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RESEARCH ARTICLE

On-farm trials towards reduced insecticides in main-crop potatoes in the Waikato Region of New Zealand

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Abstract Tomato potato psyllid (TPP), *Bactericera cockerelli* (Sulc) (Hemiptera: Triozidae), is the vector for "*Candidatus* Liberibacter solanacearum" (CLso), which causes the serious disease "zebra chip" (ZC) of potatoes. Between 2016 and 2019, a reduced-insecticide approach to control TPP was evaluated. We compared a standard-insecticide weekly spray regime that included Integrated Pest Management (IPM)-compatible insecticides plus JMS Stylet Oil® (JMS) as a wetting agent, with a reduced-insecticide regime where we used the oil on its own on alternate weeks with the insecticide/oil mixtures. Spray programme start dates were determined by: (1) crop scouting; (2) sticky-trap monitoring; and (3) degree-day calculation. Crop scouting combined with a sticky-trap action threshold and degree-day data was an effective method for determining when to start spraying. The most substantial reduction in insecticides was achieved by alternating weekly insecticides with the oil formulation on its own. Sub-samples of TPP from sticky traps situated in the trials tested for CLso confirmed the presence of the bacteria in (commonly known as 'hot') TPP throughout the trials. The reduced-treatment approach gave statistically similar levels of ZC to the standard insecticide spray programme.

Keywords *Bactericera cockerelli*, mineral oil, potato, integrated pest management, IPM.

INTRODUCTION

The first record of the tomato potato psyllid (TPP), *Bactericera cockerelli* (Sulc) (Hemiptera: Triozidae) in New Zealand was in early 2006 (Teulon et al 2009). Since then, research has been conducted to identify economically and environmentally sustainable approaches that mitigate its impact on the potato-growing industry. Such approaches included a focus on minimising the spread of the bacterium "*Candidatus* Liberibacter solanacearum" (CLso), vectored by TPP, which causes "zebra chip" (ZC) disease (Munyaneza et al 2015). This disease can render entire crops commercially non-viable. Other background research has included: assessing insect infestations and trends in unsprayed potatoes at Pukekohe Research Station over 3 years (Walker et al. 2011); validating a crop sub-sampling method for monitoring TPP infestations (Walker et al. 2013); interactions between TPP and foliage-dwelling predators (MacDonald et al 2016); and trials showing that insecticidal treatments were not required on early potato crops grown around Pukekohe (Walker et al. 2012). However, despite identifying practical reduced-insecticide approaches, there has been varied uptake from the New Zealand potato industry.

Here we report on collaborative field trials in the Waikato region between The New Zealand Institute for Plant and Food Research (PFR) and A.S. Wilcox & Sons Limited (ASW), a vegetable-production company based in Pukekohe, New Zealand. ASW provided the on-farm trial sites within their main-crop potato fields and made contributions to the execution and decision making around the research. Their objectives centred on producing potato crops with lower insecticide residues while still managing ZC. Previously conducted small-plot trials at Pukekohe (174° 50′ E, 37° 11′ S) Auckland over nine years provided four essential tools that could reduce spray applications and progress into these commercial-scale, on-farm situations (Walker et al. 2015, Wright et al. 2017).

The objective of the current research was to compare a standard, common-practice approach in main-crop potatoes, which was typically 14–16 insecticide sprays per season for this grower in this region, with a reduced insecticide programme inserting the alternation of a foliar application of mineral oil into a standard insecticide-spray programme.

MATERIALS AND METHODS

General methods

All trials were conducted in the Matamata district on ASW sites over three consecutive main-crop growing seasons (2016–2019), Four sites were used each time, with a trial area within each site. These sites were considered and analysed as replicates. A number of different cultivars were used, (Table 1). Four tools were employed: 1) weekly crop scouting for TPP using a middle leaf sub-sample and spraying once a threshold was reached (Walker et al. 2013); 2) sticky trap monitoring for TPP and spraying once a threshold was reached (Walker et al. 2015); 3) degree-day accumulation calculations and spraying once a threshold was reached (Butler et al. 2016); and 4) inserting the alternation of a foliar application of mineral oil into a standard insecticide-spray programme (Wright et al. 2017) (Appendices 1–4). Insect data will be published separately (manuscript in preparation).

Tool 1 – Crop scouting

PFR used two scouting systems in Trial 1 (2016/17) – the validated PFR system (Walker et al. 2013) and the Fruitfed PGG Wrightson commercial crop scouting system (Fruitfed), as previously and currently utilised by ASW. This approach was used to calibrate scouting methods and results, and also to gain confidence in the two approaches used over the three trials.

The PFR weekly sampling protocol was conducted using a hand lens (10 times magnification) to aid insect identification. Twenty-five leaves were sampled in each replicate for four distances (30, 60, 90 and 120-m into the treatment areas), providing 100 leaves in total per treatment area along two adjacent rows in the trial areas. Sampling by PFR occurred in both the reduced and standard spray areas at two of the four sites for each trial. Numbers and all life stages of TPP, aphids and natural enemies were recorded from emergence until the crop was first sprayed in both the reduced and standard areas at two of four trial sites per trial. A follow-up sampling event was conducted at these sites in mid to late summer for each of the three trials.

The other two sites were monitored throughout the trial duration and spray initiation determined by Fruitfed thresholds for each of the three trials. The Fruitfed protocol involved weekly sampling conducted by randomly selecting 20 representative plants from the “outer” (a 6- to 7-m edge around the crop) and checking entire plants when they were small or two stems per plant when they were bigger. The leaves were examined using a 10-times magnification hand lens to aid insect identification as needed. TPP and beneficial insects were counted, as was the presence/absence of other significant insects. This process was repeated with 20 plants from the “inner” area of the crop, and continued throughout the entire life of the crop until spray off and harvest.

