Evaluation of spray deposition in potatoes using various spray delivery systems

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Abstract The tomato-potato psyllid incurs high control costs through intensive spraying and other treatments. A field study was conducted in March 2012 in Pukekohe, New Zealand, to evaluate the pesticide deposition potential of five different spray delivery systems. The treatments included a conventional boom, a canopy submerged drop sprayer combination, a pneumatic electrostatic spraying system, an air-assisted rotary atomizer, and a high-volume air-assist boom. Each system was calibrated for appropriate spray volume rates between 167 and 400 litres/ha. Rhodamine WT fluorescent dye used as a tracer was sampled on folded Kromekote® sampling cards oriented flat and horizontally above, central to, and below the canopy. Spray coverage rates were quantified at designated heights adjacent to leaves to assess deposition throughout the potato canopy. All treatments that consisted of one or more novel technologies consistently gave higher coverage to the underside of the potato leaves than with the conventional boom.

Keywords tomato-potato psyllid, pesticide deposition, spray delivery system, canopy penetration.

INTRODUCTION

The potato industry in New Zealand yields approximately $382 million in revenue per year (Anonymous 2010). Since 2006, the tomato-potato psyllid (TPP) has been causing ~$28 million in control costs each year (Kale 2011). This cost is related mostly to the amount of inputs associated with the control of TPP and the dependence upon the frequent application of pesticides at high rates.

Unfortunately, the architecture of the potato plant canopy coupled with the close proximity of neighbouring plants creates an immense obstacle for adequate administration of pesticides. It is imperative to obtain adequate, three-dimensional coverage throughout the canopy from the soil level upwards, making contact with all surfaces. To date, there are few data in regards to spray deposition on the underside of foliage and the ideal coverage to achieve the required rates of control. Nansen et al (2010) reported acceptable control of TPP in the United States with 20 to 30% coverage of the pesticide, abamectin. However, to achieve this coverage rate in lower canopy regions and on lower leaf surfaces is unlikely with conventional delivery systems.

Previous research has demonstrated multiple methods to increase deposition among various cropping systems. These include, but are not limited to, high application rates, smaller droplet sizes (<100 µm), the use of electrostatic technologies, air-assisted particle transport, and optimised nozzle orientation (Hislop 1987; Giles & Blewett 1991; Nordbo 1992; Scudeler & Raetano 2006). The measurement of spray deposition in crops such as potatoes has historically been a labour intensive effort that has included chromatography, coated slides, miscellaneous fluorometry techniques and water sensitive paper (Waite 1977; Nordbo 1992; Hoffmann et al. 2007; Fritz et al. 2009). Kromekote® cards (K-cards) are a well known sampling surface capable of recording a durable, fine resolution colour image. The quality and potential analytical power of this record has been largely unrecognised due to the past limitations of resolution in scanning technologies and computing power limitations. For example, standard imaging may not be capable of reliably capturing stains smaller than 42 µm in diameter, the square dimension of a standard pixel. Many systems that were based on black and white imagery do a digital "high pass" to eliminate small stains of only a few microns, due to the fact that in black and white imaging there is no way do distinguish between dust or other environmental contamination and spray. This further obscures the true picture of deep-canopy deposition. Therefore, the presence and influence of the finer, canopy penetrating droplets that will highly impact control of psyllid in deep canopies could previously not be properly characterised by the methods typically used. A key hypothesis of the present study is that understanding more accurately the deposition of small droplets deep in the canopy will ultimately give a much more complete understanding of the efficacy of a spray methodology, and empower growers to make more effective choices in spray application.

Advancements in consumer electronics have made the possibility of ultra-high resolution desktop imaging an economic reality for researchers. The use of K-card collectors with high resolution scanning and quantitative image analysis is now technically possible, although few have yet attempted it at modern high-resolution capabilities. Therefore, it was the objective of this study to assess deposition from conventional and novel spray delivery systems in a potato canopy and investigate a digitised method for the analysis of that deposition.

MATERIALS AND METHODS

The study was conducted 13–15 March 2012 in Pukekohe, New Zealand (37°13'55.78"S 174°51'10.22"E). 'Moonlight' potatoes were sprayed at closed canopy when the crop was approximately 0.75 m tall. Due to the fragile nature of the crop, high variability of environmental conditions and large number of treatments evaluated, the ability to replicate treatments over a wide time period as would normally be done in a study of this type was very limited. This study involved a complex, double nested design where height and leaf side were nested within treatment. Furthermore, due to the quickly growing canopy, four separate plots of the experiment were sprayed at the same time, in one pass. Each plot then consisted of four individual replicates for a total of 16 individual replicates. Each treatment was sprayed sequentially in the same row using fresh, undisturbed and unsprayed canopy upwind or adjacent to the prior treatments to avoid contamination from previous applications as well as to minimise damage to the commercial crop.

