, preventing reliable detection. Mapping the data to an even lower GSD may help to remedy these issues though even with a higher resolution sensor, the flight times/number of flights become impracticable.

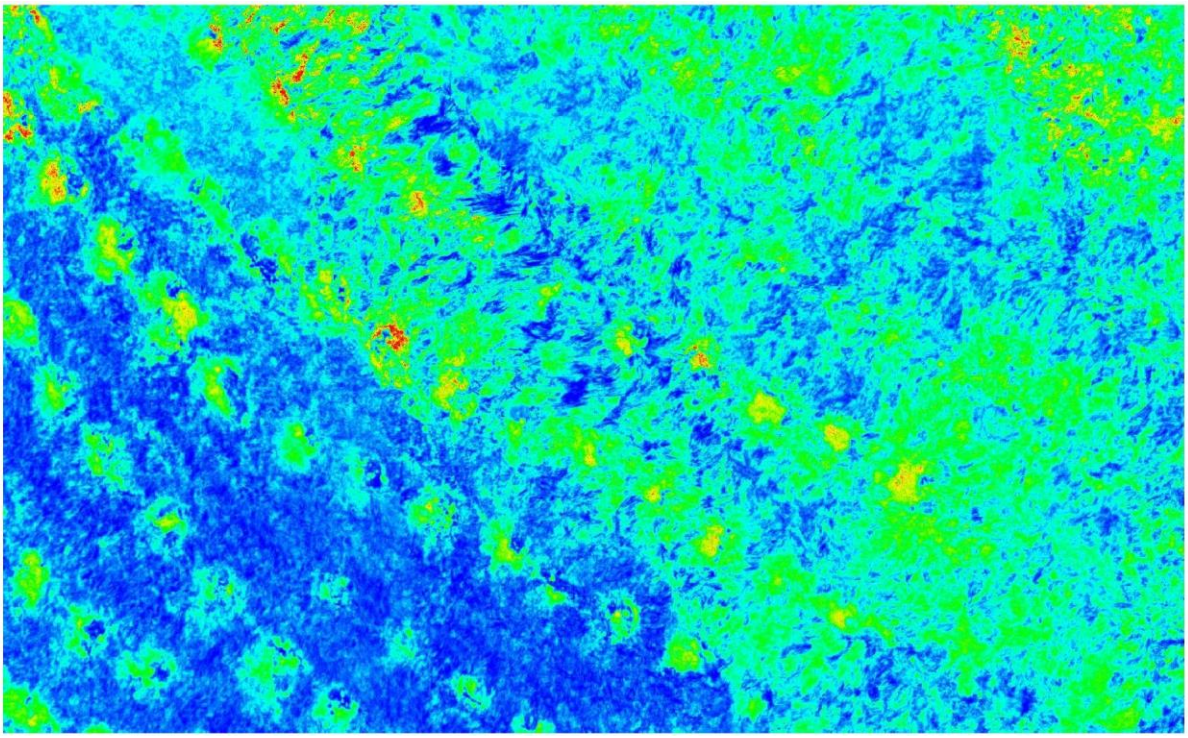


Figure 7: MSR index image of the larger trees

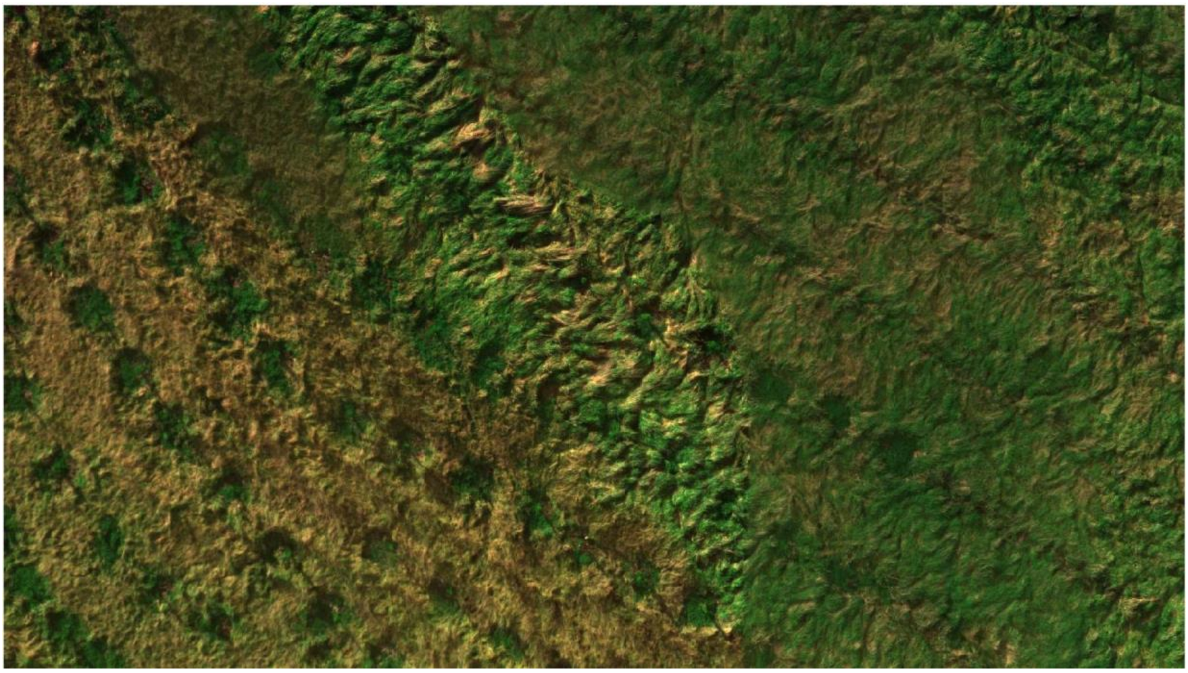


Figure 8: REG image from the RedEdge camera of the same area as figure 7

Large Trees Figure 7 demonstrates the difference that VI saturation can have on the viability of automated detection methods. The bottom left of the MSR image shows good potential for calculating the tree locations. However, this contrasts to the upper right side of the image which exhibits VI saturation, making tree location more challenging, if possible at all. Interestingly in the bottom corner it is the circle around the tree that is most visible, with (in many cases) the pine showing up highlighted in the centre of the circle. This corresponds expectedly with the RGB imagery 8 which shows that the bottom left side of the corner contains more non-green vegetation around the sprayed areas which should provide a lower response in a VI.

1.3 Lidar

1.3.1 Background and motivation

Light Detection and Ranging (more commonly referred to as Lidar) is a technology using laser sensors mounted on aircraft that fly over a landscape to capture a 3D view of the land. The sensor measures the time it takes for light to travel back and forth from the sensor to the ground. SAL uses drone mounted lidar in some of its collision avoidance technologies, though for the purpose of the release spraying work, lidar mapping was employed as an experimental method of detecting the young trees. The motivation for testing lidar for detection is that it is different from the other methods in that the information is structural/spatial in nature as opposed to being a form of visual detection like RGB and RedEdge.

1.3.2 Results

While the lidar was able to detect the larger trees that had already been release sprayed, the limited cross-sectional area of the newly planted conifers did not provide enough area to return a lidar response large enough to detect them.