In 2017/18 and 2018/19, the PFR system was used for two sites per trial, and Fruitfed continued scouting all sites with their method.

Tool 2 – Sticky trap monitoring and testing of TPP for CLso status

Five yellow BugScan® double-side sticky traps measuring 25 x 10 cm were placed into the trial area at each site once approximately 60% of plants had emerged. A single sticky trap was placed approximately midway along each side of the trial area, about 5-m into the crop. The fifth trap was placed in the centre of the crop. Electric fence standards were used to support and position the traps, so the bottom of each trap was level with the top of the crop. Bulldog clips and twist ties secured the traps in place to the electric fence standard. The traps were adjusted as the crop grew so that the bottom of the traps remained around plant height during the season. The sticky traps were changed each week,

Table 1 Number of insecticide spray applications for each treatment area over the main-crop season.

Trial	Year	Site number	Cultivar	Insecticide applications and weeks receiving full crop insecticide sprays		Reduction in insecticide spray applications (%)	Mineral oil spray applications
				Reduced areas	Standard areas		
1	2016/2017	1	‘Moonlight’	5	10	50	5
		2	‘Moonlight’	5	9	45	4
		3	‘Fianna’	3	5	40	2
		4	‘Snowden’	5	10	50	5
2	2017/2018	1	‘Satin King’	5	13	61	8
		1a	*Gold Crisp	5	13	61	8
		2	‘Agria’	5	11	55	6
		3	‘Moonlight’	7	14	50	7
		4	‘Andean sunside’	5	9	45	4
3	2018/2019	1	‘Agria’	5	10	50	5
		2	‘Agria’	3	6	50	3
		3	*Gold Crisp	6	11	45	5
		4	‘Nadine’	3	5	50	2

*indicates a commercially sensitive cultivar.

placed in clear plastic folders, and labelled with the site, date and position. From the start of the main-crop growing season, the trap counts were used as part of an action threshold for spraying, so the traps needed to be assessed as soon as possible to allow spraying to take place later in the same week if needed. All TPP adults were counted on both sides of each trap in the laboratory using a binocular dissecting microscope. TPP numbers were recorded, and numbers communicated to ASW. Once the action threshold of an average of three TPP adults per trap had been reached (Walker et al. 2015), insecticide sprays were applied to the trial areas, and trapping was concluded by PFR. Walker et al. (2015) concluded that growers should switch to a standard spray programme after this action threshold was exceeded, to minimise damage caused by subsequent generations (infestations) of TPP. Insect specimens were obtained from both PFR and Fruitfed traps spanning the entire growing period for each trial. DNA extraction and a qPCR assay of a sub-sample of TPP specimens were conducted to determine the CLso status of TPP in the field. The samples tested in 2017 used the protocol developed by Beard et al. (2013), but the 2018 and 2019 samples were analysed using a multiplex probe-based qPCR assay using internal primers (Pers. Comm. S. Thompson PFR) and CLso primers developed by Li et al. (2009). Each sample was run in triplicate. A dilution series of a plasmid standard containing the appropriate internal and CLso target sequences were used as standards on each qPCR plate. This approach enabled approximate copy numbers of CLso present in a sample to be determined and for samples to be compared between qPCR plates by standardising the results.

Tool 3 – Degree-day accumulation

Weather and temperature varied from year to year, and consequently, so did insect activity. We accessed real-time accumulated degree-day data for the Matamata region created by PFR, funded by Potatoes New Zealand Incorporated (PNZ) and available to growers on the PNZ website, to predict the onset of the rapid (exponential) increase in TPP numbers from existing low levels that are ordinarily present over winter in the North Island. The degree-day data information contributed to determining the timing of initial insecticide sprays for control of TPP early on in the growing season. The degree-day threshold for the onset of spraying is set at 980 accumulated degree-days for the Matamata region (Butler et al. 2016) based on modelling using historical data for the region. The modelling process has limitations due to the wide variety of differing crop stages at any given time and also does not consider alternative host plants for TPP being present. However, there is value in having this information available as a general indication of the trend of TPP and likely generations throughout a growing season based on temperature.

Tool 4 – Mineral oil applications

JMS Stylet Oil® (JMS Flower Farms Inc, USA), an isoparaffinic petroleum distilled oil, was used as a wetting agent for all insecticide applications. Isoparaffinic petroleum distilled spray oils have negligible mammalian toxicity, low residual activity, no reported link with development of insect resistance, and low toxicity to beneficial insects. (Buteler & Stadler 2011). They have also been reported to control numerous insect pests of several horticultural crops (Wright et al. 2017). Registration of JMS Stylet Oil® (JMS) for use as a TPP repellent on potatoes in New Zealand is currently pending. Application of JMS was alternated with the standard insecticides used in the growers' commercial spray programme. Once spraying was initiated, alternation was continued throughout the life of the crop in the reduced spray areas. In trial 2 at one site, trial areas (1 and 1a), received a different spray regime from from the 3 other sites, this is expanded upon in Trial 2: 2017/18 under Trial design and Crop Management and appears in Appendix 2. In this case, JMS was applied for four consecutive weeks before the alternation of standard insecticides with JMS commenced. The spray rate for all three trials was 1 L/ha of JMS applied in the reduced spray areas per application. Detailed spray programme information is provided in Appendices 1, 2, 3 and 4.

Previously, normal practice in main-crop potatoes was 14–16 insecticide sprays per season for this grower in this region. The reduced insecticide programme inserting the alternation of a foliar application of JMS oil into the standard insecticide spray programme decreased insecticide use by 40–61% over the three trials (Table 1).

