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Are uncrewed aerial spraying systems the future for forestry pesticide application?

Brian Richardson

New Zealand Forest Research Institute Ltd (trading as Scion)
Titokorangi Drive (formerly Long Mile Road), Private Bag 3020, Rotorua 3046, New Zealand

*Corresponding author: Brian.richardson@scionresearch.com

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Abstract

Background: Pesticide application is a primary method for managing weeds, insect pests and pathogens in New Zealand's forests. Apart from some manual spot spraying, most pesticide applications are made using helicopters, with herbicides the most widely used pesticide class. Current aerial application practices have evolved into efficient operations designed to provide a balance between performance criteria, i.e. maximising treatment efficacy, minimising unwanted environmental impacts (e.g. spray drift), and maximising productivity while minimising cost. Over the last decade, there has been a proliferation of relatively small, battery-powered, multi-rotor uncrewed aerial spraying systems (UASS) but their use to date in New Zealand forestry has been limited. This paper assesses the potential role of UASS in forest management and, where opportunities exist, identifies barriers slowing their adoption.

Methods: Publications on spray application in New Zealand forestry and use of UASS in both New Zealand and internationally were identified by conducting a Google Scholar literature search using a range of relevant keywords, and the retrieved studies were reviewed systematically. Unpublished reports from the New Zealand Forest Research Institute Ltd and Forest Growers Research Ltd were also considered. Information from the reviews was assessed critically, synthesised, and used to evaluate several potential forestry use cases for UASS.

Results: Several potential use cases for UASS were identified along with a set of research and development needs to support and accelerate the adoption of UASS into forest management operations and to provide regulators with the means to apply appropriate risk management measures. Based on the literature analysis, the opportunity for UASS, at least in the near term, is to realise the concept of 'precision spraying' rather than to replace conventional aircraft carrying out broadcast applications over large areas.

Conclusions: Recent UASS technology improvements have provided the potential for a step-change for at least some pesticide application niches within New Zealand forestry. Significant opportunities for UASS in forestry include herbicide spot spraying, treatment of boundaries close to sensitive areas, low-volume fungicide or insecticide applications, especially for small areas or in pest eradication operations; and applying variable treatments to individual plants or zones within a target area defined by remote sensing tools. A coordinated research and development programme is needed to optimise UASS use and to provide performance data to underpin regulatory processes.

Keywords: Aerial application; pest control; pest management; spray drift; unmanned aerial spraying system; unmanned aerial vehicle; weed control.

Introduction

The purpose of this paper is to assess the potential for uncrewed aerial vehicles configured for spraying, referred to in this document as UASS (uncrewed aerial spraying systems), to improve forest management practices through precision pesticide application.

New Zealand's ~1.8 million ha planted forest estate and associated wood processing industries employ about 40,000 people and produce exports with an annual value of ~$6.5 billion, which equates to about 1.6% of gross domestic product (FOA 2023). With rotation lengths typically around 25 - 30 years, managing biotic and abiotic risks is a high priority (FOA 2019). Major biotic threats include weeds, insect pests and pathogens, collectively referred to as 'pests', that all can cause tree mortality, reduce tree growth rates, and may have negative impacts on wood quality. New insect pest and pathogen introductions into New Zealand also have the potential to restrict log and wood exports in international markets because of phytosanitary constraints (Rolando et al. 2016).

Pesticide (insecticide, fungicide, and herbicide) application is a primary method for managing biotic risks in forestry because they are generally the most cost-effective option (Rolando et al. 2016). Herbicides represent the most widely used pesticide category (Rolando et al. 2013; Rolando et al. 2016) and they are applied to remove or reduce the vigour of non-crop plants that may strongly compete with, and reduce the growth and survival of, crop trees (Richardson 1993; Wagner et al. 2006). For the 90% of the planted forest area dominated by radiata pine (*Pinus radiata* D.Don), a national programme coordinates an annual aerial application of copper fungicides where needed to control Dothistroma needle blight (DNB), a disease caused by *Dothistroma septosporum* (Dorogin) M.Morelet (Bulman et al. 2016). The area treated varies annually, ranging from about 2,000 ha to 180,000 ha (Rolando et al. 2016), depending on infection levels determined by a national surveillance programme. In recent years, similar aerial application practices have also been used to control another disease of radiata pine caused by *Phytophthora pluvialis* Reeser, Sutton & E.Hansen called red needle cast (Fraser et al. 2022). Control of insect pests with insecticides is relatively uncommon in New Zealand's radiata pine plantations. However, insecticide use is important in some of the less commonly planted tree species, such as for the control of *Paropsis charybdis* Stål, a defoliator of some *Eucalyptus* species including *Eucalyptus nitens* (H.Deane & Maiden) Maiden (Withers & Peters 2017). Insecticide application has also played a critical role in nationally coordinated operations to eradicate forest insect pests (Hosking et al. 2003; Richardson & Kimberley 2010).

Aerial spray application in New Zealand forestry

Apart from manual spot spraying with herbicides (Richardson et al. 2019a), which is typically carried out when establishing young trees on ex-pasture sites, and some roadside herbicide spraying, most pesticide use in New Zealand's planted forests involves aerial spraying. Aerial spraying is generally preferred over other manual or ground-based application systems because it is the only practical option for treating tall trees and for spraying pesticides at large-scale in forest environments that are often steep, gullied and with the ground covered in accumulated logging debris and stumps. Aircraft are also more productive in terms of ha sprayed/hour than other options enabling best use of what are often small treatment windows based on crop or pest phenology and suitable weather conditions for spraying. Manual application methods are often constrained by cost and availability of labour and have the potential for worker exposure to pesticides.

Aerial application in New Zealand, as in many parts of the world, probably began in association with the availability of pilots and aircraft after World War I, and accelerated for the same reason after World War II, with an initial focus on fertiliser and seed application to pastures (Alexander & Tullett 1967; Giles et al. 2008). The first well documented aerial spray application in New Zealand forestry occurred in 1951 following an outbreak of looper caterpillar (*Pseudocoremia suavis* Butler (Syn: *Selidosema suavis* (Butler)) causing defoliation of about 2,500 ha of radiata pine in Eyrewell Forest, mid-Canterbury (Rawlings 1953). The area was sprayed with dichlorodiphenyltrichloroethane (DDT) using a Tiger moth aircraft (Figure 1).

During the early to mid-1950s, development of aerial herbicide application methods in New Zealand were being driven primarily by agriculture (Matthews, L. 1955; Currie 1959) but some experimental work on control of scrub weeds, such as gorse (*Ulex europaeus* L.), was relevant to forestry. Even during this early period, spray drift from herbicides was a concern, e.g.:

> "*... these chemicals in the wrong hands or with incorrect application can be dangerous; the avoidance of light winds is essential for both good control and for reducing the damage to neighbouring properties. Damage has been reported as much as 15 miles from the site of spraying in unfavourable conditions (Ferens 1955)*."

During the 1960s, the agricultural aviation industry was growing at an annual rate of about 6% and herbicides were the dominant type of pesticide applied. However, reservations were increasing about aerial herbicide application due to the risk of spray drift and the need for accurate flying to ensure there were no skips between flight lines (Little 1965).

The potential of helicopters to overcome some of the limitations of fixed wing aircraft for aerial application was evaluated shortly after their introduction into New Zealand in the early 1950s (Ferens 1955). Despite being more expensive to purchase and maintain, their greater

FIGURE 1: Application of DDT to control an insect outbreak in Eyrewell Forest. (Photo courtesy of New Zealand Forest Research Institute Ltd).

manoeuvrability and ability to fly at lower speeds was seen as advantageous, especially for applications to steep, gullied country (Ferens 1955; Hocking & Henry 1961; Brooks 1963). The downwash produced by slow flying helicopters was also thought to improve coverage and efficacy. Today, helicopters dominate all pesticide spraying in forestry with some limited use of fixed-wing aircraft for DNB control.

The first real focus on the science of aerial spray application for New Zealand forestry followed the 1964 introduction into New Zealand of DNB. Building on work in Kenya (Gibson et al. 1966), an intensive effort was implemented to optimise the aerial application of copper-based fungicides for DNB control. Over the course of the next ~15-20 years, copper application rates were reduced from 4.16 kg copper oxychloride in 50 litres/ha water to the current highly efficient regime of 1.66 kg copper oxychloride (or equivalent rates of other copper compounds) in 2 litres/ha of spray oil, made up to 5 litres/ha total spray volume with water (Bulman et al. 2004). In the late 1970s, the first New Zealand programme to focus purely on the process of application (as opposed to a programme focused on optimising control of a particular pest threat) was initiated by the New Zealand Agricultural Engineering Institute (Garden 1976a, 1976b).