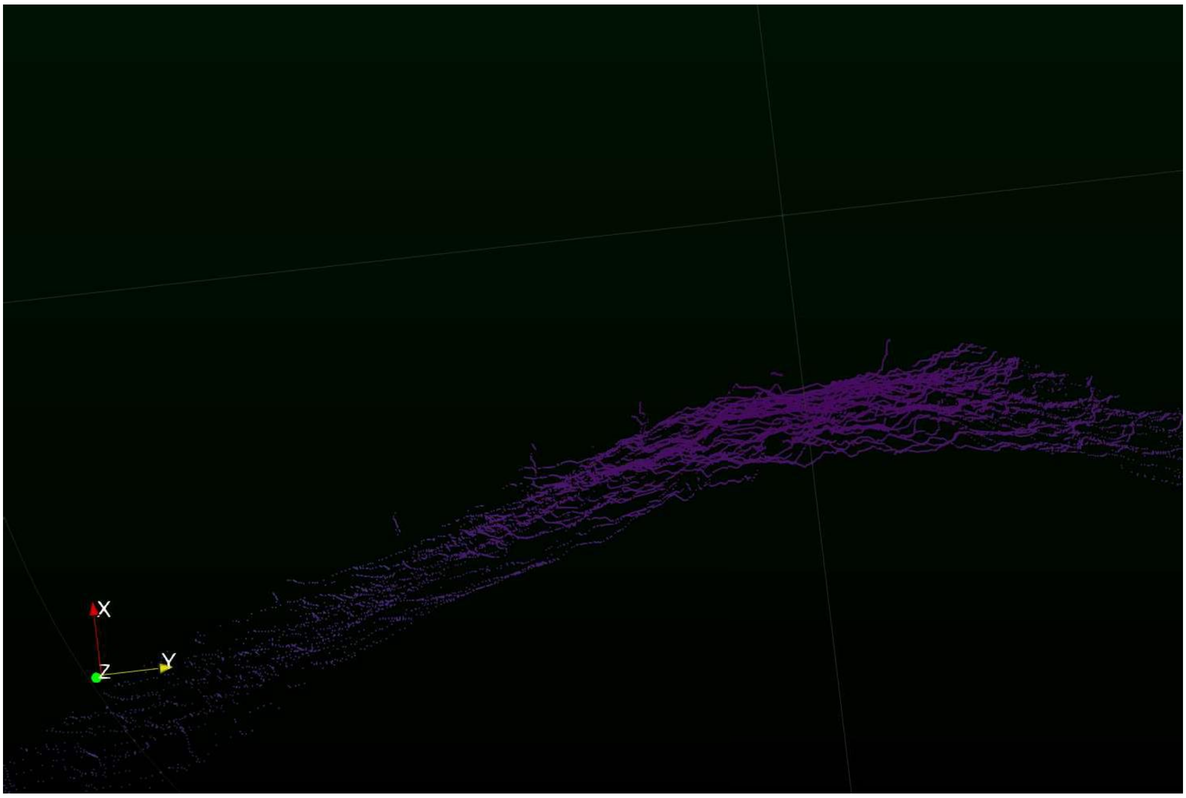


Figure 9: Cross section of a lidar scan taken from the test site

Figure 9 shows a visualisation of a lidar scan, it is a single frame taken from the lidar stream and shows a hillside with some ~ **1** m high trees that have previously been release sprayed. The presence of some trees can be seen here with the number of vertical lines present in the data. Due to the fact that these responses are limited to a single lidar line it is challenging to distinguish these trees from the noise floor present in the data. Higher resolution lidar could provide more returns per tree, allowing for easier detection but the cost of such units increases significantly with higher resolution sensors.

1.4 Conclusion

For the detection methods trialled, the use of RedEdge shows the most promise. However, for the use case of locating the small trees, even the RedEdge fails to be effective at detecting trees of such limited size. There is the potential for improvements to be made through use of a higher resolution sensor, such as the RedEdge-P. Lidar scanning also has potential for detection of the larger trees, though a higher resolution sensor would likely be required to implement a reliable system.

Overall, SAL finds that the automated detection and geolocation of the small, recently planted trees impracticable within the given timeframe for release spraying. With further investigation, SAL believes there is potential merit for detection of the larger trees or areas that have been pre-sprayed, though this is of more limited benefit.

2 Pre-spraying

Due to the challenge posed by locating the planted trees after that have been planted, SAL suggests implementing a pre-spraying method in which to autonomously spray the tree planting locations before planting. The spray flight could then be repeated precisely once the trees needed to undergo release spraying. This method eliminates the uncertainty that is inherent with detection methods, as any detection method intrinsically has some level of error in the form of false positives and false negatives. Section 2.1 outlines the proposed method steps. Section 2.2 talks about optimizing tree placement, the assumptions that have been made **in** the flight plan generation and discusses the customizability and control that is potentially available through use of such a system.

2.1 Method Outline

The pre-spraying method can be broken down into several steps

1. Collection of a shape file that outlines/geolocates the areas to be planted as well as details of areas to be avoided such as waterways, tracks, existing trees, fences, etc.
2. Generation of tree locations within the outlined planting area. These tree locations are then converted into a flight plan for the spray aircraft. More detail can be found **in** section 2.2.
3. Generation of tree locations within the outlined planting area. These tree locations are then converted into a flight plan for the spray aircraft. More detail can be found **in** section 2.2
4. Optional, high altitude mapping flight can be done over the areas to be planted **in** order to produce a digital terrain map. This can be used to optimise and improve the spray drone's navigation. This may not be strictly necessary if the final spray payload has sufficient development in the area of real time collision avoidance. Section 2.3 contains more detailed information
5. Spray mission is performed using the SAL Icon spray machine.
6. Trees are planted in the centre of each sprayed circle once the grass has had time to visibly die off.
7. Once the grass has resumed growing and needs to be release sprayed the same spray mission can be performed.

Using the RTK system installed on the SAL ICON spray machine the drone GPS has a ± 2cm accuracy during repeated flights meaning this is not a significant source of error between spray flights. The largest foreseen source of error with regards to the repeated spray flight is that if the wind conditions differ significantly between flights in both speed and direction then the spray patched has the potential to be slightly displaced from the original marks. However due to the adverse effect of moderate winds on any type of spray operation, both flights should ideally be taking place with very limited wind, limiting the potential to spray drift.

2.2 Flight plan Generation

Spray flight plans for each location can be generated automatically by SAL. As these flight plans are computer generated, there is the potential for significant high-level control over the design and general layout of the tree locations. The simplest way of generating a flight plan is based upon the 3x4 rectangular layout, similar to that used by industry at present. This pattern gives a density of~ 833 trees per hectare. If we require the trees to be planted in rows that are 4 metres apart and for the trees **in** each row to be 3 metres apart, then it will not be possible to devise a more efficient layout for tree planting than what is outlined here. By computer generating the planting patterns we can come up with alternative planting patterns and apply concepts from geometric packing problems. Packing problems are a class of optimization problems in mathematics that involve attempting to pack objects together into containers. The goal is to pack a single container with the maximum number of objects of a given size, minimising the wasted space in the container.