Trial design and crop management

In each of the three trial years, four different commercial potato sites were used. Each trial at each site had an area of approximately 1 ha of standard spray area with a reduced spray area of 120 m x 17 m (approx. 0.2 ha) located within it from one edge. Fertilisers, herbicides, fungicides and irrigation (where stated in Table 2) were applied to the entire crop by the grower. For Trial 1 (2016/17) at each site, scouting was carried out at set distances of 30, 60, 90 and 120-m from the crop edge for both the reduced and standard insecticide areas. The aim was to determine if insect activity varied from the outer edges of a crop (i.e. TPP moving into the crop from the edge), compared with plants in the centre of the trial area. No significant difference between distances was found, so the data were combined to provide a scouting sample of 100 middle leaves sampled in an area of 120 m x 17 m in total for the reduced and standard areas. Two of the sites were used over two trials, and the remaining eight sites were used once only. The trial layout remained the same throughout the trials, but the trial area for the reduced spraying regime increased over consecutive trials. This reflected the "adaptive" approach of the research, incorporating collaborative decisions and recognising that, due to the applied nature of the research, minor adjustments were sometimes required. Hence, the trials did not simply repeat the same methods over the three seasons. Of the four sites for each trial, PFR scouted two sites, while Fruitfed scouted all four sites. PFR and ASW shared decision making around the initiation of spray programmes at the two PFR scouted sites, while Fruitfed scouts and ASW determined spray initiation at the other two sites. Once spray programmes were initiated at all four sites, insecticide and/or JMS applications continued weekly for the duration of the crop. In the second trial, one site

Table 2 Irrigation status, cultivar and yield of reduced and standard spray areas at all sites. Yields shown in **bold** were statistically different (P<0.05)

Trial	Site number	Irrigated/dry	Potato Use	Cultivar	Yield (t/ha)	
					Reduced insecticide sprays	Standard insecticide sprays
1	1	Dry	process/fresh	'Moonlight'	51.6*	52.4*
	2	Irrigated	process/fresh	'Moonlight'	68.2	63.1
	3	Dry	process	'Fianna'	**50.5**	**66.3**
	4	Dry	process	'Snowden'	57.4	61.9
2	1	+Partly irrigated	process	'Satin King'	73.9	60.0
	1a	+Partly irrigated	process	+Gold Crisp	48.6	50.5
	2	Dry	fresh	'Agria'	40.4	37.9
	3	Dry	process	'Moonlight'	74.5	80.2
	4	Irrigated	fresh	'Andean sunside'	33.5	37.2
3	1	Dry	process	'Agria'	74.7	64.4
	2	Dry	fresh	'Agria'	**97.9**	**92.8**
	3	Irrigated	process	++Gold Crisp	79.5**	91.5**
	4	Irrigated	fresh	'Nadine'	**61.1**	**57.4**

*indicates site with low harvest due to flooding; **indicates uncharacteristically high yields for this cultivar.
+indicates where irrigation did not cover the entire site; ++ indicates a commercially sensitive cultivar.

received a different insecticide spray regime, as previously described, with application of oil for four consecutive weeks before spraying began.

Each year, the PFR harvest was conducted just before commercial farm harvests. A sub-sample of potatoes was taken from the reduced and standard spray areas for assessments. Four 5-m strips at intervals along the 120-m datum row along one mound were marked out. These were fork-dug out and all potatoes collected into sacks for assessment. All potatoes were retained at 8–10ºC in a coolstore until assessment. All trial potatoes were assessed by PFR for ZC, where sub-samples were fried and assessed (200 marketable potatoes per treatment, per site) and scored using a 0–9 visual scale (Anderson et al. 2013) with the commercially acceptable standard set at 2 or less. Crop yields were compared with standard commercial potatoes (from the same fields). Specific gravity assessments (SG) were also conducted. SG is an expression of density and is a measurement of potato quality. There is a very high correlation between tuber SG and its dry matter (DM) or total solids content (Wilson & Lindsay 1969). For processing cultivars, potato tubers with DM content >20% are required to achieve a good fry colour and better quality of the processed product, so DM is the primary focus for these purposes. For fresh potatoes, this percentage is not applicable. ASW conducted their regular assessments across areas in each field for yield/weights and numbers, marketable/reject tubers, dry and wet weights of sub-samples of marketable tubers to calculate SG/DM content, and sub-samples were fried to assess ZC.

Trial 1: 2016/17

Each of the four sites had a reduced spray area that was one tractor boom-width wide (17-m) (18–20 mounds) and extended approximately 120-m in length into the field, starting from one edge of the crop and reaching into the standard spray regime of the main crop. This became known as "the strip". PFR scouting was conducted weekly at two sites from the emergence of potatoes until the spray action threshold was reached. This was also undertaken in conjunction with Fruitfed scouts to enable technical information sharing between Fruitfed and PFR. The efficacy of Fruitfed's system was compared with that of the PFR method by PFR staff using both scouting methods each week. Previously, the standard action threshold for initiating seasonal insecticide spray programmes for a field used by ASW was to detect TPP eggs to first instar nymphs. This triggered spraying the "perimeter" (a 15-m border around the edge of the crop) and then either the perimeter again or the entire crop after a review the following week.

Trial 2: 2017/18

This trial had four sites with the trial areas the same size as in Trial 1. Two changes from Trial 1 were made to Trial 2. Firstly, an additional trial area was added at one of the sites (1a) that was approximately 2 ha. This extra trial area was divided in half, one half of the field received standard weekly sprays and the other half received the reduced insecticide programme. The aim to achieve a less "shielded" area on a more "farm scale", as the previous year's trial strips may have received prophylactic protection by being located within standard spray areas. Secondly, PFR employed its weekly scouting technique for two sites from the emergence of potatoes until the insecticide-spray action threshold was reached and Fruitfed scouted all four sites independently for the duration of the crop.

Trial 3: 2018/19

The trial was run at four sites. However, the size of the reduced spray areas was increased to approximately 1 ha per site, with the reduced areas measuring five tractor-boom widths comprising 90–100 mounds. The increased trial area was based on encouraging results from the larger trial area in Trial 2 at Site 1a. PFR employed its weekly scouting technique for two sites from the emergence of potatoes until the insecticide spray action threshold was reached. Fruitfed scouted all four sites independently for the duration of the crop.