On the back of the success of improving the aerial application efficiency of DNB control, coupled with ongoing concerns about the risk of herbicide drift, the New Zealand Forest Service initiated a new programme to improve aerial herbicide application in about 1982. Outcomes from this programme had a large influence on today's aerial herbicide application practices including reducing total spray volumes (Ray et al. 1999b; Gaskin et al. 2013) and improving efficacy (Zabkiewicz 2000) through use of adjuvants, providing good practice guidelines for spray drift mitigation (Richardson et al. 1990; Richardson et al. 1996; Richardson et al. 2020), and the introduction of new spray modelling tools to optimise application practices (Richardson & Ray 1993; Ray et al. 1999a; Schou et al. 2001).

Probably the biggest leap forward for aerial pesticide application over the last 30 years was the introduction of Global Navigation Satellite Systems (GNSS) in the 1990s (Kirk & Tom 1996) to support track guidance, resulting in dramatic improvements in flying accuracy. Another benefit associated with this technology was the introduction of flow rate control based on true ground speed. However, even with the aid of GNSS for track guidance, flying accuracy, and resulting spray deposit variability is still dependent on pilot skill (Richardson & Thistle 2006).

The recent development of automated multi-rotor UASS, with their highly accurate navigation systems and slow flying speed, may offer the opportunity for another step-change in forest pesticide application practices. Based on a review of scientific literature, the purpose of this paper is to evaluate potential opportunities for using UASS in New Zealand forest management based on several performance measures including comparison to current standard practices. The review also helps to inform research and development needs to further evaluate or realise opportunities for a range of UASS use cases.

Methods

A series of Google Scholar searches were undertaken to seek research articles on the use of UASS for forestry-related pesticide applications using the key words: UAV, UASS (and other equivalent terms including drone, RPAAS, RPA, UAS (Ozkan 2023)), pesticide, insecticide, fungicide, herbicide, spray, forest, forestry. This search turned up virtually no papers with a focus on the use of UASS for forest pest management in New Zealand or internationally. A few papers mentioned the potential of UASS in forestry but most articles that mentioned forestry did so in the context of remote sensing. Subsequently, a series of additional searches were carried out using combinations of the following key words: UAV, UASS, RPAAS, RPA, UAS, helicopter, fixed wing, pesticide, herbicide, insecticide, fungicide, spray, spay drift, efficacy, productivity. This search revealed a rich recent literature on UASS performance measurements mainly focused on some of the big global crops such as cotton, wheat, rice, and citrus. Several recent reviews provide excellent summaries of UASS research, the current state-of-the-art in terms of technology development, and performance attributes in comparison to conventional pesticide application platforms (Zhang, R. et al. 2020; da Cunha et al. 2021; OECD 2021; Chen et al. 2022; Delavarpour et al. 2023; Hafeez et al. 2023; Bonds et al. 2024). While the UASS literature relating to forestry pesticide applications was minimal at best, there is a comprehensive body of work relating to conventional pesticide aerial application platforms (helicopter and fixed wing) and their use in New Zealand forestry. On top of the published literature searches, several reports and articles were sourced from the New Zealand Forest Research Institute Ltd archives and from Forest Growers Research Ltd.

Information from the sourced literature was synthesised and used to develop performance criteria that provided a basis for evaluating several possible use cases for UASS in New Zealand forestry. Using these criteria, perspectives were also provided on research and development needs to fill gaps in knowledge on UASS performance and potential use niches.

Uncrewed aerial spraying systems

Uncrewed aerial spraying systems have been commercially available since the introduction in the 1990s of the Yamaha RMAX, a mini-helicopter with a single main rotor and a tail rotor (Del Cerro et al. 2021). However, over the last decade there has been a proliferation of relatively small, battery powered, multi-rotor spray UASS that are commercially spraying very large areas in some countries such as China and Japan (Huang et al. 2009; Wang, S. L. et al. 2017; Del Cerro et al. 2021). While most UASS today are multi-rotor designs, there are many variations in terms of numbers of rotors, rotor position and size, and spraying system configuration

(Huang et al. 2014; Tang et al. 2017; Ozkan 2023). There are currently no international standards defining optimal spray UASS design, and it remains to be seen whether the basic UASS designs will converge over time towards a single optimal configuration. Nevertheless, there clearly have been many improvements to UASS technology over the last decade.

Most of the latest UASS produced by major manufacturers all have features such as RTK (real-time kinematic) positioning to improve the accuracy of GNSS, technologies to support obstacle avoidance and terrain following (maintaining a constant height above the ground or vegetation even in complex environments), and the ability for multiple aircraft to be flown in an integrated manner from a single control unit. Spraying systems are configured either with nozzles located directly under rotors or with a conventional boom and nozzle arrangement. A number of manufacturers utilise rotary atomisers (Figure 2), which have the advantages over hydraulic nozzles of producing a narrower droplet spectrum, at least within a defined size range (Matthews, G. 2008; Craig et al. 2014), and are adjustable during flight to either change droplet size or maintain droplet size while changing flow rate. The overall trend is for these ‘small’ multi-rotor UASS to increase in size, with today’s top-of-the-line models available in New Zealand, such as the XAG P100Pro (XAG Ltd., Guangzhou, China) or DJI T50 (Dà-Jiāng Innovations, Guangdong, China) having payloads of up to 50 kg.

It is well recognised that these multi-rotor UASS have a useful niche for treating small areas that are not readily accessible or too costly to treat by other means. However, their adoption to date for forest management operations in New Zealand and internationally has been relatively low based on the paucity of publications in that regard. Although some aspects of UASS performance will be generic across primary production sectors, there are also differences that may affect their performance. For example, the challenging topography of many forest sites can lead to variable spray release heights and spray deposit variability, plus the risks of collisions with random branches or piles of vegetation from logging debris. However, advances in obstacle avoidance and terrain following technologies are overcoming these issues. It is also likely that the slow development of specific regulations for agrichemical application using UASS, at least in OECD countries (OECD 2021), means that potential benefits are constrained by operating under regulations for conventional aircraft.

FIGURE 2: XAG P20 fitted with spinning disc atomisers under each rotor (Photo credit: Brian Richardson).

To displace or supplement existing methods of pesticide application in forestry, UASS technology must be shown to be superior, or at least as good, as current practices across a range of performance criteria. The next section presents performance criteria that can be used as a basis for comparing UASS with conventional spraying systems, for evaluating possible use cases for UASS within forest management, and to identify research and development needs to either realise opportunities or overcome performance limitations.

Pesticide application performance criteria

Any efficient pesticide application (application efficiency) must satisfy at least three performance criteria:

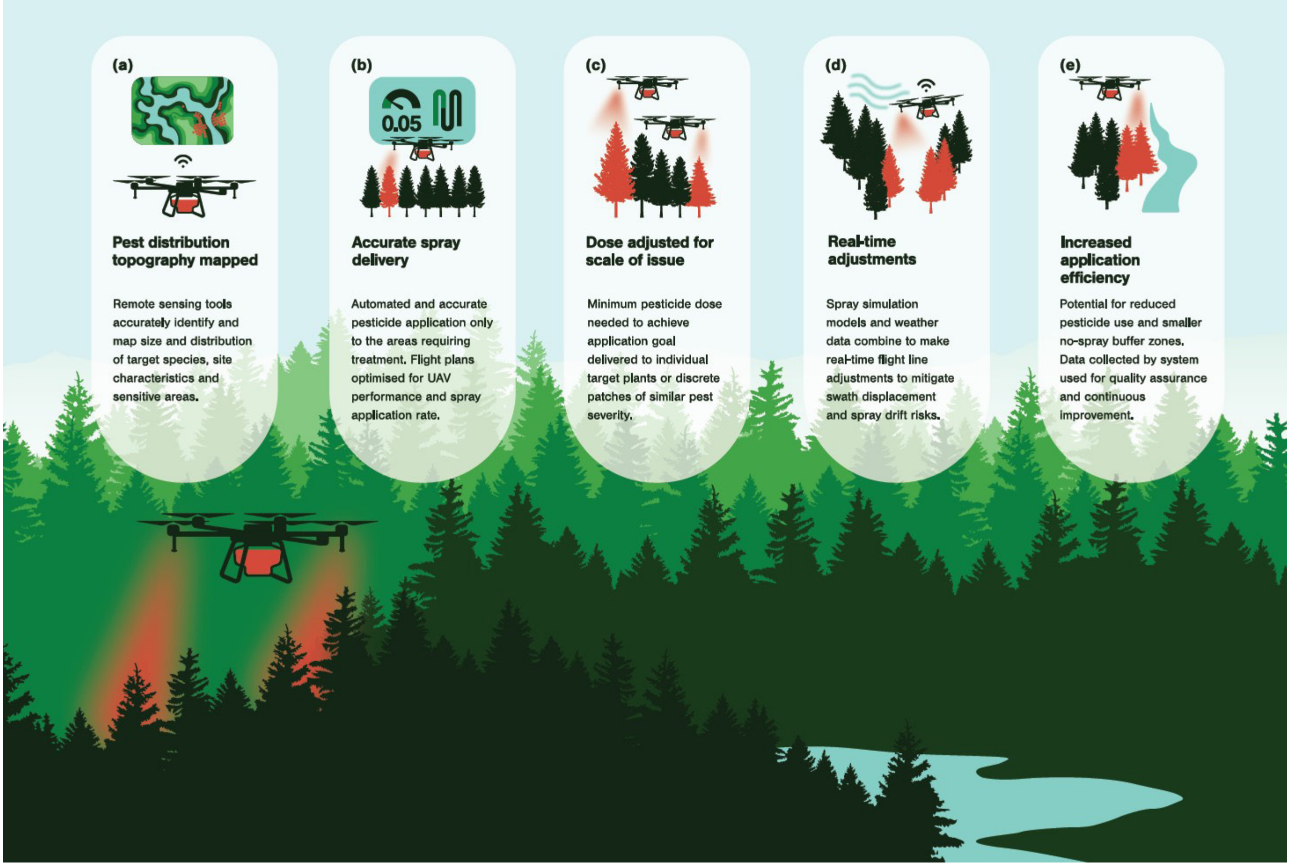
(i) achieve the desired biological **efficacy** (e.g. level of pest control) using the minimum amount of pesticide;

(ii) minimise or eliminate **spray drift** beyond the boundaries of the target area to below levels likely to lead to adverse effects, including operator exposure; and

(iii) maximise **productivity** (e.g. ha sprayed/hr) or work rate of the aircraft while minimising application **costs**.

The use of UASS may enable a step change in application efficiency over current aerial application methods, at least for some niches, and fully realise the potential for ‘precision’ aerial pesticide application. In this context, the concept of precision spraying encapsulates several elements (Figure 3):

- Use of remote sensing technologies to characterise the treatment zone and to accurately identify and map specific target and sensitive areas within this zone (Figure 3a). This process could include mapping of individual trees or weeds (Hunter III et al. 2020; Pearse et al. 2020) and quantifying weed competition indices (Richardson et al. 1999; Watt et al. 2007), disease distribution and severity, or other measures of tree health (Iost Filho et al. 2020; Watt et al. 2023). While combining remote sensing and spray application into a single operation has appeal from an efficiency perspective (Delavarpour et al. 2023), the current standard approach is for the remote sensing to be undertaken by a separate, lighter survey drone, partly because of the limitations in endurance of existing UASS. Having the treatment area pre-mapped enables efficient route planning for the heavier UASS.



Pest distribution topography mapped

Remote sensing tools accurately identify and map size and distribution of target species, site characteristics and sensitive areas.

Accurate spray delivery

Automated and accurate pesticide application only to the areas requiring treatment. Flight plans optimised for UAV performance and spray application rate.

Dose adjusted for scale of issue

Minimum pesticide dose needed to achieve application goal delivered to individual target plants or discrete patches of similar pest severity.

Real-time adjustments

Spray simulation models and weather data combine to make real-time flight line adjustments to mitigate swath displacement and spray drift risks.

Increased application efficiency

Potential for reduced pesticide use and smaller no-spray buffer zones. Data collected by system used for quality assurance and continuous improvement.

FIGURE 3: UASS have the potential for delivering a step change in precision and accuracy of aerial pesticide application in forestry. (Image courtesy of Forest Growers Research, New Zealand).

- Automated and accurate delivery of pesticide only to the areas requiring treatment using the minimum amount of pesticide needed to achieve the application goal (Nan et al. 2023) (Figure 3b, c). An example could be applying fungicide to different zones in a block where disease is present, or delivering herbicide to individual wilding conifer trees, with the dose scaled to tree size. Accurate spray delivery also implies automated, real-time adjustment of flight plans to account for changing weather conditions that could cause swath displacement or excessive spray drift (Figure 3d). Accounting for these factors would improve application efficiency (Figure 3e).

- Use of sensor technologies to collect detailed records of operations that can be used immediately for quality assurance. When connected with similarly detailed records of the outcome of the operation, this database can be used for continuous improvement of the spraying system, using artificial intelligence or machine learning algorithms (Guo, H. et al. 2020a).

While it is beyond the scope of this article to discuss in any detail the many interacting factors that influence the outcomes of any aerial spray operation (Figure 4), it is relevant to consider the predominant differences between typical UASS and standard practices (i.e. primarily helicopter application plus a small amount of manual spot spraying). This assessment helps to identify the pros and cons of the UASS and barriers to uptake for forestry applications.

Efficacy

The purpose of any pesticide application is to achieve a specified minimum level of control of the target species, leading to improved performance of the tree crop. Two recent reviews of UASS performance concluded that efficacy from UASS applications tend to be comparable with all other pesticide application methods (Bonds et al. 2024) or have slightly reduced efficacy compared with ground-boom or knapsack sprayers (OECD 2021), with the caveat that the formulations tested with UASS had more concentrated active ingredients and were not necessarily optimised. None of the reviewed studies included situations or species relevant to New Zealand forestry, or forestry in general, and relatively few studies focused on herbicide applications.

On the face of it, if a well calibrated UASS applied the same spray mix at the same rate as a helicopter then the same biological result would be expected. However, factors that could differentially influence efficacy are spray deposit variability and the influence of UASS downwash on droplet velocities and retention on foliage (Zhao et al. 2022; Zeeshan et al. 2024). Given the low carrying capacity of multi-rotor UASS, there is also the incentive to reduce application volumes to

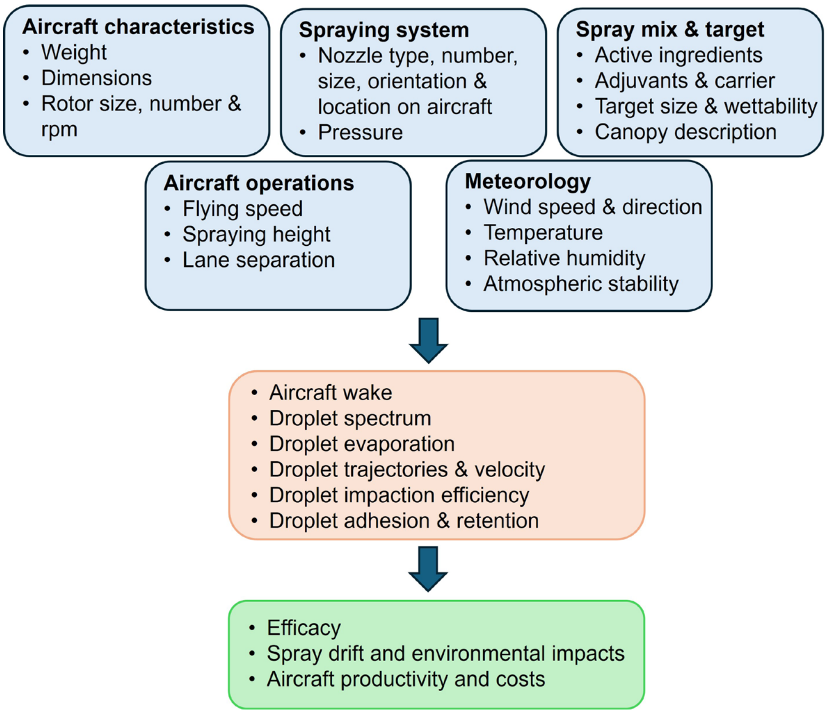


FIGURE 4: Many interacting factors (blue boxes) influence a wide range of processes (orange box) that ultimately affect outcomes of a spray operation (green box) including efficacy, environmental impacts and aircraft productivity.

improve aircraft productivity (work rate) (Wang, G. et al. 2020a; Wang, J. et al. 2020b). Doing so, changes spray mix properties in ways that could influence efficacy, particularly for herbicide spraying using very large droplets (Combellack 1984; Zabkiewicz 2000). This issue is dealt with in the following section discussing specific use cases.