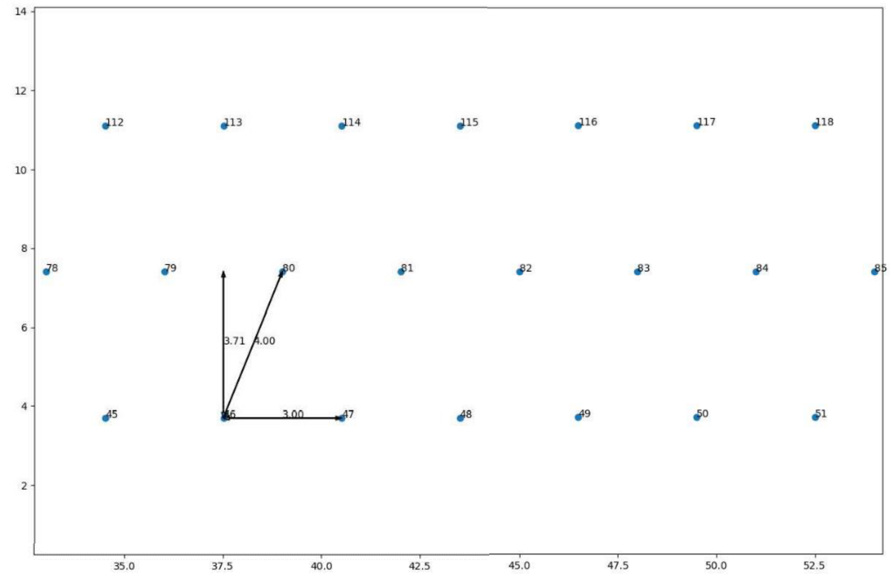


Figure 10: Diagram of the tree spacing using a 3-meter distance between trees within a row and 4 meters distance between trees in parallel rows.

If we adjust our planting spatial requirements to be that the trees in each row must be 3 metres from each other and a tree in a row must be at least 4 metres from the trees in other rows (inter-row tree to tree distance), then we can employ packing methods to calculate a new layout.

This subtle difference in requirements results in an approximately 7.8% increase in planting density when compared to planning in a simple grid pattern. This value is based on a Monte Carlo method (n=lO000) in which a random polygon is populated with points in a grid pattern and the number of contained points is compared to using the optimized pattern shown in figure 10. The exact change in planting density depends on the geometry of the area to be planted. The caveat to using this planting arrangement is that the tree rows are no longer spaced 4 metres apart, rather they would be approximately ~ 3.71 m apart. A similar change in planting density could be achieved using the standard grid pattern and reducing the between row distance by a similar amount, but this would not guarantee a 4-metre distance between trees of different rows. Ultimately, the merit of this method is contingent on the distinction between the distance between rows versus the distance between trees in adjacent rows.

As the flight plan generation is automatic, the input parameters can be tweaked to determine what values are most appropriate. The user defined values are as follows:

- Distance between trees in a row.
- Distance between rows of inter-row tree to tree distance.

Or

- Specify a desired planting density and have that single variable determine the inter-row distance.

Regardless of planting density, generating the tree locations programmatically and automatically carries significant advantages in terms of flight repeatability. Each flight plan would also have a number of parameters that can either be specified by the user or determined automatically using optimization. Optimization can automatically determine planting parameters such as the angle/bearing of the planted rows or the offset/zero points (*x*, *y* displacement of the whole planning grid within the geometry).

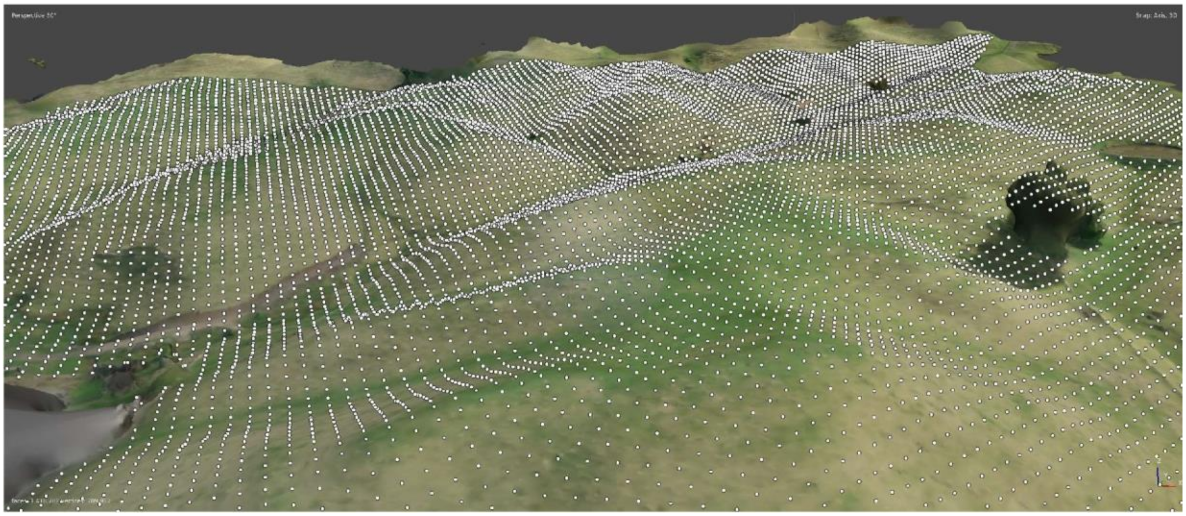


Figure 11: Preliminary tree planting locations plotted onto a 3d mesh of the site.

Figure 12: Top-down view of the preliminary tree planning locations.

Figure 11 shows a visualization of what a planting plan could look like on a real-world site. The base map is generated from data collected in Napier, on the 19 Ha newly planted site. Figure 12 shows the same planting matter but from a more overhead view.

2.3 Optional Pre-Mapping

For the simple method outlined above, an area mapping mission is not strictly required. However, performing a mapping mission does have the potential to provide some advantages.

- Opportunity for terrain aware tree placement. The method proposed here does not take land

terrain into account. Performing a mapping mission allows for the generation of a digital terrain map (DTM) which could be incorporated into the planning phase for more intelligent tree formation generation.
Resource for land management analytics. Using the georeferenced DTM and orthophoto this opens up the potential for future analysis such as volumetric measurement or health, pest and disease management.