ASW applied all sprays onto both treatments with the reduced spray areas receiving either the same insecticide as the “standard” area or JMS only, or no spray at all if thresholds were not reached, for all three trials.

Statistical analyses

All analyses were done using Rx64 (Version 4.0.3; R Core Team 2020). Exploratory graphs were produced with the *ggplot2* package (Version 3.3.2; Wickham 2016). Estimated means and confidence intervals were generated and corrected using the *predictmeans* package (Version 1.0.4; Luo et al. 2020). The differences in DM between treatments were determined by analysis of variance (ANOVA), where site and spray method and their interaction term were fitted as fixed effects. The Benjamini & Hochberg method (Benjamini et al. 1995) was applied post hoc to identify significant differences between treatment means at the 5% significance level. Zebra Chip and yield data were fitted using generalised linear models (GLM) with binomial errors and the logit link function. The total number of potatoes was considered as a binomial variable with the number of marketable potatoes (success) and unmarketable potatoes (failure). Site, spray method and interaction terms between the two were fitted as fixed effects. Back transformed means and 95% confidence intervals were estimated to identify significant differences.

RESULTS

Tool 1 – Crop scouting

In Trial 1 (2016/17), the two scouting methods were compared at two sites to identify the number of insects detected with each approach (manuscript in preparation). The Fruitfed system detected higher numbers of TPP eggs than the PFR method, while the middle-leaf sampling process undertaken by PFR detected more TPP nymphs present at low levels than the Fruitfed system. Both systems picked up similar numbers of beneficial insects. It was concluded that each system provided reasonable assessment data. Both sampling systems were therefore continued for Trials 2 and 3. Weekly scouting also reduced the overall number of insecticide sprays applied throughout the trials by delaying initiation of spray programmes when pest pressure was below the action thresholds set.

Tool 2 – Sticky-trap monitoring and testing of TPP for CLso status

TPP from sticky traps over the three seasons were removed, and a sub-sample was tested for CLso. TPP was described as “hot” if CLso was detected and “cold” where it was not detected. If TPP were “cold”, they were not considered a risk for infecting potatoes with CLso, thus causing zebra chip symptoms. Increased resources in Trial 3 provided for higher levels of testing to give more confidence in the level of CLso detection. CLso was detected in 0.03–0.04% of TPP tested in all three trials, even with the lower numbers tested in Trials 1 and 2 (n=32) compared with Trial 3 (n=102).

Tool 3 – Degree-day accumulation

The degree-days threshold was set at 980 for the Matamata region, and, for Trial 1, was reached in the week starting 2 January 2017. For Trial 2, this occurred in the week starting 24 December 2018. For Trial 3, similarly reached on 23 December 2019. Spray initiation did not specifically align with the degree-day threshold on its own, which acted more as a ‘predicter’ to initiate sprays. However, there was a stronger case for spray initiation if the sticky-traps catches of TPP were approaching the trap threshold and also coincided with increased insect pressure detected by scouting in the trial areas and this was near the degree-days threshold.

Tool 4 – Mineral oil applications

The reduced insecticide programme inserting alternating a foliar application of JMS oil into the standard insecticide spray programme decreased insecticide use by 40–61% over the three trials.This decrease in insecticides used also added the benefit of a reduction in costs for the grower, reinforcing that the system was economical as well as a more environmentally sustainable approach.

The effect of the spraying regimes was assessed by the level of zebra chip, crop yield and DM content at harvest.

Harvest assessments: Zebra chip

Zebra Chip data were fitted using generalised linear models (GLM) with binomial errors and the logit link function. The total number of potatoes was considered as a binomial variable with the number of marketable potatoes as binomial success and unmarketable potatoes as binomial failure. Site, spray method and interaction terms between the two were fitted as fixed effects. Back transformed means (% acceptable) and 95% confidence intervals (CI) were estimated from GLM models to identify significant differences.

There were no statistically significant differences in the incidence of ZC between the reduced and standard spray treatments for all three trials (Figure 1). All potatoes were combined and sold commercially.

Harvest assessments: Crop Yield

There was no statistical difference in crop yield across different cultivars, irrigation and spray regime in any area in Trial 2 (Table 2 and Figure 2). In Trial 1, the reduced spray areas had lower yields at Site 3. In Trial 3, the reduced spray areas had lower yields at Site 4 but had significantly higher yields than the standard spray area at Site 2.

Harvest assessments: Dry Matter (DM) content

Estimated = fitted mean % dry matter from ANOVA model, 95% CI were also calculated to stay consistent with other plots presented.

The differences in DM between treatments were determined by analysis of variance (ANOVA), where site and spray