Deposit variability

No spray application is ever completely uniform meaning that some areas within a spray block will receive pesticide doses greater than the nominal application rate and other areas will receive doses below this rate. Spray deposit variability is both economically and environmentally undesirable because any pesticide applied at a higher than necessary rate is effectively wasted and increases the likelihood of adverse environmental effects; conversely, target species that receive sub−lethal doses may not be controlled and associated crop growth rates or yields can be reduced due to weed competition or disease/insect impacts (Richardson 1993; Richardson et al. 2004). Sub-lethal herbicide doses can also contribute to development of herbicide resistance (Kudsk 2014). For typical broadcast spray operations (wide area spraying), spray deposit variability is also influenced by the distance between flight lines, known as lane separation, effective swath width or bout width, which in turn is influenced by the swath (deposit) pattern width. There is an incentive to maximise lane separation to increase productivity (work rate) but deposit variability also increases with increased lane separation (Parkin & Wyatt 1982). Excessive underdosing is one consequence of any flying track errors when operating at the limits of acceptable deposit variability based on maximising lane separation.

The automated operations of slow and low flying UASS, coupled with their RTK-GNSS navigation, may improve flying accuracy and eliminate the potential for pilot error that still exists with helicopter operations (Richardson & Thistle 2006). Also, at higher speeds any small perturbation (e.g. turbulence) will move the aircraft further off track before corrective action can be taken. Improved application accuracy with UASS could in principle reduce spray deposit variability. This would not be observed as a difference in efficacy compared with helicopters because current application rates are designed to accommodate standard sources of variability (Richardson et al. 2004). But, if it were demonstrated that UASS applications consistently reduced deposit variability, there could be the potential for at least a small reduction in herbicide rates. However, published work suggests that field variability from UASS applications may be higher than expected, at least in some situations (OECD 2021; Anken et al. 2024; Byers et al. 2024). Currently, there are no data from UASS applications in forestry situations that compare spray deposit variability with helicopter applications.

Droplet velocity and retention on foliage

Downwash from the rotor blades of a UASS or helicopter is the dominant mechanism driving released spray droplets into the plant canopy (Teske & Thistle 2018). Slow flying results in higher vortical circulation and more downward motion on the released spray droplets.

While slow flying with helicopters is expensive, tiring for the pilot and increases wear-and-tear on the machine, it is the normal mode of operation for small multi-rotor UASS which typically fly at groundspeeds of around 2 – 5 m/s. The speed of droplets entrained in multi-rotor UASS downwash has been reported up to 12 m/s (Tang et al. 2017). For comparison, terminal velocities in still air for water droplets with diameters of 100, 500 and 1000 μm are respectively about 0.28, 2.1 and 3.5-4.0 m/s, depending on environmental conditions (Matthews, G. 2008).

High droplet velocities at the point of impact reduces their likelihood of retention on foliage surfaces through a variety of mechanisms, especially when using large droplets sizes typical of aerial herbicide applications and with hard-to-wet weed species (Forster & van Leeuwen 2010; Dorr et al. 2014). High downwash also causes considerable disturbance of foliage elements in plant canopies. Results from studies quantifying the effect of downwash from UASS on canopy penetration have been mixed and further studies are warranted (OECD 2021) to understand whether droplet retention, canopy penetration, and consequently efficacy, are reduced, especially for foliar herbicide applications using large droplets.

Spray drift and environmental impacts

All spray nozzles produce a range of droplet sizes referred to as a droplet spectrum. Droplet spectra are often characterised either using the volume median diameter (VMD) or by using a classification system which ranges from Extremely Fine to Ultra Coarse, based on the American Society of Agricultural and Biological Engineers (ASABE) standard or other equivalents (ASABE-Standards 2009; Fritz et al. 2012). Spray drift can be defined as the airborne movement of particles of an applied material outside of the intended target area (Craig et al. 1998). A useful indicator of the potential for spray drift is the proportion of total spray volume that is contained in droplets with diameters of less than either 100 μm or 150 μm (or some other threshold size), often referred to as the driftable fraction (Fox et al. 1998; Henry et al. 2015). As a generalisation, as droplet VMD increases, the driftable fraction decreases (Richardson et al. 2020).

Minimising spray drift is a primary concern for any aerially applied pesticide with potential for significant negative impacts on the environment or human health. One effective drift reduction strategy typically used for herbicide spraying in forestry is to use nozzles that produce droplet spectra with large VMDs (800 – 1200 μm range) but very low driftable fractions (Richardson et al. 1996; Richardson et al. 2020). One consequence of using large droplets for foliar applied herbicides, especially poorly translocated products, is the need to maintain higher spray volumes to ensure adequate coverage and efficacy.

While the driftable fraction defines the potential for spray drift, actual spray drift is a function of many other interacting variables and understanding these interactions is the basis of spray drift management (MPI 2023). Apart from droplet size, the most sensitive variables influencing spray drift include spray release height and wind speed but many other factors also play a lesser role (Richardson & Ray 1993; Teske & Barry 1993). In principle, and assuming everything else being equal, the lower spray release height of UASS will result in lower spray drift than from helicopter applications. A recent review of studies to quantify spray drift from UASS supported this assertion (Bonds et al. 2024) but was based on only one field study that directly compared drift from a UASS with a conventional fixed wing aircraft (Li, H. et al. 2022). The review also noted that UASS spray drift is likely to be higher than ground boom applications and similar to orchard airblast applications and gave the caveat that individual use cases and other application variables will need to be considered to determine if these generalisations are valid. Nozzle location on the UASS is likely to be a significant factor influencing the amount of drift and may be reduced with nozzles located under the rotors to avoid areas of upwash and rotor tip vortices (Chyrva et al. 2023; Bonds et al. 2024). No studies have been undertaken to quantify long-range drift, and only one has quantified short-range drift (Richardson et al. 2019b) for UASS configured for herbicide applications with specifications relevant to New Zealand forestry.

Productivity

With their higher spraying speeds, much larger carrying capacity, and large fuel tanks, it is not surprising that helicopter productivity by far exceeds that of UASS, at least with respect to broadcast spraying operations. Previous work has estimated the productivity of an AS350 Squirrel helicopter spraying a 30-ha rectangular block with a total spray volume of 300 L/ha is either 38 or 41 ha/hr, depending on spraying speed (Ray et al. 1989). A similar calculation for an application to a square 50 ha block at a rate of 100 L/ha, typical for current herbicide applications, provides a productivity estimate of about 56 ha/hr. The recently developed DJI T50 UASS is advertised as achieving 4 ha/hr for orchard spraying at 90 L/ha. While actual productivities will be situation-specific, the key point is that even with three UASS working together they will not come close to matching the productivity of a helicopter for large-scale operations and they will also have battery management challenges.

Although small multi-rotor UASS are not suited to the scale of broadcast herbicide application needed by many of the larger forestry companies, there may be niches for broadcast spraying of small farm forestry blocks and for spot spraying. An analysis of work rates and costs would need to be undertaken to evaluate whether there is an area threshold under which UASS can compete with today's standard operating procedures for broadcast applications using different application rates (e.g. 100 L/ha for herbicides versus 5 L/ha for fungicides). With their higher accuracy, UASS are ideally suited for spot spraying, and preliminary calculations (B. Richardson, unpublished data) indicate that this method will be cost-competitive with, and have higher productivity than, the current manual spot spraying operations (see Use Case section).

Actual costs for commercial UASS operations are hard to estimate with so few operators working in forestry and the need to develop and optimise standard practices. Current UASS have much lower capital costs than a helicopter. UASS efficiency will also be increased where a single operator controls multiple UASS. While figures are not available, it also seems reasonable to assume costs for pilot training and maintenance will be lower for UASS than with helicopters. Not enough information is available to confidently translate the various costs and work rate data into cost/ha data for comparing UASS performance with standard practice for helicopter or manual applications in forestry. There is some evidence from non-forestry sectors that UASS are more efficient than manual operations in terms of higher work rates and reduced costs (Sarri et al. 2019; Martinez-Guanter et al. 2020).