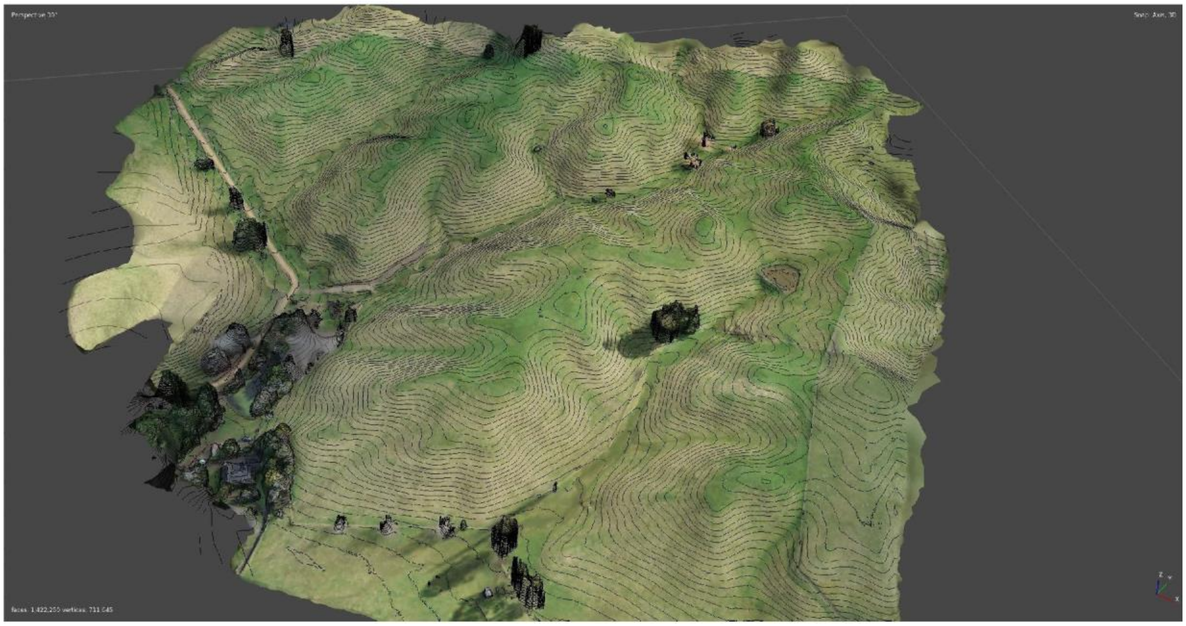


Figure 13: Generated 3d mesh, overlayed with 1 m contour lines.

Figure 13 shows an example of a generated 3-dimensional map of a 19-hectare area at the Napier site. This map is represented by a 3-dimensional georeferenced mesh using 266 images, which was collected during a single 40-minute flight. Maps such as these are valuable for detecting flight obstacles such as trees or powerlines.

2.1 Expandability and Potential Future Work

The deployment of a system such as the one outlined in section 2.1 presents the opportunity for a significant amount of future remote sensing and information collection.

- Assuming a pre-mapping flight is conducted, because the position of each tree is known, each tree can effectively be monitored using subsequent mapping flights. This can be done by generating a digital surface map (DSM) for each flight and measuring the volumetric or surface height change at the location of each tree.
- If the tree planting density needed to be reduced in the future, then the tree could be programmatically thinned via drone to the desired density.

Appendix B

SPS Automation, SCION, Pan Pac forestry block release spraying trial.

SPS Automation
LTD

October 30, 2022

Contents

Introduction

SPS Automation (SPSA) in conjunction with SCION performed a trial of an automated Unmanned Aerial Vehicle (UAV) release spraying system for Pan Pac forestry sites in November 2022.

This report begins by giving a brief description of the UAV operation procedure and spray methods used to give context. Next the brief high-level results and produced logs/data are described. The operational challenges encountered while on this trial are then discussed, along with any potential solutions and/or recommended future development work to overcome these issues. Swath and spot spraying is discussed in more detail along with the idea of pre-spray and respray operations. Concluded with a brief summary and a word on the practicality and future of the project.

This document assumes the reader is familiar with how the trial was carried out, and what the trial required.

1 Method / context

1.1 Equipment / system components

- Base
  - A central location with visibility of the operation location. Laptop, ground station, and RTK antenna are located here.
- Ground station
  - Connects to the UAV and injects RTK GPS as well as radio control.
- RTK antenna
  - An external antenna used for RTK GPS. Must be connected directly to the ground station.
  - Used to survey a RTK point
- Radio control hand controller
  - Controls the UAV in flight. Requires a wireless connection to the ground station
- Laptop
  - Used to monitor and manage the UAV and inject RTK GPS. Requires a wireless connection to the ground station.
- UAV
  - Aeronavics ICON retrofit with a petrol generator and customised spray system. The spray system uses four nozzles (AITX8001VK). These are a hollow cone, air induction, low flow rate nozzle.
- Pilot
  - Pilot in command, flies the UAV using the hand controller.
- Flight plan
  - A sequential list of targets that the UAV will visit in order. Generated by SPSA pre trial.

1.2 System operation

While operating, the UAV is in an automated flight mode, following a set of predetermined waypoints. The waypoints are generated programmatically using a flight plan generated prior to the trial. These waypoints tell the UAV where to fly to, and when to actuate its spray system. Typically, the pilot arms the UAV, takes off, positions the UAV near the beginning of the flight plan, then puts the UAV into an automated flight mode where it begins its flight plan.

1.3 Spray methods

For this trial, two spray methods were used: spot spraying, and swath spraying.

1.3.1 *Spot spraying*

This involves the UAV flying to the exact location of the tree, stopping, then ejecting its pre-programmed amount of spray. The main challenge involved with this method operating accurately surrounds the accuracy of the supplied GPS coordinates and UAV GPS system. This method is simple but is limited in terms of efficiency as the UAV must constantly stop and start moving.

1.3.2 *Swath spraying*

This involves the UAV flying to a location a set distance before the tree, beginning spraying, then continuing to fly over the targeted tree, ‘swathing’ the tree with spray as it flies over it. This method is more complicated but in theory allows for more efficient, smoother operation where the UAV is constantly in motion over the lines of trees, actuating its spray system only as it flies over the tree.

When compared to spot spraying, swath spraying has significantly more challenges associated with it:

- Timing
- GPS accuracy
- Dose delivery accuracy

2 Results

Currently other than the produced logs, the only results available are empirical results from those present at the trial, all results are purely observational.

Quantitative results will be produced at a later date once an aerial survey of the area has been completed and analysed. These results will ideally provide an insight into the accuracy of the swath and spot spraying using the provided logs.

2.1 Data description

Contained with this report is a CSV file (spray data.csv) detailing the locations sprayed per each zone seen in the map of the forestry plot also attached with this report (forestry map.pdf). The CSV fields are described as below:

- Spray run
  - The spray run the UAV is operating on. Each time the UAV lands after spraying chemical, this is iterated
- Iteration
  - The internal counter of which tree the UAV is up to within its spray run
- Spray zone
  - The zone the UAV is operating in as seen on the forestry plot map
- Spray amount (mL)
  - The amount the UAV is told to spray
- Latitude
  - Latitude of the targeted tree

- Longitude
  - Longitude of the targeted tree
- Intended rangefinder (m)
  - The altitude the UAV has been told to follow the terrain at
- Actual Rangefinder (m)
  - The altitude of the UAV at the exact moment of finishing spraying
- Time
  - The timestamp of the UAV when spraying finishes
- Spray type
  - Spot spraying
  - Swath spraying
- Notes
  - Any manually taken notes at the time the spraying was taking place, comments on weather, abnormal UAV behaviour, noted issues etc

3 Discussion and analysis

3.1 Operational challenges and recommended future work

Discussed below are the encountered operational challenges and any potential solutions and/or recommended future work.

3.1.1 *Aircraft / equipment failure*

Challenges Throughout this trial, the UAV presented an array of issues which at times prevented the operation from continuing. These issues originate from the raw UAV used. These issues primarily resulted in delays to the operation as they took time to resolve. A primary issue involved the RTK GPS not being injected properly / at all.