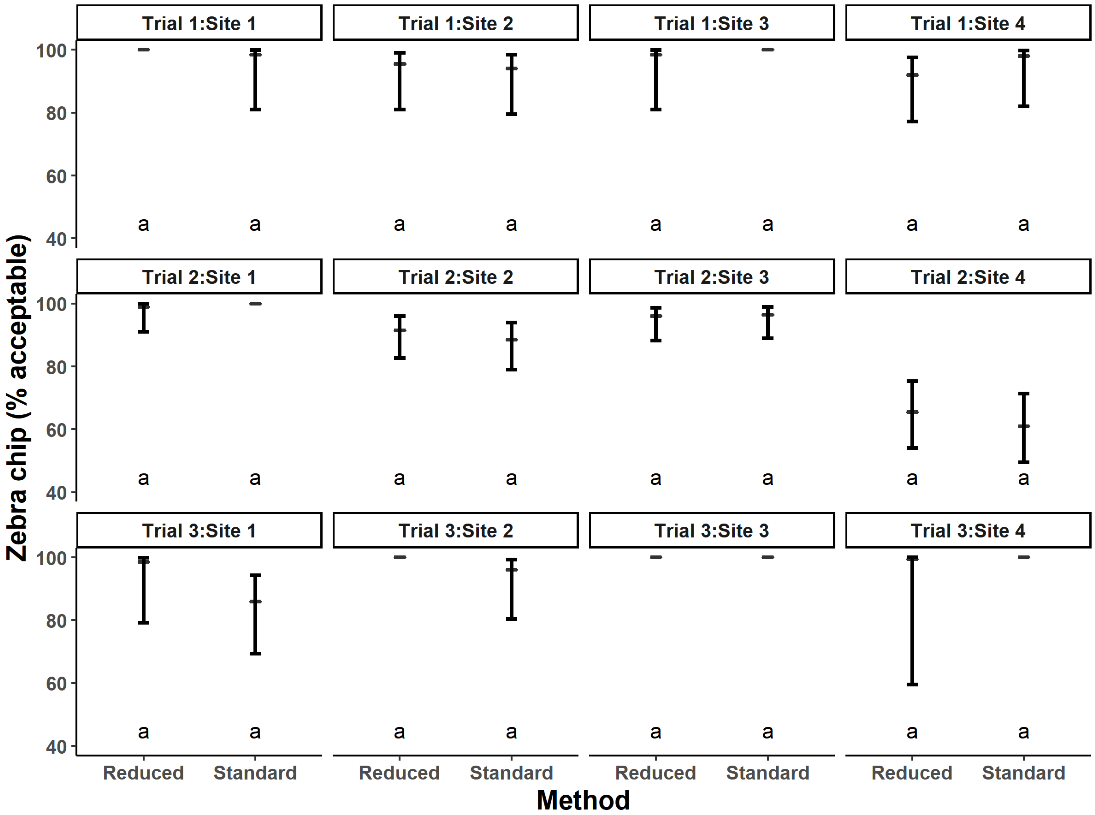

Figure 1 Zebra chip assessment: percentage of commercially acceptable potatoes from reduced and standard spray areas in Trials 1, 2 and 3. Means with the same letter are not significantly (P<0.05) different. Error bars on the plots are the estimated % mean with its 95% confidence interval.

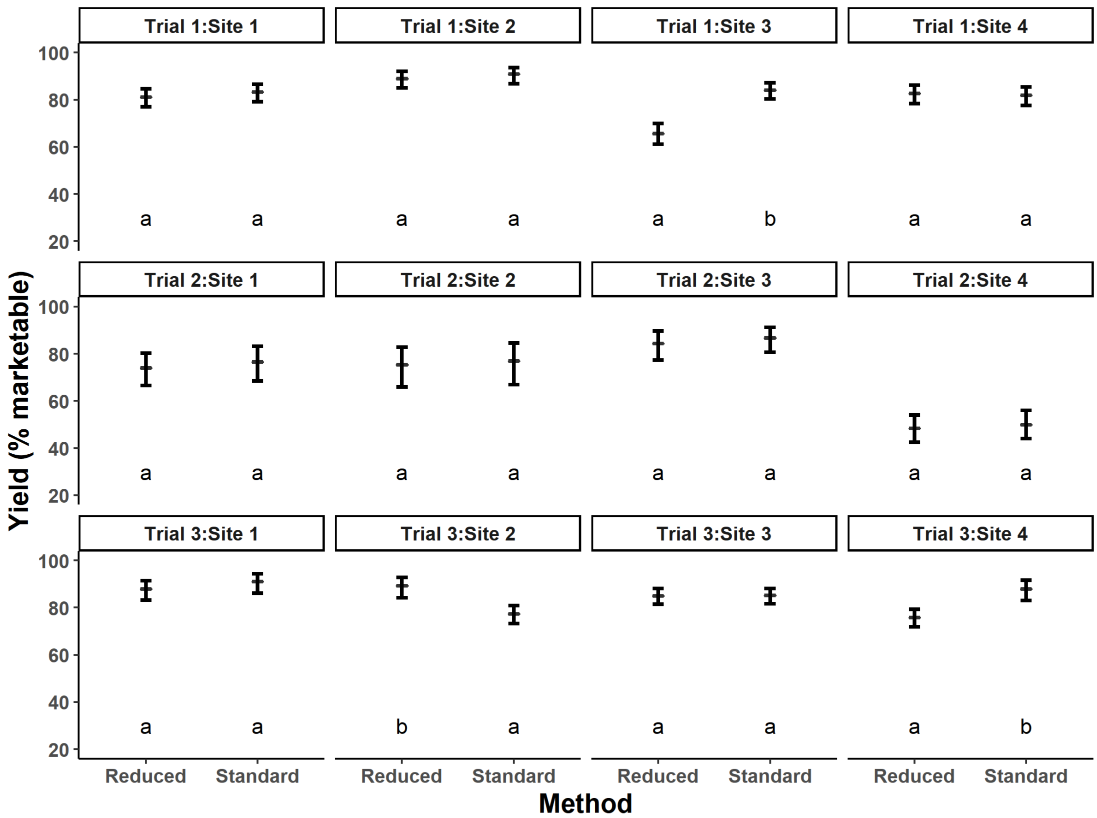

Figure 2 Yield in terms of percentage of marketable potatoes from reduced and standard spray areas in Trials 1, 2 and 3. Means with the same letter are not significantly (P<0.05) different. Error bars on the plots are the estimated % mean with its 95% confidence interval.

method and their interaction term were fitted as fixed effects. The Benjamini & Hochberg method (Benjamini et al. 1995) was applied post hoc to identify significant differences between treatment means at the 5% significance level.

There was no statistical difference in DM content for the standard and reduced spray treatments in Trials 1 and 2, but DM content was lower in the reduced spray area at Site 1 site in Trial 3 (Figure 3).