Pilot safety and worker exposure

Pilot (or operator) safety and avoidance of worker or bystander exposure to pesticides are additional considerations when assessing the pros and cons of choice of application method. Risks to pilots are clearly reduced when using uncrewed aircraft (Giles et al. 2016) and early evidence suggests UASS applications have less potential for operator exposure (Bonds et al. 2024).

Potential UASS use cases

The introduction of UASS for forestry applications is appealing because of the potential benefits from 'precision spraying'. However, the limitations of current UASS and the lack of data to demonstrate their benefits and to support their regulation are currently constraining their adoption. The pros and cons of UASS are discussed below for several possible forestry use cases:

- Pre-and post-plant herbicide spot or line spraying.
- Targeted spraying of individual plants or discrete patches.
- Broadcast spraying and treating sensitive boundaries.
- Pest eradication operations.

Pre- and post-plant herbicide spot or line spraying

Spot weed control involves manually applying herbicides to a small area around each individual tree and has the advantage of using less herbicide than broadcast treatments (Davenhill et al. 1991; Richardson et al. 2019a) (Figure 5). Manual spot applications are generally made using either a liquid spray, typically one or two passes of a flat fan nozzle over each tree producing a square 'spot', or with a granular applicator held over each tree producing a circular spot. The optimal spot diameter depends on the tree response to release from weed competition and the herbicide treatment costs (Richardson et al. 2019a). However, the manual labour needed for spot spraying operations is becoming increasingly more difficult to source (Baker 2018). Multi-rotor UASS offer the opportunity to automate spot spraying operations, reducing reliance on manual labour and likely reducing operator exposure to herbicides (OECD 2021; Bonds et al. 2024).

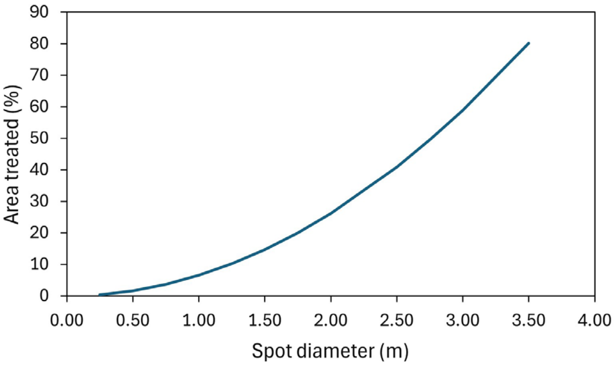


FIGURE 5: The proportion of a forest site treated with herbicide for different weed control spot diameters and assuming a stocking of 833 stems/ha.

There are several spot spraying scenarios that place different demands on UASS requirements:

(i) Pre-plant spraying to mark planting spots and minimise competition at planting.

(ii) Post-plant release spraying where the tree locations are known via a prior pre-plant spray using a UASS or by recording locations at the time of planting with a GPS-enabled planting spade or a GPS-unit on a planting machine.

(iii) Post-plant release spraying where the tree locations are not already known but the trees are detectable by aerial imagery and tree identification algorithms.

Pre-plant spot spraying

A relatively small number of forest companies carry out pre-plant spot spraying, mostly on pasture sites being converted to forestry. The benefit from a pre-plant spot spray on these sites is that trees are planted in the centre of the clearly identifiable spots, speeding up the planting operation, and delaying competition from weeds. Except for sites oversown with grasses and legumes, most cutover sites receive a pre-plant broadcast spray often negating the need for a pre-plant spot spray.

There already have been examples of UASS carrying out pre-plant spot spraying in New Zealand. The UASS flies the block along pre-programmed lines with a spacing representative of planting rows and rapidly fires pulses of spray at a specified time interval set by the ground speed and required distance between spot (tree) centres. While a quantitative analysis of the effectiveness of this approach, in terms of uniformity of spacing, weed-free spot sizes achieved, and comparison of the cost-benefit with manual spot spraying, has not been published, anecdotally it appears that this method holds promise.

Looking to the future, the development of variable tree spacing plans within a site, to account for future mechanised operations (e.g. pruning) and variation in micro-site quality, would require a means of guiding a planting crew to achieve the right spacing and planting density. Assuming UASS can deliver highly accurate spot spacing (see next section), they could easily be programmed to deliver herbicide spot sprays on pasture sites or marker dye to indicate the planting positions on clean cutover sites.

Post-plant spot spraying

While the following discussion focuses on post-plant spot treatments in planted forests, many of the ideas presented are relevant to any type of spot treatment (e.g. wilding conifer treatments or application of fertiliser at the individual tree level). Post-plant spot spraying is a more common operation than pre-plant spot spraying but creates a significantly higher challenge and reward for UASS development (Figure 6). The important challenges are:

(i) knowing the exact location of each tree and being able to navigate to that tree with a small margin for error while operating at speeds that achieve a competitive work rate; and

(ii) evenly distributing the correct herbicide dose to the target zone, which for spot spraying in *P. radiata* plantations is typically an area of area of about 2 m^2 (a square of 1.4 x 1.4 m or a circle with diameter of about 1. 6 m) centred on each tree.

The scale of these two challenges is significant given to the small acceptable margin for error in post-plant spot spraying coupled with the need to fly fast enough to make the application cost-effective compared with manual methods.

Tree location and navigation

There are several possible ways of defining tree locations prior to spraying:

- Using positional data from pre-plant spot spray operations. This approach requires the assumption that the relationship between the exact position of spray release and the centre of weed control on the ground is known and accounts for swath (or spot) displacement effects resulting from factors that affect droplet trajectories (e.g. UASS wake, forward speed, wind velocity, droplet size distribution). It also assumes the tree planter places the tree in the centre of the spot, which may not happen due to practicalities such as the presence of a large rock or stump.
- Using remote sensing and tree identification algorithms to generate tree location data. This is a viable approach when trees are planted into largely weed-free sites, either pasture sites that have been spot sprayed or cutover sites which have had good pre-plant control and remain clean of other vegetation. The disadvantage of this approach is the cost of needing an additional operation and the difficulty of detecting the trees when they are small and/or there is other vegetation on the site.
- Recording tree location data at the time of planting is probably the best approach, assuming the location data are accurate. Options for recording tree locations include using GPS technologies attached to a planting spade or a mechanised planter.

FIGURE 6: Field trial with UASS preparing to spot spray individual trees. (Photo courtesy New Zealand Forest Research Institute Ltd).

The first recorded attempt at quantifying the accuracy of post-plant spot spraying from a UASS indicated a root mean square error of 0.71 m for the distance between the nominal tree location and the centre of spot weed control (Hartley et al. 2023) Although this was a promising result, the UASS stopped to release spray while hovering over each tree meaning that productivity was very low. To be cost-effective, the goal needs to be more accurate targeting while in continuous flight.

Accurate targeting from continuous flight

For cost-effective spot treatments applied to pre-specified locations, a UASS must be able to accurately deliver treatments while in continuous flight.

There are three steps to achieving this goal:

(i) Accurate navigation. To achieve the desired growth benefit, there is little margin for error with the aim of delivering a weed-free spot with an area of 2 m^2 centred on the crop tree. While there is no published data describing the effect of delivery accuracy on tree growth response, there is clear evidence demonstrating the sensitivity of the growth response to the area of weed control (Richardson et al. 2019a). Defining the accuracy requirement is an area of future research but as a working goal, it is suggested that the spot centre should ideally be within +/- 0.2 m of the target tree or location.

(ii) Developing navigation procedures such that the UASS moves to and passes over each tree while maintaining a constant speed. While this need would be easily met if tree spacing was always exact, the reality is that it is not! Tree spacing varies, especially with manual planting, depending on factors such as topography and the distribution of material like logging debris, stumps, or rocks that require planting positions to be moved.

(iii) Quantifying the point of spray release needed to deliver the desired spray deposit distribution on the ground, centred on the target tree or location. Many factors will influence spray droplet trajectories such as the number and location of rotors, droplet size, nozzle location relative to rotors, flying speed, spray release height and meteorological conditions. Research and new modelling tools are needed to quantify these effects on droplet trajectories and spray deposition, especially to enable operations to be undertaken at the highest speed possible without compromising targeting, using real-time positional adjustments based on changing meteorological conditions. To date no craft has achieved this goal.