Proposed work SPSA is currently working with the manufacturer to resolve these problems.

3.1.2 *Low altitude*

Challenges While spraying, the UAV should be as close to the tree it is attempting to spray as possible as this increases spray accuracy and reduces the effect of spray drift. Currently the aircraft is set to follow the terrain at 3 metres by default, with 2 metres being allowed with closer supervision and further prior site inspection / assessment. During this trial, the UAV was flown at 2 metres for a short period of time. Then later increased to 3 metres to reduce risk.

Operating at <3 metres begins to exponentially increase the risk of collision with the ground or other obstacles due to several factors; The UAV is extremely heavy, meaning that it is comparatively slow to react to a requested increase of altitude. The rangefinder is mounted statically to the UAV. This means that as the aircraft ‘leans’, either due to correcting for wind, or being in forwards flight, the rangefinder reads the distance to the ground at the angle the UAV is pitched/rolled. This read value is usually larger than the true distance between the UAV and the ground.

The worst possible scenario occurs when the UAV is climbing a hill as it sprays or leans into the wind. The rate at which the UAV increases its altitude in response to the increase in hill gradient is insufficient to maintain a safe distance from the ground, this leads to the pilot occasionally intervening as the UAV almost clips obstacles / trees it should have climbed over.

Proposed work There are two current potential solutions to this problem which should be explored.

Gimballed rangefinder The downwards facing rangefinder could be mounted on a gimbal, which ensures it is always facing downwards, regardless of how aggressively the UAV is rolling or pitching. This would require minimal work and would give an immediate improvement, however, is limiting when compared to the other potential solution.

Sideways mounted lidar The 360-degree lidar system could be mounted sideways, so that specified groups of lasers can be used as an individual rangefinder, allowing for multiple rangefinder data streams to be injected to the UAV internal flight software. These groups of lasers should be selected based on the roll and pitch of the UAV, allowing the UAV to have a more complete vision of the ground and obstacles directly in front of it, regardless of how the UAV is flying. This solution also allows for pre-processing to be done on the lidar data, which means groups of lasers can be smoothed, averaged out and arranged in a way that is optimal for following the terrain.

Additionally, to each of these solutions, the UAV should have several altitude control parameters tuned, in particular the maximum altitude increases acceleration value. This will ensure the UAV can more aggressively increase its altitude if necessary.

3.1.3 *GPS point accuracy / Conversion*

Challenges The UAV used by SPSA operates solely on the coordinate system WGS84, this means for the UAV to be flown to any coordinate provided in any other GPS coordinate system, a conversion must be performed.

Before this trial began, SPSA was given the GPS coordinates of all target points in the GPS coordinate format NZGD2000 Which were then converted to WGS84 by SPSA (using the online LINZ tool). In this process, an error of approximately 0.6 metres was introduced. This resulted in the UAV consistently not arriving directly above the tree by a consistent offset error.

Points were regenerated by SCION, producing a slightly different coordinate set which was verified to be correct through a series of tests.

Proposed work There are two potential solutions to reduce future GPS coordinate errors:

- To reduce the number of conversions done and so the potential for error, SCION gives all coordinates to SPSA in WGS84.
- Before every trial, a verification of coordinates process is completed, where the SPSA coordinates are compared to SCION coordinates.

3.1.4 *Obstacles / Obstacle avoidance*

Challenges In anticipation of this trial and the obstacles potentially encountered, SPSA developed an obstacle avoidance module using a 360-degree 32 line lidar. This module would detect obstacles within a certain threshold of the aircraft, and make the UAV fly up and over the obstacle using a technique known as 'vertical bendy ruler'.

However, on the first day of the trial, it was found that using this module stopped the UAV from smoothly following / flying through waypoints. The module would make the UAV stop at each waypoint, and do a small amount of processing before the UAV could move on. It was found that this is a known current issue within the UAV's flight control software, which is third party software to SPSA.

This meant that throughout the trial, in order to have the UAV operate in a time efficient manner, this obstacle avoidance module must be turned off. This was not a significant problem for this trial, as the operation location could be chosen in such a way that there was little to no obstacles present and the pilot has a clear view of the UAV so can intervene if need be.

However, for full autonomous and Extended Visual Line of Sight / Beyond Visual Line Of Sight (EVLOS/BVLOS) operation a robust and reliable method of avoiding obstacles is required. Additionally, on inspection of several of the proposed spray areas, there were trees which are not suitable to be sprayed with a UAV, regardless of how well the proposed obstacle avoidance works. For example, large shrubs/trees overhanging the tree, and fences running directly next to trees in such a way that the UAV legs would easily get caught if flying at a low altitude.

Proposed work In order to solve this problem and so enable EVLOS/BVLOS operation, a significant amount of development and testing must be done in order to create a complete, reliable, and robust obstacle avoidance system. This system would use the 360-degree lidar, either mounted as described in 3.1.2, or as it is currently mounted.

In order for this module to be used by the UAV with no required pilot intervention/input, the UAV software system needs to have the ability to identify when a tree / area is not suitable for the UAV to fly into / operate in. The UAV must then be able to modify its own flight plan to exclude those areas. This again requires additional development and testing.

3.1.5 *Operation location*

Challenges For this trial, a specific area of the forestry plot was selected based on several key attributes:

- Visibility (of the UAV)
- Access, vehicles and equipment
  - Affected by wet weather
- Lack of obstacles
- Take-off / landing zone
- Available base location(s)
- Wind exposure

Due to the nature of the terrain the forestry plot is located in, there were approximately 4 out of 18 appropriate sites that SPSA deemed appropriate to operate on. The sites were deemed inappropriate due to the above factors.

Proposed work In order to be able to safely operate in a more varied environment and so a larger number of forestry sites, the technology outlined in 3.1.4, 3.1.2, 3.1.6 need to be developed. However, several factors laid out in 3.1.5 will be difficult to overcome. Base location, and the take-off/landing zone will likely always be a difficult location to choose, and wind exposure is impossible to control and can only be managed by choosing where to operate based on what the wind is doing.

3.1.6 *Flight plan manipulation*

Challenges Prior to the spray trial, flight plans were generated for the 18 zones as laid out in the forestry plot map. A flight plan is made up of locations, intended to be visited sequentially.

When on site and selecting an operation location, the considered locations are limited by the shape, border, and size of their respective generated flight plans. For example, if a generated flight plan passes over the proposed base, it either has to be clipped somehow, or completely discarded.

This is difficult to do when out in the field with no way to regenerate flight plans, or accurately select which trees or areas should be excluded.

Proposed work In order to quickly modify existing flight plans or regenerate custom flight plans when out in the field, a bespoke application is required to be developed. This application on a high level would require the following features:

- Import existing tree locations
- Import existing flight plan
- Display all existing tree locations
- Display a flight plan on a map
- Modify a flight plan
  - Using single points
  - Using drawn exclusion areas
- Generate a flight plan using an area drawn on a map
- Touch screen functionality
  - Ideally run on a tablet

3.1.7 *Spray drift / wind*

Challenges When the UAV was operating in sheltered areas, the spray drift was minimal, even with considerable wind being measured from the base. However, this changes as the UAV begins to climb out of its sheltered terrain towards ridgelines or more exposed areas.