DISCUSSION

In Trial 1, initiation of insecticide application onto the entire reduced-insecticide block was delayed at one site by one week when scouting was combined with degree-day data and a sticky-trap action threshold. Comparing the two scouting methods provided useful information as the methods were quite distinct, yet had similar detection rates (manuscript in preparation). There were no significant differences in TPP numbers recorded between distances in this trial, so scouting samples at different distances were combined. However, Walker et al. 2013 reported that at the start of the season, TPP are more abundant on plants at field edges. Our findings, (no more TPP at the edges than further into the crop) may be due to a number of factors. Main-crop potatoes are grown later than early (table) potatoes, so the TPP may be more evenly distributed later in the growing season throughout the local area, crop size may be important, along with the make-up of crop margins that may be important reservoirs for natural enemies of TPP. The strategy of comparing combined crop-scouting data, along with considering degree-days and sticky-trap catches resulted in spray decisions that reduced the number of insecticides applications onto the potato crop. However, the most significant factor providing the greatest reduction in insecticide use was the alternation of weekly insecticides with JMS oil on its own.

In Trial 2 at Sites 1 and 1a, the initiation of insecticide spraying was delayed by four weeks using the combined monitoring approach. The strategy employed in this trial area provided a significant step toward achieving the greatest reduction in insecticides. These results improved our confidence sufficiently to justify an increase in the area receiving reduced insecticides for the following season in Trial 3, with all four sites producing over 300 tonnes of reduced-insecticide potatoes in this way. The harvest qualities of the reduced-treatment potatoes were similar to those of the standard-treatment potatoes so the grower was able to combine the two and supply them to the commercial market. This was a significant step forward towards reducing pesticide residues, a key priority for the grower ASW.

The use of five oil sprays without an insecticide included over the course of one season meant that reduced-treatment potatoes were produced at a lower cost than the standard industry regime used by the grower. JMS is a useful option for a spray programme if TPP resistance to current insecticides becomes an issue. Future research identifying any TPP resistance to current insecticides being used by growers in New Zealand will be a key part of extending IPM in potatoes.

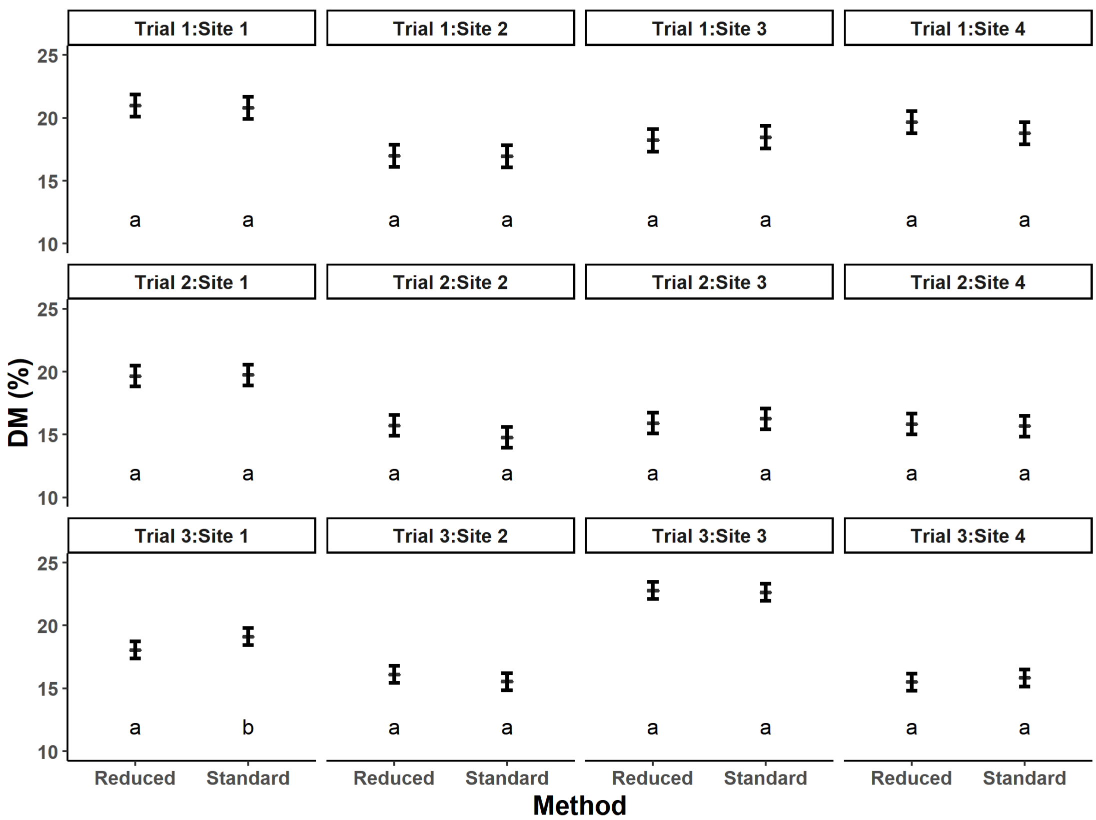

Figure 3 Dry matter (%) in potatoes from reduced and standard spray areas in Trials 1, 2 and 3. Means with the same letter are not significantly (P<0.05) different. Error bars on the plots are the estimated % mean with its 95% confidence interval.