Other opportunities for improving UASS productivity and easing the targeting challenge should also be evaluated including considering hybrid UASS to provide greater endurance, use of larger spray droplets to reduce effect of wind speed on spot displacement, and using multiple UASS working together.

Line spraying

Similar to spot spraying, line spraying will reduce herbicide use compared to broadcast spraying and involves a small swath of weed control along each tree row. Although accurate line spraying with a UASS will not be as difficult to achieve as spot spraying, the challenges of predicting swath displacement for different operating and meteorological conditions, and dealing with planting rows that are not straight, remain.

Targeted spraying of discrete zones

Pesticide treatments targeting specific zones within a larger treatment area are a good fit for applying concepts of precision spraying with a UASS (Figure 3). There are three steps to realising this concept:

(i) Remote sensing tools are needed to accurately identify the specific target zones of interest (e.g. weed species and/or size, disease symptoms, level of defoliation, tree nutritional status or other measures of tree health).

(ii) Following target identification, treatment zones can be accurately mapped and stratified if there is the potential for application rates to be scaled according to the severity of the problem.

(iii) Finally, treatments are applied only where needed and with pesticide rates scaled to achieve the biological objectives.

The concept of targeted zone spraying could be implemented at an individual plant level (such as for control of scattered wilding conifers), to small groups of plants (e.g. a patch of weeds or a group of crop trees with similar levels of disease severity), or to larger zones (e.g. a proportion of the treatment area with similar levels of weed competition). A big advantage of this approach compared with conventional broadcast application is that overall pesticide use and potential for off-target drift would decrease.

Although helicopters have been used for targeted treatments, such as spot spraying of individual weeds (Popay et al. 2003), wilding conifers (Gous et al. 2015), or host trees during pest eradication operations (Strand et al. 2014), this method is very expensive. UASS would be ideally suited to this task because of their potential for highly accurate application, automated delivery of variable rates, and making adjustments to optimise targeting as meteorological conditions change. One exciting opportunity from this concept, is the potential to unlock and implement past research in ways that were not previously possible. Taking weed competition as an example, during the 1990s and early 2000s, models were developed that describe the effects of weeds on tree growth using competition indices (Richardson et al. 1999; Watt et al. 2007) along with dose-response functions to describe the effect of herbicide rate on weed species (Richardson et al. 2012). Modern remote sensing technologies could quantify competition indices and UASS have the potential to deliver herbicide treatments with doses scaled to the level needed to reduce competition indices to acceptable levels. Similarly, research has shown that the herbicide dose needed to achieve control of wilding conifers depends on tree size (Rolando et al. 2021). Remote sensing data describing wilding tree size and location combined with dose-response algorithms can be used by UASS to deliver appropriate doses. The same concepts apply to insect and disease control and to fertiliser application at individual tree or small zone scales.

Broadcast spraying

Broadcast or wide-area spraying involves application of pesticide to an entire area using successive overlapping swaths. Aerial broadcast applications in forestry are made using herbicides, fungicides and insecticides but the methods for herbicide application are fundamentally different so are dealt with separately below.

Herbicides

As noted earlier, current UASS will not be able to compete with helicopters in terms of productivity and work rate for large-scale broadcast herbicide applications with current total spray volumes around 100 L/ha. However, there may be a niche for UASS to support conventional broadcast spraying operations by treating spray block edges or boundaries of exclusion zones within spray blocks. For operations that require no-spray buffers, a significant proportion of the target area may be left unsprayed, reducing tree crop growth rates and leaving a residual population of the target weed which could re-invade the stand (and the same issue also relates to insect or pathogen control). For example, a 10 m or 20 m buffer around the edge of a square 25 ha block respectively represents about 8% or 15% of the total area (about 2.0 or 3.8 ha). With their likely lower drift potential, UASS may significantly reduce the width of buffer needed to protect any sensitive areas such as water bodies. However, new data and models would be needed to provide quantitative evidence to regulatory authorities that justify reductions in buffer requirements based on a reduced drift potential from UASS of different configurations and for site-specific scenarios.

There may be scope to decrease herbicide spraying volumes to 50 L/ha or less, at least for some herbicide/weed combinations (Ray et al. 1999b; Gaskin et al. 2010; Gaskin et al. 2013). Any reduction in volume would improve the competitiveness of UASS, especially for broadcast applications to small areas. However, total spray volumes can reduce spray coverage on target foliage as well as changing the properties of the spray mix. Droplet size can be reduced to compensate for reduced coverage, but that action will increase the potential for spray drift. Hence, research is needed to optimise UASS performance for broadcast herbicide application by quantifying the potential for volume reductions and also considering any trade-offs with spray drift and buffer zone widths.

Insecticides and fungicides

Broadcast insect and disease control spray operations, such as control of the foliar diseases DNB and red needle cast on radiata pine and the insect *P. charybdis* on eucalypts, are usually carried out using small droplets within the driftable size range and low or ultra-low volumes, making them more obviously suitable for UASS, at least for small treatment areas. The viability of UASS for this type of application will be dependent on calculations of work rates and costs for spray blocks of different sizes. However, there will be several additional benefits from using UASS for this purpose that could make precision application a viable proposition even if application costs are slightly higher than conventional methods.

One opportunity is to apply the concept of zone spraying, as discussed above, using remote sensing to identify areas of disease or insect outbreak, stratify by severity and then apply appropriate doses with the UASS. There is also a large opportunity to maximise on-target deposition and minimise drift by implementing a variable flight line spacing strategy. This strategy was recommended for helicopter DNB control operations in 2001 (B. Richardson - unpublished data) but was never implemented in New Zealand because of challenges operationalising the concept. Automated UASS flight would manage this more complex approach to spraying with ease. However, this concept has been tested overseas for both manned and uncrewed aircraft with promising results (Thistle et al. 2020; Bonds et al. 2023). The idea of flight line optimisation could apply to any pesticide spray application but is most relevant for insect and fungicide applications that utilise very small droplets and are most prone to swath displacement (Figure 7). The conventional approach for quantifying lane separation (distance between flight lines) is to measure the swath pattern (the distribution of spray deposits along a line perpendicular to the direction of flight) with the measurements normally undertaken in a light headwind to minimise bias in the swath characterisation (Parkin & Wyatt 1982; Richardson et al. 2004). However, most spraying is carried with some wind present; in fact, for DNB control, spraying in the presence of wind is encouraged (Bulman et al. 2004). The effect of swath displacement from a crosswind is to flatten the swath and spread it over a larger area (Figure 7a). When successive flight lines are overlapped assuming a light crosswind is present, a small amount of swath displacement means that the application rate is not actually reached until about the 5th flight line (Figure 7b). However, when spraying in a significant crosswind with the calibrated lane separation, the application rate at the upwind edge is extremely low due to high swath displacement. In this example using only 10 flights lines (i.e. a block width of 200 m), the actual application rate at the downwind edge is still well below the required application rate with a high proportion of the applied spray being deposited outside of the treatment area (Figure 7b). One option for compensating for these