Proposed work The lower the UAV flew to the ground, the less the spray swath was affected by wind. So, in order to reduce spray drift, the UAV should fly at the lowest altitude possible while operating safely. This requires the solutions described in 3.1.2 and 3.1.4 to be developed. Other than this, flying in sheltered areas, or in low wind (<2 m/s wind) will reduce spray drift.

3.1.8 *Smooth waypoint following*

Challenges In order for this system to operate both smoothly, and efficiently, the UAV needs to smoothly follow waypoints, without the need to stop and start abruptly. In order for this to happen, the UAV must satisfy a variety of conditions for it to 'arrive' at a waypoint and so allowing it to progress to the next waypoint. These conditions can be configured through a number of parameters within the UAV autopilot software.

The first day of the trial consisted of SPSA tuning these parameters in an attempt to make the UAV fly smoothly though waypoints, eventually an acceptable tune was created, however it is not currently optimal. For example, the UAV flies smoothly through waypoints, however it slows down when approaching waypoints, resulting in a longer flight than necessary.

Proposed work The UAV parameters need to be further tuned and optimised for forestry plot release spraying. Parameters that should be further optimised relate to the following:

- Vertical acceleration / deceleration values
- UAV preferred orientation in relation to direction of flight
- Maximum horizontal acceleration and velocity
- Waypoint arrival threshold
- Velocity when approaching waypoints

3.1.9 *Smooth terrain following*

Challenges The UAV operates in 'terrain follow mode', using a downwards facing rangefinder / single point lidar. This means the aircraft maintains a set distance between it and the ground (or any- thing caught in between). Through testing, SPSA found that the rangefinder sometimes temporarily reads a very low value, causing it to increase its altitude abruptly, and 'bob' up and down. These low values are caused by the rangefinder laser hitting the exhaust smoke from the petrol generator, the liquid sprayed from the spray system, or as the laser 'slides' on and off the side of a tree / obstacle below it.

Proposed work To improve terrain following, the technology discussed in 3.1.2 should be developed. Preferably the sideways mounted lidar method as this would give the ability to adjust and smooth the incoming data. Similar to 3.1.8, there is also a set of UAV parameters that should be tuned to improve this behaviour.

3.1.10 *Data / logs recorded*

Challenges Due to time constraints coming up to this trial, a portion of the software running on the UAV was under tested / underdeveloped, in particular the constant data capture and logging functionality. This led directly to one incomplete log / data capture.

Latitude Longitude / Location reported Due to the cut down nature of the logging soft- ware running on this system. The locations recorded are taken as the latitude longitude of the way- point/target the UAV is attempting to fly to and centre over, not the latitude longitude of the UAV at the immediate time of the UAV spraying. In the future both latitude, longitudes will be recorded.

Incomplete data capture Spray runs 1 - 14, excluding spray run 7, were recorded successfully. Spray run 7 however was not due to an edge case triggering an internal error causing a data loss.

An attempt at reconstructing the log was made, using the information manually noted down at the time relating to which trees, what height, and which type of spraying was done. This log data was reconstructed as spray run 7.

This spray run was accompanied by placing metal plates around every second tree, in an attempt to get a clearer visual representation of the spray distribution.

Proposed work The software system running is a considerably cut down version of SPSA's Wilding Pine control system which has been significantly modified. This means that certain features / functionality, although developed elsewhere, is not currently in this software. One feature in particular is the much more robust data recording / logging.

In order to ensure there are no data losses or inaccuracies as with this trial, more time and development work is required to improve the system logging software to a satisfactory level. The software system then needs to be comprehensively tested.

3.1.11 *Swath spraying*

Challenges In order for a swath spray to be successful, a conceptually simple process must be followed:

- UAV flies towards the targeted tree at
- UAV actuates its sprays system just before the targeted tree
- UAV flies over the tree at a constant velocity
- UAV turns off the spray system just after the targeted tree

There are two ways this process can be completed, a spatially calculated method, or a volumetric dose accurate method.

Spatial This method relies on the kinematics of the UAV as it flies over the target. The UAV flies at a calculated velocity based on the flow rate of the spray system and the desired spray coverage area. The spray system is turned on a pre-calculated distance before the target. This distance is calculated based on the UAV velocity, then adjusted to take into account any lag in actuating the spray system or the spray swath lagging behind the UAV. The spray system is then turned off a calculated distance after the target. Again, this is calculated using the UAV velocity and adjusted to take into account any external factors.

In theory this method will deliver a correct spray dosage and smoothly fly over each target. However due to several significant issues, this is not the reality.

One significant problem with this method is due to the issues laid out in 3.1.8. The UAV cannot reliably fly smoothly through waypoints and the velocity the UAV has been told to fly at is often not consistent. Another problem is that the lines of targets in the forestry plots are not uniformly straight, so the UAV must often turn corners of up to 60 degrees between targets, disrupting its smooth flight. This can be seen as an issue with the flight planning process carried out at SPSA. It is difficult to programmatically create flight plans that follow the natural contours and terrain that the trees were planted on when they cannot be numerically defined.

Volumetric This method ensures that the correct dosage is delivered per target. This method instead flies to a distance before the target, then tells the spray system to spray the correct dosage. The UAV then continues to fly over the target as the spray is being applied. The distance the UAV flies to before the target is a distance is usually determined empirically.

One problem to note with this method is that in terms of performance, it begins to blur the line between spot and swath spraying.

This method ensures that the correct dose is applied per target. However, it begins to lose the benefits of swath spraying. Due to the nature of the waypoints / missions created via this method, the UAV flies in a sometimes jerky manner. This is potentially caused by the close proximity of waypoints next to each other; The UAV arrives at one waypoint, then due to adjusting for wind, or potentially due to GPS error, has also immediately arrived at the second waypoint. This problem is negated in the spatial method as the waypoints tend to be further away from each other as they assume the UAV is flying at the velocity it has been configured to. Whereas this method experimentally configures the distance the UAV should start spraying at. The accuracy of this method is also yet to be determined.

During this trial, the volumetric method was used in preference over the spatial method. This is due to the very early tests done by SPSA; the spatial method proved to require a significant amount of work done before it should be used on a trial or with chemical due to how unpredictable it could be.

Proposed work In order to improve the reliability, accuracy, and effectiveness of swath spraying the problems described in 3.1.8 should first be addressed. Being able to smoothly follow waypoints with little to no stopping / abrupt flight movements will drastically improve the effectiveness of swath spraying. SPSA should then conduct a series of development and testing cycles, focussed on improving the volumetric method of swath spraying. This work should have a focus on ensuring smooth, consistent and reliable flight through waypoints with an optimal pre-spray distance. These tests should use a visual marker of some kind to reliably ascertain the accuracy of the swath.

3.2 Spot vs swath spraying

Though quantifiable results from this trial are yet to be seen, there are empirical results that can be derived from this trial.

Spot spraying appears to be more consistently accurate than swath spaying. This could be seen from basic visual inspection of targets for each type after operation. Spot spraying is less susceptible / vulnerable to wind or issues arising from the UAV navigation / movement, for example 3.1.8. SPSA believes that the benefits of swath spraying will not be seen until significant development is done into the technique as it is currently still in a very early stage.