ZC mitigation was reasonable with no statistically significant differences in ZC incidence between the reduced and standard spray treatments for all three trials, despite "hot" TPP being present throughout the trials. CLso was detected in 0.03-0.04% of TPP tested in all three trials. The TPP individuals that did test positive for CLso were detected as 'very hot' (Addison, pers comm). This was considered a low incidence of CLso when compared to findings from testing TPP for CLso in the Pukekohe region (Gardner-Gee and Puketapu 2014) reporting 2% incidence of CLso. In each of the trials where ZC incidence was higher at some sites, this situation occurred in both the reduced and standard spray areas suggesting it was due to an overall control failure rather than being related to a specific treatment/spray regime. Crop yields were lower at one site in the reduced-spray areas in Trials 1 and 3 but compared favourably in Trial 2. Trial 3 had one site where the reduced-treatment yields were higher than the standard-treatment yields. Future research with larger sample sizes would be useful to fully understand if there is a treatment effect on yields. Over 3 years and twelve sites, only one reduced treatment area at one site in Trial 3 gave statistically significantly lower DM content when compared to the standard-treatment area. Overall, these results suggest that replacing some insecticide sprays by inserting JMS into a spray programme does not have a negative effect on the processing quality of potatoes. PFR has previously conducted smaller-scale studies on ASW farms and has significantly benefitted from this valuable industry connection to facilitate larger scale "on-farm" trials in a more collaborative way, contributing to grower uptake and practical applications of the research. With the focus remaining on managing TPP, scouting assessments conducted on commercial potatoes from emergence through to first insecticide applications provided vital information to the grower at four sites over the three trials. Scouting also provided the platform for regular, collaborative interaction between PFR and ASW's crop managers and was instrumental in conducting the trials.

Insect data from the trials (data not shown) indicated that the reduced insecticide areas also had greater numbers of resident beneficial insects and fewer other insect pests than standard spray areas, as seen in other trials inserting JMS into potato spray programmes (Wright et al. 2017).

CONCLUSIONS

The number of insecticide sprays was reduced by at least half at each site by using JMS on its own as an alternative to using it in a mixture with insecticides. There are multiple economic and environmentally sustainable benefits using this reduced insecticide, more IPM-friendly system. With the primary objectives of ASW to effectively manage ZC, and produce commercially acceptable crops with fewer residues, this approach has demonstrated a way towards achieving that, and one that can be readily adopted. JMS is currently pending registration for use as a "soft option" protectant on potatoes but is permitted for use as an adjuvant/wetting agent and is used for this purpose by some New Zealand potato growers.

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Appendix 1 Spray regime: Trial 1 2016/17: White indicates standard spray areas, green indicates the reduced areas and grey indicates both standard and reduced areas.

10-Oct-16		planted site 1										
17-Oct-16												
24-Oct-16								planted site 3			planted site 4	
31-Oct-16												
7-Nov-16												
14-Nov-16					planted site 2							
21-Nov-16												
28-Nov-16		standard	reduced									
5-Dec-16	perimeter	JMS +Avid						standard	reduced			
12-Dec-16		JMS +Avid						JMS +Avid				
19-Dec-16		JMS + Movento	JMS		standard	reduced	perimeter	JMS +Avid				
26-Dec-16		JMS +Avid		perimeter	JMS +Avid			JMS +Avid			standard	reduced
2-Jan-17		JMS + Benevia	JMS		JMS +Avid			JMS +Avid		perimeter	JMS +Avid	
9-Jan-17		JMS + Mavrick			JMS + Movento			JMS + Mavrick			JMS + Mavrick	
16-Jan-17		JMS + Avid	JMS		JMS + Avid + Oberon	JMS		JMS + Avid + Oberon	JMS		JMS + Avid + Oberon	JMS
23-Jan-17	whole block	JMS+ Mavrick			JMS + Mavrik		whole block	JMS + Mavrick			Jms +Avid + Oberon	
30-Jan-17		JMS + Avid +Oberon	JMS		JMS + Avid +Oberon	JMS		JMS + Avid +Oberon	JMS		JMS + Mavrik	JMS
6-Feb-17		JMS + Sparta		whole block	JMS + Sparta			JMS + Sparta		whole block	JMS + Sparta	
13-Feb-17		JMS + Sparta	JMS		JMS + Sparta	JMS		sprayed off			JMS + Sparta	JMS
20-Feb-17		JMS +Tripsol			JMS +Tripsol						JMS +Tripsol	
27-Feb-17					JMS + Karate+ Pyrinex	JMS					JMS + Karate+ Pyrinex	JMS
6-Mar-17		sprayed off			JMS + Karate + Pyrinex						JMS + Karate + Pyrinex	
13-Mar-17					sprayed off						JMS + Karate + Pyrinex	JMS
20-Mar-17											sprayed off	
27-Mar-17												
3-Apr-17												
10-Apr-17												
17-Apr-17					harvested			harvested			harvested	
24-Apr-17		harvested										
no. of insecticides		10	5		9	5		5	3		10	5
weeks in ground		28	28		22	22		25	25		25	25

Appendix 2 Spray regime: Trial 2 2017/18: White indicates standard spray areas, green indicates the reduced areas and grey indicates both standard and reduced areas.