Six application scenarios involving five different spray delivery systems were evaluated to assess a wide array of application volume rates, particle size spectra, placement, and physical augmentation. Treatments consisted of (i) a conventional four-nozzle boom paired with fine twin-tip nozzles (type TJ60-110-04, Teejet Spraying Systems, Wheaton, Illinois, USA) at an application volume of 300 litres/ha; (ii) a combination application where 25% of each swath was sprayed with a conventional boom with Teejet XR 110-04 nozzles and 75% from an engineered, up-angled drop-nozzle (DropSpray®, Micron Sprayers Ltd., Bromyard, UK) system with WRW-4 nozzles (Delavan, Eau Claire, Wisconsin, USA) applying 260 litres/

ha; (iii) a pneumatic atomiser in combination with induced electrostatic charge spray system (Electrostatic Spraying Systems MaxCharge™ nozzles, ESS Watkinsville, Georgia, USA), at 167 litres/ha with charge disengaged (ESS/off); (iv) an ESS MaxCharge™ with charge engaged (ESS/on) at 167 litres/ha; (v) an air-assisted rotary cage style atomiser (Proptec™ PT100, Ledebuhr Industries, Lansing, Michigan, USA) delivering 200 litres/ha; and (vi) a Gambetti (Milan, Italy) self-propelled, air-assisted boom sprayer with hollow cone nozzles (TeeJet TXVK12) at 400 litres/ha. Driving speeds for the sprayers ranged between 4.7 and 6.8 km/h, based on manufacturer recommendations or local grower standards for the given technology. Once output was calibrated, a spray solution of 0.2% v/v rhodamine WT (Abbey Color, Philadelphia, Pennsylvania, USA) fluorescent tracing dye and 1% v/v Actiwett™ non-ionic surfactant (Nufarm, Middleton, NZ) was added as a standard spreader/sticker adjuvant. Detailed treatment information including scaled application volumes can be observed in Table 1.

Deposition was measured qualitatively as coverage on K-cards and quantitatively through physical washing and capturing of leaf rinsate (the leaf wash data are not presented here). K-cards were prepared by cutting to uniform sizes of 2.54 × 15.24 cm and appropriately labelled for sample identification. The day of the trial, prepared cards were affixed, shiny side out, with alligator clips to a fabricated metal stand and placed on the angled slope of the potato bed in the centre of the spray swath between plant beds. On the stands, two cards (96 cards/treatment) were orientated horizontally and flat at three canopy levels: flush to the top of, middle of and beneath the canopy, approximately 10 cm above the soil. Once application was completed, the cards were allowed to dry a minimum of 5 min or as needed to prevent card smearing. Cards were then placed in dark storage in individual re-sealable bags to avoid photodegradation.

Data were digitized using a high resolution scanner in true 4800×4800 dpi mode (Canon LIDE 120, Canon Corporation) where a randomly selected, 4 cm^2 image was digitally captured and stored using uncompressed Bitmap (.BMP) format to preserve colour and resolution data. This image size was chosen due to a combination of technology limitation and practical utility: each 2 cm square image was 44 megabytes of data. The software buffers of the scanner would allow approximately 1 gigabyte of scan file per scan. Eight unfolded cards filled a platen, and the subsequent 16 images totalled 704 megabytes. The total process time for the full platen scan including loading the cards was approximately 20 min. Increasing resolution to 9600 dpi would have made each image nearly 2 gigabytes, for a change in resolution from 5.3 µm to 2.6 µm. This increase in resolution was not deemed sufficiently valuable to justify the corresponding geometric increase in scanning and processing time.

Scans then underwent colour transformation

Table 1 Detailed treatment information.

Treatment	Droplet size classification	Application volume (litres/ha)	Scaled application volume (%)	Speed (km/h)	Air velocity (m/sec)
Conv. boom	Medium	300	75	6.8	na
Drop-spray	Up:fine/drop:coarse	260	65	6.8	na
ESS/off	Very fine	167	42	4.7	25
ESS/on	Very fine	167	42	4.7	25
Proptec	Fine	200	50	6.8	20
Air-assist	Medium	400	100	6.4	na

and quantification of percent coverage using Metlab (7.2.0.232). Data were then subjected to analysis of variance using SAS (9.3) and means separated with Fisher's Protected LSD (P<0.05).