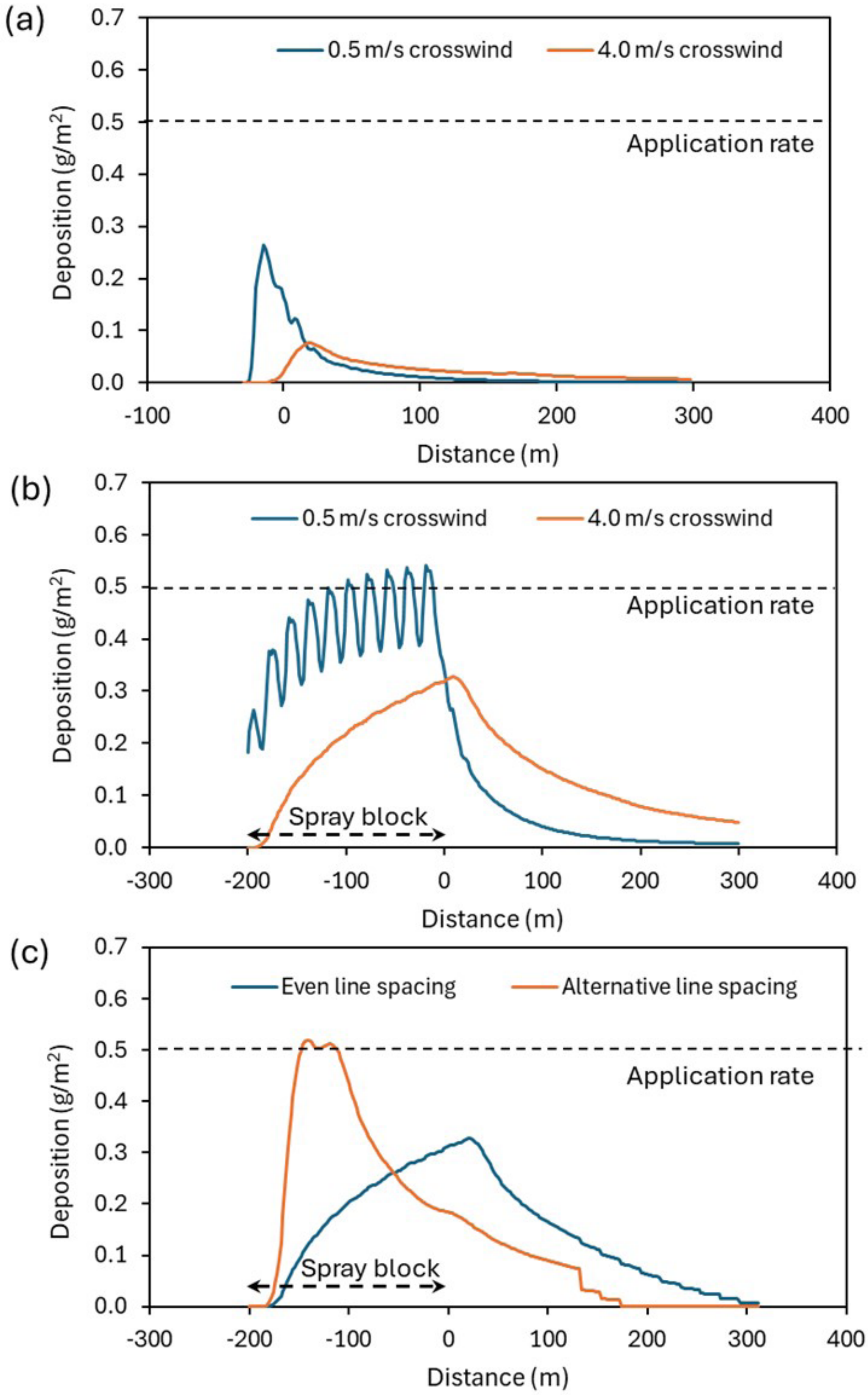


FIGURE 7: (a) Aerial applications using a spray release height of 6 m and small droplets are susceptible to swath displacement as wind speed increases; (b) Depending on the specific meteorological conditions, droplet size and block width, and with a regular flight line spacing, the application rate may never actually be reached, and a high proportion of the applied spray may deposit outside of the target zone defined as the area from -200 to 0 m on the x-axis; (c) An alternative flight line spacing scenarios will significantly improve spray efficiency.

problems is to change the flight line spacing. By spraying back and forth over the first line multiple (six) times and treating the next two lines as double passes, a much higher proportion of spray lands within the spray block and the application rate is achieved at least over part of the spray block (Figure 7c). Where it is possible to increase flow rate without changing droplet size, the number of repeat passes could also be reduced. An even better strategy could be to offset the first line upwind of the target area.

Automated flight operations with UASS could accomplish the task of irregular flight line spacing, significantly improving spray efficiency. To optimise flight line spacing on a real-time and site-specific basis, a flight line optimisation algorithm would be needed along with a means of collecting reliable real-time meteorological data representative of the area to be sprayed, and a spray dispersion simulation model that could model swath patterns.

Accounting for swath displacement and optimising flight line spacing would be especially relevant to broadcast spraying or treating large individual tree crowns in pest eradication operations. During pest eradication operations, especially in urban environments, it is critical to achieve a lethal dose within the target zone while minimising spray drift outside of the target area (Richardson, B. 2002).

Pest eradication operations

Much of the above commentary on using UASS for broadcast insect and disease control and for targeted spraying of discrete zones relates equally to pest eradication operations. One difference between many pest eradication operations and forestry applications is that incursions are often centred in urban environments close to air and shipping ports. The use of UASS for broadcast spray operations in these environments has the same challenges and limitations as for any large-scale broadcast spray operations as described previously. However, where pest populations are limited to small areas, UASS may have a useful role for targeted spraying where only individual trees or small areas are treated. Targeted spraying from a helicopter hovering over an individual tree or small groups of trees has successfully been applied for eradication of *Paropsisterna beata* (Newman) (Strand et al. 2014; Yamoah et al. 2016). UASS would be ideal for this task with their increased accuracy. Initial research simulating a small-droplet insecticide application to an isolated tall tree demonstrated that good canopy penetration and coverage through the crown could be achieved using a slow flying UASS producing a strong downwash (J. Nairn, unpublished data). However, swath displacement became problematic as wind speed increased. While the use of UASS for pest eradication in urban environments would undoubtedly be a quieter and lower profile operation that using a conventional helicopter, there may still be reservations about social acceptability of applying this technology in urban areas (Ogilvie et al. 2019).

Research and development needs

There are clearly many opportunities for relatively small UASS to support forest management operations, especially with recent developments such as increased useful load and battery performance, RTK-GNSS providing accurate positioning, and improved technology for obstacle avoidance and terrain following (Delavarpour et al. 2023). However, despite these improvements UASS have yet to find their commercial niche in regular forest management and many questions remain as to their cost-benefit compared with current management options and their performance in terms of balancing efficacy, spray drift (environmental impacts), and work rate. There are some clear research and development needs that, if met, would provide a clearer picture of benefits of adopting UASS as well as supporting some of the use cases described above.

1. Regulation

At present there is a lack of high-quality data and models to support specific regulation of UASS and inclusion of UASS as an application method on agrichemical product labels in New Zealand and many other countries (OECD 2021). The default expectation would be that where aerial application is permitted, the applicator follows rules and guidelines for conventional aerial application practices, potentially limiting the benefits that could be delivered using UASS.

Current regulatory processes tend to be prescriptive, such as by specifying a requirement for a minimum buffer zone width based on a worst-case scenario analysis. Inevitably, these buffers are sometimes wider than necessary depending on the specific meteorological conditions during spraying and the UASS operating specifications (e.g. droplet size). Performance-based regulations would enable flexibility over buffer zone widths depending on the actual spray drift risk during spraying. This performance-based approach would represent a transformation of the regulatory process that potentially could be enabled by validated real-time models.

2. Deposition and drift data

While significant international efforts are progressing to address needs for UASS spray deposition and drift data (Bonds et al. 2024; Jerome et al. 2024; Teske & Whitehouse 2024), there are relatively few published studies highly relevant to forestry situations, especially for herbicide applications. This information is needed to optimise UASS configuration (e.g. nozzle position relative to rotors), operating conditions (e.g. release height, speed) and understand trade-offs between application factors, such as droplet size, spray volume, and droplet retention and performance measures (efficacy, drift, productivity). As well as carrying out field studies in controlled, uniform environments, it is important to quantify UASS performance metrics, such as spray deposit variability, swath displacement and spray drift, in typical forestry situations that include steep, broken terrain and tall tree canopies.

3. Industry-led trials

As more individual forestry companies start to trial UASS for different use cases there would be industry-wide benefits from taking a collaborative approach to this work and operating to consistent standards. With such a wide range of UASS configurations, site types and operating conditions, no one company is likely to carry out a comprehensive evaluation. However, by adhering to some standard guidelines and sharing data, progress towards optimal solutions for different situations will be much more rapid. If each company carries out ad hoc trials with no standardisation, progress will be slower and outcomes less certain. Forming a UASS interest group could be one means of progressing this idea.