2-Oct-17							planted site 2							
9-Oct-17														
16-Oct-17										planted site 3				
23-Oct-17														
30-Oct-17		planted site 1 and site 1a											planted site 4	
6-Nov-17														
13-Nov-17														
20-Nov-17							standard	reduced		standard	reduced			
27-Nov-17		1		1a		perimeter	Movento/JMS		perimeter	Movento/JMS				
4-Dec-17		standard	reduced	standard	reduced		Movento/JMS		perimeter	Avid/JMS			standard	reduced
11-Dec-17	perimeter	Movento/JMS				whole block	Movento/JMS	JMS	whole block	Movento/JMS		perimeter	Movento/JMS	
18-Dec-17	whole block	Movento/JMS	JMS	Movento/JMS	JMS		Avid/JMS			Avid/JMS	JMS	whole block	Movento/JMS	
25-Dec-17		Movento/JMS	JMS	Movento/JMS	JMS		Movento/JMS	JMS		Movento/JMS			Avid/JMS	JMS
1-Jan-18		Avid/JMS	JMS	Avid/JMS	JMS		Mavrik/Avid/JMS			Mavrik/Avid/JMS	JMS		Movento/JMS	
8-Jan-18		Movento/JMS	JMS	Movento/JMS	JMS		Benevia/JMS	JMS		Benevia/JMS			Avid/JMS	JMS
15-Jan-18		Avid/JMS					Avid/Oberon/JMS			Avid/Oberon/JMS	JMS		Mavrik/JMS	
22-Jan-18		Mavrik/JMS	JMS	Mavrik/JMS	JMS		Karate/JMS	JMS		Benevia/JMS			Karate/JMS	JMS
29-Jan-18		Benevia/JMS					Avid/Oberon/JMS			Avid/Oberon/JMS	JMS		Avid/Oberon/JMS	
5-Feb-18		Avid/Oberon/JMS	JMS	Avid/Oberon/JMS	JMS		Sparta/JMS	JMS		Sparta/JMS			Sparta/JMS	JMS
12-Feb-18		Sparta/JMS					Sparta/JMS			Sparta/JMS	JMS		Sparta/JMS	
19-Feb-18		Sparta/JMS	JMS	Sparta/JMS	JMS		Tripsol/JMS	JMS		Tripsol/JMS				
26-Feb-18		Tripsol/JMS					sprayed off			Tripsol/JMS	JMS		sprayed off	
5-Mar-18		Tripsol/JMS	JMS	Tripsol/JMS	JMS		harvested			Pyrinex/JMS				
12-Mar-18		Pyrinex/JMS								Karate/JMS	JMS		harvested	
19-Mar-18		sprayed off								sprayed off				
26-Mar-18		harvested												
2-Apr-18										harvested				
9-Apr-18														
no.of insecticides		13	5	13	5		11	5		14	7		9	5
weeks in ground		21	21	21	21		22	22		24	24		19	19

Appendix 3 Spray regime: Trial 3 2018/19: White indicates standard spray areas, green indicates the reduced areas and grey indicates both standard and reduced areas.

Date	Site 1 area	Site 1 standard	Site 1 reduced	Site 2 area	Site 2 standard	Site 2 reduced	Site 3 area	Site 3 standard	Site 3 reduced	Site 4 area	Site 4 standard	Site 4 reduced
24-Sep-18											planted site 4	
1-Oct-18					planted site 2							
8-Oct-18		planted site 1						planted site 3				
15-Oct-18												
22-Oct-18												
29-Oct-18												
5-Nov-18												
12-Nov-18												
19-Nov-18												
26-Nov-18												
3-Dec-18		standard	reduced		standard	reduced					standard	reduced
10-Dec-18	perimeter	Movento/JMS		Perimeter	Movento/JMS			standard	reduced	perimeter	Movento/JMS	
17-Dec-18		Movento/JMS			Movento/JMS		perimeter	Movento/JMS			Movento/JMS	
24-Dec-18		Avid/JMS	JMS		Avid/JMS	JMS		Avid/JMS			Avid/JMS	JMS
31-Dec-18		Movento/JMS			Movento/JMS			Movento/JMS		whole block	Movento/JMS	
7-Jan-19		Benevia/JMS	JMS	whole block	Benevia/JMS	JMS		Benevia/JMS	JMS		Benevia/JMS	JMS
14-Jan-19		Avid/Oberon/JMS			Avid/Oberon/JMS			Avid/Oberon/JMS			Avid/Oberon/JMS	
21-Jan-19	whole block	Avid/Oberon/JMS	JMS		Avid/Oberon/JMS	JMS		Avid/Oberon/JMS	JMS		sprayed off	
28-Jan-19		Benevia/JMS			sprayed off			Benevia/JMS				
4-Feb-19		Uphold/JMS	JMS				whole block	Uphold/JMS	JMS			
11-Feb-19		Uphold/JMS						Uphold/JMS			harvested	
18-Feb-19		Tripsol/JMS	JMS					Tripsol/JMS	JMS			
25-Feb-19		sprayed off			harvested			Tripsol/JMS				
4-Mar-19								Karate/JMS	JMS			
11-Mar-19								Pyrinex/JMS				
18-Mar-19		harvested						sprayed off				
25-Mar-19												
1-Apr-19												
8-Apr-19								harvested				
no.insecticides		10	5		6	3		11	6		5	3
weeks in ground		23	23		21	21		26	26		20	20

Appendix 4 Product, active ingredient, spray rate, supplier/registration of insecticides and JMS.

Commercial product name	Active ingredient	Rate of application	Registration/Supplier
Organic JMS Stylet Oil®	Mineral oil	1 L/ha	JMS FlowerFarms Inc, USA/UPL NZ Ltd.
Movento®	Spirotetramat	560 mL/ha	The Bayer Group/Bayer Crop Science.
Avid®	Abamectin	600 mL/ha	Syngenta Group Company/Syngenta Crop Protection Ltd.
Benevia®	Cyantraniliprole	500 mL/ha	FMC Agricultural Solutions (or affiliates)/FMC NZ Ltd.
Mavrick®	Tau-fluvalinate	750 mL/ha	Adama Group Company/Adama NZ Ltd.
Oberon®	Spiromesifen	600 mL/ha	The Bayer Group/Bayer Crop Science.
Sparta®	Spinetoram	375-500 mL/ha	Dow AgroSciencesLtd/Corteva Agriscience.
Tripsol®	Acrinathrin and Abamectin	850 mL/ha	FMC Agricultural Solutions (or affiliates)/FMC NZ Ltd.
Pyrinex®	Chlorpyrifos	1 L/ha	Adama Group Company/Adama NZ Ltd.
Uphold®	Spinetoram	375-500 mL/ha	Dow AgroSciences Ltd/Corteva Agriscience.
Karate® Zeon	Lambda-cyhalothrin	100 mL/ha	Syngenta Group Company/Syngenta Crop Protection Ltd.