RESULTS

The use of the high resolution scanner, colour transformation and digital quantification was successful. A P-value of 0.73 indicates that all runs could be pooled when separating leaf sides. Thus, the data are presented in the simplest form of individual leaf side.

Upper leaf side

Table 2 compares treatments according to canopy height on the upper leaf side. Deposition was acceptable by industrial standards (>80%) with five of the seven treatments, ranging between 82 and 97%. However, this is to be expected as the drop-sprayer and the engaged ESS are physically influenced by nozzle direction and/or electrostatic properties (i.e. the drop-sprayer is submersed in the canopy and the ESS/on particles are electrostatically attracted to new plant parts). Percent coverage in the middle and lower sections has few notable differences with the exception of the air-assisted Gambetti (49 and 70%, respectively). This, however, is likely a function of application volume because the Gambetti was saturating the canopy with a relatively high spray rate of 400 litres/ha. Furthermore, the uniformity between canopy levels is important as shown in Table 2. No treatment showed uniform deposition throughout all three canopy levels. The Gambetti air-boom had similar coverage in the middle and upper strata. However, only the drop-sprayer and both ESS treatments were similar in both the lower and middle canopy.

Lower leaf side

Table 3 shows few notable differences. The ESS engaged and disengaged demonstrated the best coverage at the upper canopy level with 11 to 17%, probably due to the flux of the finer

Table 2 Spray coverage (%) to the upper leaf-side by individual heights compared by treatment. Means followed by the same English letters within columns and Greek letters within rows are not statistically different based upon Fisher's Protected LSD (P<0.05).

Treatment	Lower			Middle			Upper		
Conv. Boom	22.63	b	α	56.56	ab	β	97.15	a	γ
Drop-spray	25.33	b	α	25.60	d	α	59.73	d	β
ESS/off	34.70	b	α	43.56	bc	α	84.70	abc	β
ESS/on	27.38	b	α	40.29	cd	α	73.95	c	β
Proptec	25.62	b	α	46.35	cb	β	87.22	ab	γ
Air-assist	49.03	a	α	70.01	a	β	82.24	a	β

Table 3 Spray coverage (%) to the under leaf-side by individual heights compared by treatment. Means followed by the same English letters within columns and Greek letters within rows are not statistically different based upon Fisher's Protected LSD (P<0.05).

Treatment	Lower			Middle			Upper		
Conv. Boom	0.1	c	α	0.12	d	α	0.41	d	β
Drop-spray	1.61	abc	α	1.73	cd	α	3.49	cd	α
ESS/off	0.91	bc	α	2.84	cb	α	11.32	ac	β
ESS/on	5.64	ab	α	2.48	c	α	17.06	ac	β
Proptec	3.71	abc	α	5.70	a	αβ	7.56	bcd	β
Air-assist	6.05	a	α	4.82	ab	α	9.81	bc	α

droplets as illustrated in Table 1. The Proptec and Gambetti sustained the best coverage in the middle strata with 4.8 and 7.7%. The hardest to reach, under leaf side at the lower canopy level, was best covered with the Gambetti at 6%, the ESS/on at 5.64%, and the Proptec at 3.71%. The conventional of boom consistently achieved the least amount deposition to the underside of the leaf with 0.1 to 0.41%.

DISCUSSION

The high resolution scanner was able to achieve resolution down to ~5.3 µm droplets per pixel. This resolution, coupled with image transformation and quantification, has simplified the way in which data are collected and reduced subjectivity associated with manual analysis by eye. Colour transformation enables the user to set thresholds and assign classification for appropriate data quantification. For instance Figure 1 shows that when a threshold was set to capture faint hues and transform them into black, deposition was more visible against the white background. The coverage has been presented in terms of percent coverage, but this technique also would provide data on droplet density, distance between droplet centroid(s) and stain size. This is similar to the digitisation of Franz (1993).

