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DISCLAIMER

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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GROWER SUMMARY

Headline

Treatment of seed with thiamethoxam was the most effective way of controlling willow-carrot aphid and foliar sprays of six coded treatments were also effective. All treatments increased yield significantly compared with the untreated control. For control of second generation carrot fly, treatment programmes based on a novel product were the most effective and there was no difference in the levels of control whether additional sprays of lambda-cyhalothrin were applied subsequently or not.

Background

Carrot and related crops are infested by three 'main' pests; willow-carrot aphid, carrot fly and cutworm. The risk of infestation by all three pests varies with season and geographical location. Cutworms in particular are sporadic pests. Willow-carrot aphid usually infests carrot crops during May-June following the migration of overwintered aphids from their winter host, willow. Willow-carrot aphid provides a threat to crops through its presence, direct damage and the transmission of several viruses, which have been implicated in crop damage. Again some insecticides are approved already for application of foliar sprays to control willow-carrot aphid and others have been identified in the SCEPTRE project, of which some are progressing towards approval. Growers are also able to import seed treated with thiamethoxam (Cruiser) to control aphids and this treatment may have activity against first generation carrot fly. Apart from direct efficacy of the treatments on aphid mortality there is an additional question about the control of virus transmission.

Until quite recently, control of carrot fly (*Psila rosae*), has relied on using pyrethroid insecticides, applied either as seed treatments or foliar sprays (lambda-cyhalothrin, deltamethrin, tefluthrin seed treatments). Although is no evidence that populations of carrot fly have become resistant to pyrethroids, the addition of a new active (Coragen®) has offered the industry another tool to control this pest and could reduce the risk of resistance developing through reliance on just one group of insecticides. Project FV 414 showed that a single spray of Coragen® can persist for at least 6 weeks but is insufficient, on its own, to provide more than about a 25% reduction in damage. However, two sprays of Coragen® timed 1 week before carrot fly emergence and 3 weeks after, or at 0 and 2 weeks after emergence, offered similar levels of damage reduction to a full pyrethroid programme. Timing of Coragen® applications may not be as critical as Hallmark applications but the current view is that they should be applied at the start of a programme to get maximum benefit from these treatments.

It seems that despite the addition of a new active ingredient to their armoury, some growers have been finding it more difficult to control carrot fly in recent years. This may be in part due to the unusual pattern of second generation emergence in 2013 and 2014 which occurred over a very long period and may have been the result of high temperatures. In addition, although work undertaken 15 years ago indicated that there was no need to control third generation carrot fly beyond the end of September (Julia Vincent, PhD project), as eggs laid after that did not lead to sufficiently large larvae to cause damage, this situation may be changing as a result of generally warmer weather in recent years. Changing conditions such as these may require some revision of the control strategy. Finally, the SCEPTRE project has identified a number of new active ingredients for control of vegetable pests. However, carrot fly was not considered as part of this project and so there is an opportunity to explore some of these insecticides for their performance against carrot fly.

The aim of this project is to evaluate a range of strategies for deploying approved products for aphid and carrot fly control to optimise timing and thereby efficacy and to determine how novel actives might be incorporated into programmes in future. Aphids of several species, including willow-carrot aphid, were particularly abundant in 2015 and led to virus problems in a number of crops, particularly carrot and lettuce crops.

Summary

Objective 1 Evaluate insecticide treatment programmes applied to control willow-carrot aphid, their impact on virus transmission and their role in control of first generation carrot fly.

Plots of carrot cv Nairobi were sown on 8 April 2015. The trial consisted of 8 treatments x 4 replicates. Most of the plots were sown with insecticide-free seed but one treatment was sown with seed treated with thiamethoxam (Cruiser) at the commercial rate. The remaining insecticide treatments were applied as foliar sprays. Willow-carrot aphids started to migrate from mid-May and once aphids were relatively abundant in the crop the plots were sprayed on two occasions: 21 May and 4 June. The trial was sampled to record the numbers of aphids on three occasions: 1 June (1), 9 June (2), 25 June (3). The numbers of alate (winged) and wingless (adults and nymphs) aphids were counted on the foliage.