Although in theory swath spraying is faster than spot spraying due to the UAV constantly being moving, in this trial there was no significant time benefit from using swath spraying. In order to more clearly determine which method gives more accurate and efficient results, each method should be further developed using the recommendations set out in this report, then tested against one another in a future trial.

3.3 Pre-spray and respray

For this trial, the flight plans were generated for pre-existing tree locations. These locations were not necessarily laid out in a uniform way as the planting was done by human workers. As a result, it is difficult to programmatically create flight plans that follow the natural contours and terrain that the trees were planted on when they cannot be numerically defined and so the created flight plans are not optimal. This results in reduced time efficiency and potentially introduces error as the UAV makes mistakes due to the irregularity of the flight plan in areas.

If SPSA laid out the grids that the trees are planted in, completed the initial spraying, then flew the same flight plan when the trees needed to be release sprayed, many of the problems arising around non optimal flight plans and GPS inaccuracies would likely be resolved. In particular, straight flight plan lines would improve swath spraying performance as it would enable the UAV to fly smoothly over each target without the need to abruptly change direction.

SPSA believes this is a much more practical method of completing release spraying in the future that will produce more accurate and efficient results.

4 Conclusion

The automated UAV release spraying system developed by SPSA is capable of performing release spraying, with its efficacy yet to be determined at a later date via an aerial survey of the area. The system is limited in several aspects, notably by the areas it can operate in, which in turn limits the total number of trees that can be release sprayed. In some cases, relocating the base to give the pilot visual line of site can increase the area the UAV can operate in. However, relocating the base requires surveying a new RTK point to be used by the base station which can take a significant amount of time, as well as finding an appropriate take-off and landing site for the UAV and an appropriate base location.

In its current state, it would be impractical to attempt to carry out any additional release spraying or trials until significant work has been done. The system requires significant development before it can be operated as EVLOS/BVLOS and so on larger plots of land with greater time efficiency per tree. This is mainly due to obstacles present in the environment, and the nature of the terrain that forestry plots are typically located in. The primary development required is a robust and reliable obstacle avoidance module, where other lower priority features needing development will increase the efficiency and efficacy of the system and the reliability and accuracy of recorded data.

As for results from the trial, after a period of time fine tuning the system, the system appeared to perform its function adequately. The trial revealed multiple issues that must be solved. With a significant amount of development and resource allocation, the system will be vastly improved and will become significantly more viable as a product for release spraying larger forestry plots accurately and in a time-efficient manner. Additionally, SPSA believes that a pre-spray and respray technique will be more reliable and accurate as opposed to respraying an already planted area.

Once the results from this trial become available, there may be additional results requiring more exploratory work or required functionality.

Appendix C

Rapidly assessing the releasing spray potential of a SPS Automation UAV system

Author:	John Henry
Version No:	1.0
Version Date:	09 August 2022

CONTENTS

TRIAL APPROACH/METHODOLOGY

1. Introduction

Competition and overtopping by weed species negatively impacts the growth of *Pinus radiata* seedlings. Typically, over-spraying with a herbicide mix that kills existing weeds and temporarily retards the growth of new weeds, but does not harm the *P. radiata* seedlings is undertaken once or twice after planting. Commonly, this operation is carried out by spot spraying using knapsack sprayers or by broadcast spraying with aircraft. However, UAVs calibrated to spot spray *P. radiata* seedlings might potentially carry out this release spraying more efficiently than human ground crews and would result in lower total volumes of herbicide use than arise from broadcast application.

SPS Automation has been contracted to develop a UAV system for release spraying *P. radiata* seedlings. The current requirements are to accurately and evenly deposit 45 mL of herbicide (Valzine 500) mixture to 1.5 m x 1.5 m squares (but see a late edit in section 2.3) at predetermined GNSS locations (notwithstanding any onboard processing by the UAV that is outside the scope of this trial). An operational demonstration of this system is scheduled for Spring 2022 in Hawke's Bay. This project aims to test, and aid development of, the SPS Automation system prior to deployment in Hawke's Bay.

2. Materials and Methods

2.1 Trial location

It is proposed to undertake the trials at a yet-to-be defined location in the vicinity of Christchurch. The site should be a flat paddock with low vegetation. Importantly, spray patterning using the string collector system (section 2.6) can be undertaken if vegetation is less than 30 cm. However, simple checking of spray patterns (section 2.5) and any droplet sizing (section 2.6) will require vegetation of short stature (< 5 cm). The site should have good vehicle access and must be large enough to safely conduct UAV operations. The site should not be readily accessible to the public. Furthermore, depositing of spray dye to areas of soil or vegetation should not be problematic.

2.2 Spray mixes

The spray mix for testing will be a 1% mix of Bright Dyes FWT Red Fluorescent Dye (in water).

2.3 Spray nozzles and the spraying system

SPS Automation have several spray nozzles available to test. Preliminary assessments will be undertaken by SPS and a subset of nozzles will be selected for testing. Due to the soil activity of terbuthylazine and hexazinone (the active ingredients of Valzine 500), coarse droplets will reduce the effect of wind on spray deposition whilst still providing adequate weed control.

Edit: For completeness, SPS are currently testing two UAV systems[3]. One UAV (with nozzles under each rotor) is set up to pause at each location before spraying. The other (currently with a boom system) is planned to spray during continuous flight. This means the first system is likely to result in a circular (disc pattern of deposition) whilst the second should result in a square pattern. All calculations and measurements in this document are based on spraying a 1.5 m x 1.5 m square during continuous flight, so adjustments might be necessary depending on the results of the preliminary testing by SPS.

2.4 Weather conditions

Light winds (< 2 m/s) and dry conditions are required. Ideally, warm air temperatures and low relative humidity would allow the collector strings to dry rapidly. No formal monitoring of weather conditions will be carried out, but a Kestrel Pocket Wind Meter will be available to assess suitability for spraying.

2.5 Simple checking of spray patterns

SPS will plot a GNSS target across which strips of paper (approximately 30 cm wide) can be laid in a cross pattern over the target and anchored with weights/rocks (Figure 1). The UAV will then overfly the target and release 45 mL (20 ml per square metre) of dye mixture. Visual assessment of coverage and accuracy can then be made. Possibly, multiple GNSS targets will be generated and used to allow drying between spray reps.

[3] In the actual spray trials reported in the main body of this report, the Aeronavics Icon with a nozzle under each rotor was used.