4. Aerial application simulation models

Many detailed studies of UASS wakes have been carried out using computational fluid dynamics (CFD) methodologies (Zhang, B. et al. 2016; Yang et al. 2017; Yang et al. 2018; Zhang, B. et al. 2018; Guo, Q. et al. 2020b; Zhang, Haiyan et al. 2020; Ni et al. 2021; Li, H. et al. 2022; Zhang, Hao et al. 2022). While this approach yields useful insights into the physical process influencing spray deposition and drift from UASS, the methodology is too complex and costly to be effective as an end-user model. However, there may be potential for either deriving an end-user model from multiple CFD analyses or using CFD analysis to evaluate the sensitivity of simplifications that could be applied through analytical modelling approaches.

The AGDISP aerial application simulation model (Bilanin et al. 1989; Teske et al. 2003; Teske et al. 2011) has been valuable for optimising treatment prescriptions for applications using conventional aircraft and supporting associated regulatory processes (Bird et al. 2002). A recently developed commercial version of AGDISP called AGDISPpro (Teske et al. 2018; Teske & Whitehouse 2024) includes an approach for modelling UASS wakes, but the software code for this system is not in the public domain or open source and therefore may not be suited as a regulatory model. Because AGDISP was developed for computers with minimal processing capacity, it required many simplifying assumptions that have also been carried over into AGDISPpro. These assumptions maintained the overall integrity of the model, as demonstrated by numerous validation studies (Bird et al. 2002; Teske & Whitehouse 2024), but also placed significant limitations on how the model can be used.

Despite the international modelling efforts described above, new models are needed that support accurate targeting of spray deposition from UASS at scales down to the individual tree-level, can accommodate variable UASS configurations, real-time meteorological inputs and input variability, and account for effects of topography and canopy characteristics on meteorology. Together with new model development, quality data from controlled field studies, designed according to international standards and published in peer-reviewed journals, are critical for model validation and acceptance by regulatory authorities.

5. Real-time adjustments

Several of the use cases described previously require real-time or close to real-time adjustment of the UASS position or operating specifications in response to changes in meteorological conditions particularly wind speed and direction (Teske et al. 2011; Faiçal et al. 2014; Faiçal et al. 2017). These changes would be needed to account for swath displacement or to provide warnings if there is a risk that spray drift will exceed a defined threshold. To realise these concepts there are three primary needs:

(a) Either a real time version of a spray application simulation model that can run quickly enough to make timely corrective actions, or a pre-populated data look-up table derived from model runs relating to the situation and potential envelope of conditions for that specific scenario. The concept of a fast-running real time model was first proposed in the mid 1990s, but was not implemented (Teske et al. 1996). More recent work has demonstrated the value of this approach (Thistle et al. 2020; Bonds et al. 2023).

(b) A means for collecting meteorological data in real-time, either on the aircraft itself or through monitoring at one or more fixed points on the site (Faiçal et al. 2014; Faiçal et al. 2017). Challenges from fixed point monitoring in complex forestry environments include determining how to extrapolate data across the site and account for surface roughness and topographic effects. Alternatively, it may be possible to derive wind speed and direction from UASS rotors' speeds and the UASS acceleration and position (Wang, J. Y. et al. 2018).

(c) Finally, a methodology would have to be defined for averaging meteorological conditions and assessing when a threshold has been exceeded requiring corrective actions from the UASS.

6. Positional accuracy

New studies to quantify UASS positional accuracy using RTK-GNSS, now that the SouthPAN satellite-based positioning system is active, would be useful as the scale of positional/navigation error places a limit on what will be achievable in terms of accurate pesticide dose delivery.

7. Optimising spray mixes

Reducing total spray volumes would significantly improve the work rates of UASS, especially for herbicide applications. However, reducing volumes can change efficacy by increasing the concentration of active ingredients and reducing coverage. The high downwash produced by UASS may also have negative effects on droplet retention on foliage, especially when using large droplets for drift reduction. Conversely, reducing droplet size to compensate for loss of coverage and/or to increase retention will increase the drift potential. These factors need to be evaluated and optimised for UASS applications (Xue et al. 2024).

8. Data collection and its use

The potential for UASS to act as a broad data collection system as well as being a platform for pesticide (or fertiliser) delivery is central to concepts of precision application and may significantly add value to this technology. Either using and integrated data collection and spraying system or using two separate systems, there is the opportunity to collect data on the crop trees, their size and health, the site, the weed or pest species present and their distribution, the details of any spray application and associated meteorological conditions, and the results of the spray application (e.g. weed control, tree response, change in infection severity and distribution).

With such a rich dataset, artificial intelligence and machine learning can support continuous improvement for factors such as weed or disease detection and optimising application prescriptions (Gao et al. 2019; Guo, H. et al. 2020a; Hunter III et al. 2020).

9. Battery life, load carrying capacity and tele-operation

The interplay between battery life, useful load, type of spray operation (such as spot versus broadcast application), and operational parameters (such as spray volume) has a major influence on the work rate of a UASS compared with manual or conventional aircraft operations. While battery endurance has improved over time (Nahiyoon et al. 2024), the introduction of hybrid technology, where liquid fuel drives a generator charging a battery, may significantly improve the productivity and cost-benefit of UASS and should be evaluated. Another trend for multi-rotor UASS over the last decade is for systems to get larger, with greater tank capacities (Nahiyoon et al. 2024). If this trend continues, in time the UASS may be able to compete with manned helicopters on work rate and cost. However, if this approach results in craft that need to fly faster and higher above the canopy or ground, partly to mitigate risks from low flying given the higher capital cost, then many of the features of UASS that support the concept of 'precision application', such as highly accurate low and slow flying, may be lost. With technology and connectivity improvements it is also feasible to imagine tele-operation of fleets of UASS (Faiçal et al. 2014; Faiçal et al. 2017) with pilots operating from remote headquarters and 24-hour operations as long as weather conditions are suitable. Operators on-site would still be required for loading, refuelling and maintenance (Delavarpour et al. 2023).

10. Remote sensing

Although not a focus of this review, remote sensing combined with artificial intelligence methodologies is a vital component of the precision application concept, needed to accurately detect and record the position and health of the crop trees to be protected or the pests to be targeted (Dash et al. 2017; Hunter III et al. 2020; Pearse et al. 2020; Etienne et al. 2021; Wang, D. et al. 2022; Watt et al. 2023; Zheng et al. 2023). Lidar, multispectral, hyperspectral and RGB imagery are all tools that are being used for identifying target pests (e.g. weeds, insect damage, disease) and quantifying crop health, (Hunt Jr et al. 2010; Aasen et al. 2018; Dash et al. 2019; Hunter III et al. 2020; Hafeez et al. 2023). It is vital for delivering the precision application concept that this remote sensing work goes hand in hand with UASS developments. Combining accurate mapping of crop health or pest distribution with three-dimensional terrain models and maps of any other surface features, creates the opportunity for navigation path-planning (Hu et al. 2022). Optimal path planning considers both the attributes of the UASS, in terms of payload and endurance, the areas to be treated, and the take-off and landing positions for one or several UASS operating as a cooperative swarm (Li, P. & Duan 2012; Xu et al. 2021; Jiao et al. 2024).

Conclusions

While multi-rotor UASS have been available in New Zealand for at least a decade, their application in forestry has been limited. However, with significant improvement to the technology in recent years, including in terms of payload, battery endurance, terrain following and obstacle avoidance, the potential for a step change in application practice is possible for at least some use cases. Their opportunity, at least in the near term, is not to replace conventional aircraft carrying out broadcast applications over large areas because UASS are unable to compete in terms of productivity. However, the value proposition for UASS is much stronger for 'precision spraying'. With their ability to operate at slow speeds and with low spray release heights, UASS can achieve a level of accuracy beyond what is realistic for helicopters. Further, automated flight more easily offers the opportunity to accommodate adjustments to the flight plan based on changing meteorological conditions than manned flight. To fully realise the opportunities for precision spraying in forestry and to provide regulators with the means to apply appropriate risk management measures, new data is required on all aspects of UASS performance along with new spray simulation modelling tools. Modelling tools are also needed to support improved efficiency for spray applications, especially by accounting for swath displacement effects and to provide spray drift warnings. Significant opportunities for UASS application in forestry include:

- herbicide spot spraying and treatment of boundaries close to sensitive areas;
- low volume fungicide or insecticide applications, especially for small areas or in pest eradication operations;
- applying variable treatments to individual plants or zones within a target area defined by remote sensing tools e.g., areas with different levels of weed infection; individual weeds (e.g. wilding conifers); or variable levels of weed competition within a stand defined using competition indices.

Competing interests

The author declares that he has no competing interests.

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