A variety of views exist among scientists on appropriate sampling media for spray deposition studies. While no artificial medium can fully represent natural foliage, the use of cards such as Kromekote® can provide extensive information on spray distribution within crops. As with any sampling surface including leaves, issues such as measurement accuracies, spread factor, penetration and absorption on K-cards are matters for consideration when establishing a study (Waite 1977; Sundaram et al. 1991; Franz 1993). However, for the present study, these concerns are acceptable as the aim was to capture a tracer for a large perspective study of deposition with a specific focus of three dimensional, sub-layer depositions. In fact, sample cards can give more information about deposition because contrast allows high resolution of droplets on cards compared to textured leaves. When residue levels are low, the quality of coverage is essential and the data gathered using the Kromekote® paper is valuable. Conversely, when deposition is high, the quantity of deposited active ingredient can range greatly because surfaces can only adsorb a capacity amount of spray before runoff causes losses to the ground (Nordbo 1992).

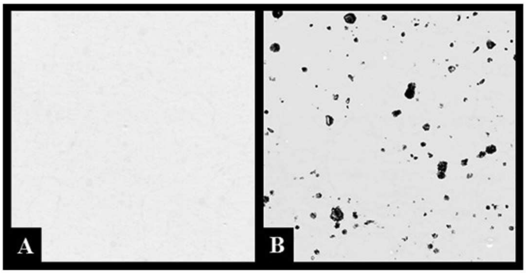

Figure 1 Colour transformation from (a) red and pink to (b) black on a white background.

Theoretical work from Walklate et al. (1996) showed an exponential decrease of velocity and turbulent kinetic energy in canopy spraying. Canopy density must be taken into consideration when studying air-assisted spraying systems. Gupta et al. (2012) have conducted recent work to better understand the complexity of air velocity and its relation to canopy density. Their research also affirmed that there is a severe loss of velocity towards the canopy bottom and that a critical velocity of 15 m/s is needed to penetrate the upper canopy of bittergourd, chilli and eggplant. The present study was carried out above this critical level at 20 to 30 m/s, and high penetration through the upper canopy reflected this.

Small droplets with diameter below 100 µm are often desirable for canopy penetration and deposition. However, small droplets also have greater drag and lose kinetic energy more quickly than larger droplets (Hislop 1987). Transport assistance through electrostatic charging and/or air carriage can facilitate the transport of small droplets into canopies. Electrostatic and air-assisted technologies have also shown efficiencies through reductions in application volume rates, which are important when taking waste into consideration. For instance, Giles & Blewett (1991) found no difference in the deposition rate of the active ingredient Captan (N-trichtoromethylthio-cyclohexene-1,2-dicarboximide) with a 50% reduction in application volume on strawberries. The savings in water usage and associated reduced transport costs and treatment times from rate reductions can favour reductions in application volume rates where coverage is still maintained or even improved. This is also important when considering the high volume, air-assisted treatment of the Gambetti. Although it is one of the few treatments with relatively uniform deposition regardless of canopy height, the deposition pattern that was observed in this study further demonstrates the consequence of the relatively high application volume rate. With higher deposition on the upper and lower canopy on the *under* leaf side than in the middle strata, turbulence and/or bounce may be important. Furthermore, with an application volume rate of 400 litres/ha, much of the deposition was a result of canopy saturation, which suggests a high risk for product waste through runoff to the soil. Law (2001) explains that 60 to 70% of applied product can meet a non-intended fate. This is also discussed in research by Walklate et al. (1996), which indicated that air-assistance needs to be matched with canopy density, although their research did not look individually at leaf side, but rather at cumulative transfer efficiency. Ironically, the ESS/on application resulted in a similar deposition pattern as the Gambetti. This would appear to be a product of the smaller droplet size (~41 μm) and the effects of electrostatic and air-assistance as this pattern is not observed with the ESS/off treatment.

Much of the research conducted for drop-spray application technologies has concluded that the canopy-submerged placement results in better deposition within the canopy. For instance, Mahood et al. (2004) studied spray deposition in cotton, finding that coverage to the underside of the leaf was related to the spray release angle and liquid pressure, achieving at least 66% coverage with a nozzle angle of 30°, pressure of 4 bar, and a spray velocity of 4 km/h. Also in cotton, Womac et al. (1992) found control of beet armyworm to be 'numerically' better with a drop-sprayer than with a conventional sprayer, thus providing better armyworm control.

In conclusion the deposition from the various treatments varied less than expected. However, all treatments that consisted of one or more novel technologies consistently gave higher coverage to the underside of the potato leaves than with the conventional boom. When battling any pest such as TPP, where the success of the crop is reliant upon coverage, every percent of active ingredient administered to the pests' habitable site is essential. Furthermore, as the use of pesticides increases, so does the awareness to their environmental fate. Therefore, it is paramount that the research of drift reducing technologies advances proportionally for the protection of New Zealand agriculture.

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