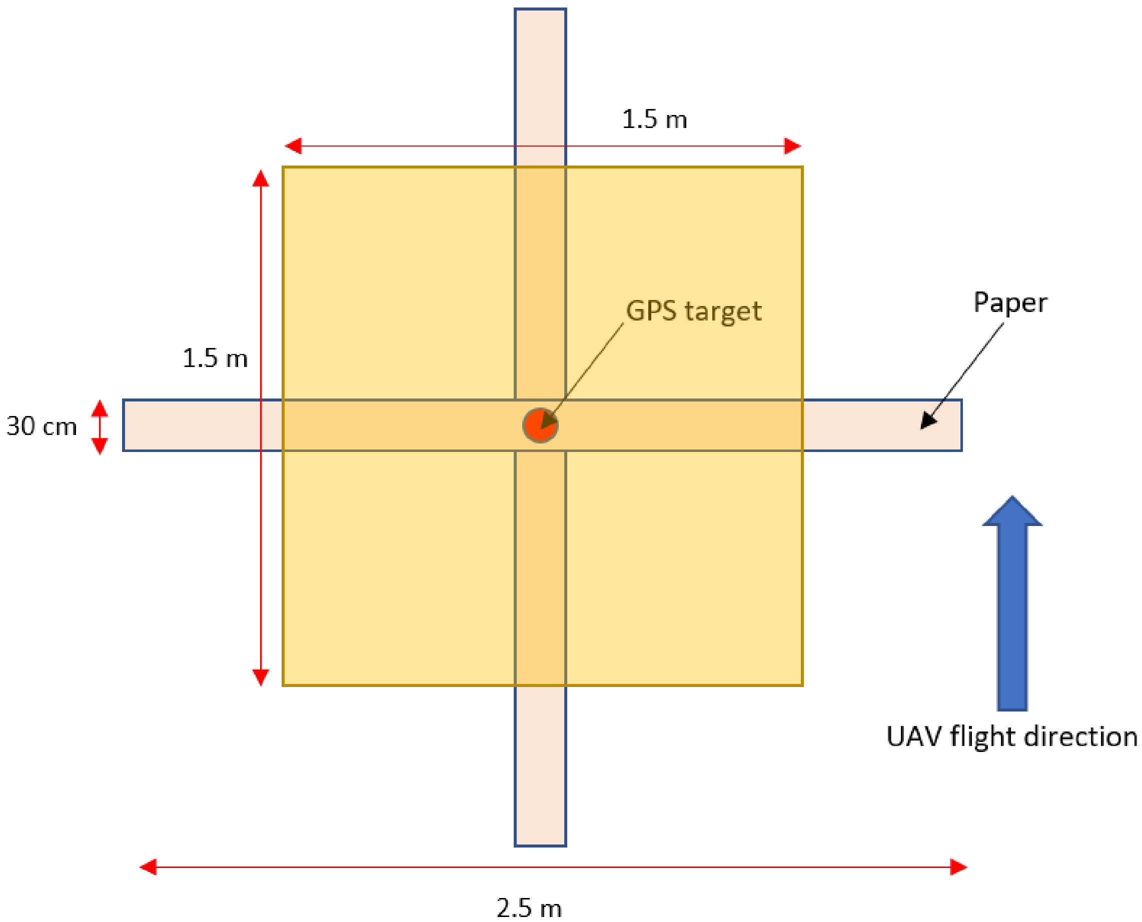


Figure 1: Layout for simple checking of spray patterns. Two strips of paper are arranged in a cross pattern over a GPS (GNSS) target. The UAV then overflies and deposits 45 mL of dye mixture (the idealised deposition shown as a yellow square) that can be visualised and measured.

2.6 Spray patterns with the string collector system

Once parameters such as nozzle selection and UAV altitude are refined in both preliminary testing and Section 2.5, more formal testing of the system will be carried out. Using the same GNSS target as per Section 2.5, the Flight-Line Collector System (string system) (WRK of Oklahoma, OK, USA) will be set out, orientated into the prevailing wind, with a 15 m section of string between the two tripods (Figure 2). The setup will be such that the tripods are equidistant from the GNSS target and the string should pass above the target. The height of the tripods will be kept to the minimum necessary to carry out the testing. The UAV will then overfly the string whilst depositing 45 mL of dye mixture. Once the string is deemed to be dry, it will be wound up and new string installed. A minimum of 5 repetitions are needed for this testing, and more repetitions will be completed if time allows. Once spraying is completed, the string fluorescence will be measured with a WRK String Spectrometer (WRK of Oklahoma) and the data subsequently quantified using the AccuPatt v1.06 software (University of Illinois, IL, USA).

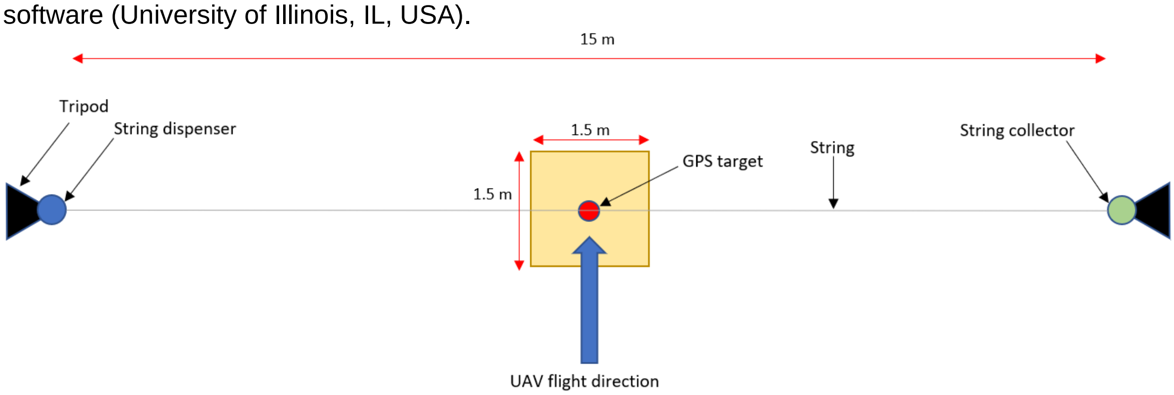


Figure 2: Layout for spray patterning with the string system. Mounted to tripods equidistant from the GPS (GNSS) target, the string dispenser (always mounted on the left) and the string collector (always mounted on the right), will be positioned such that a 15 m length of string passes over the target. Equipment will be set up so the UAV flies into the predominant wind direction.

2.7 Droplet sizing

Although outside the primary motivation for this testing, if time allows, some investigation into spray droplet size will be made. Formal droplet sizing might be undertaken, using the operational herbicide mixture, at a later date. For this testing, three wooden blocks will be arranged under the string system. The first block will be directly over the GNSS target. The second will be positioned 35 cm to the right, and the third another 35 cm to the right. KromeKote cards will be pinned to the blocks to collect the dye mixture. Depending on drying rates, probably three repetitions will be completed.

2.8 Flow rate testing

Again, although outside the primary motivation for this testing, an attempt will be made to validate the volume of spray released from the UAV. Ideally, this will be completed using the operational spray mixture, which might be difficult to complete in the time available. Although, this testing can be conducted in the lab and could be also used to confirm the system will spray Valzine 500 without clogging.

3. Equipment

- Roll of paper (SPS)
- Ground marking spray paint (SPS?)
- 20 L water (SPS)
- Generator (SPS)
- Earmuffs
- Bright Dyes SDS
- Valzine 500 SDS
- Wooden blocks x 3
- Droplet cards x 40
- Pins for droplet cards
- Plastic bags for droplet cards
- Sharpie for marking cards
- 8 m tape measure
- Nitrile gloves
- String collector system
- Spare string
- Spectometer
- Green and red Vivids
- Scissors
- Bright Dyes
- 5 L measuring jug
- 1 L measuring jug
- Measuring cylinders
- 50 mL Falcon tubes x 5
- 50 mL All Clear 2X
- Eye protection
- High vis
- Kestrel
- H&S plant
- Masking tape
- Old water sensitive paper