There was no evidence of phytotoxic effects due to any of the treatments in any of the trials. On 1 June (11 days after the first spray) all of the insecticide treatments provided a good level of control compared with the insecticide-free plots. All treatments reduced numbers of

wingless aphids (adults and nymphs) compared with the untreated control. When comparing the treatments the thiamethoxam seed treatment reduced numbers compared with all other treatments, HDCI 078 reduced numbers compared with HDCI 079 – 082 and HDCI 079 reduced numbers compared with HDCI 080 and HDCI 082. Numbers of winged aphids were reduced by the thiamethoxam seed treatment compared with all other treatments.

On 9 June (5 days after the second spray) adult wingless aphids and nymphs were assessed separately. All treatments reduced numbers of both life stages compared with the untreated control. When comparing the treatments the thiamethoxam seed treatment, HDCI 078, HDCI 079, HDCI 081 and HDCI 083 all reduced both life stages compared with HDCI 080 and HDCI 082 and the thiamethoxam seed treatment, HDCI 078 and HDCI 083 also reduced numbers of nymphs compared with HDCI 079. The total numbers of wingless aphids followed the same pattern as the nymphs. No treatment reduced numbers of winged aphids compared with the untreated control.

On 25 June (21 days after the second spray) wingless adults and nymphs were assessed separately and all insecticide treatments continued to provide a good level of control of both life stages. All treatments reduced numbers of both life stages compared with the untreated control. When comparing the treatments the thiamethoxam seed treatment and HDCI 078 all reduced the numbers of both life stages compared with HDCI 080 – 083, the thiamethoxam seed treatment and HDCI 078 also reduced the numbers of nymphs compared with HDCI 079. The total numbers of wingless aphids followed the same pattern as the nymphs. There were very few winged aphids and the analysis was not significant. Figure A shows mean numbers of wingless (adults and nymphs) willow-carrot aphid (50 plants) on 3 occasions.

Plant counts were made on two occasions and a sample of roots (2 m row) was harvested, washed, assessed for carrot fly damage and weighed on 28 July 2015. There was little or no seedling/plant mortality due to either carrot fly larvae or aphids. Damage due to carrot fly larvae when the roots were harvested was relatively low. However, the thiamethoxam seed treatment and HDCI 072 (two sprays) both reduced the percentage by number of roots with no and <5% damage. The total yield from all the plots treated with insecticide was greater than from the untreated control and the yield from the plots treated with the thiamethoxam seed treatment was significantly greater than the yield from any of the plots treated with foliar sprays of insecticide.

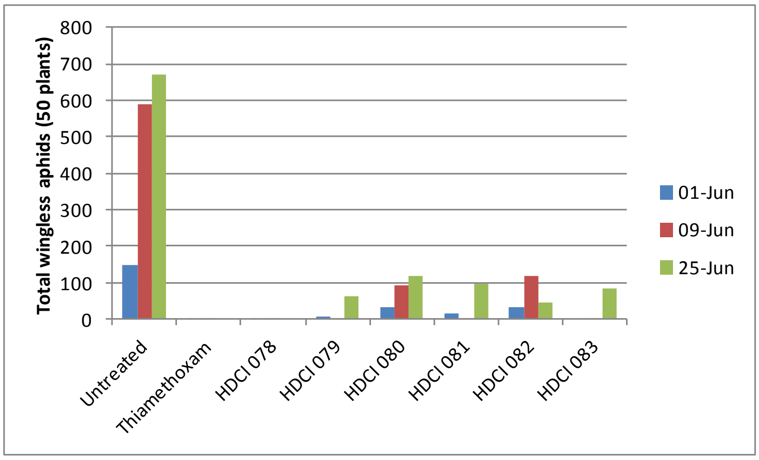

Figure A. Mean numbers of wingless willow-carrot aphid (50 plants) on 3 occasions.

Foliage samples were taken on 15 July from the four replicate plots of four of the treatments: the untreated control, two effective treatments – the thiamethoxam seed treatment, HDCI078 (coded foliar spray) and one less effective treatment (HDCI80 – coded foliar spray) and assessed for the presence of 3 viruses by Adrian Fox and his group at Fera to evaluate the approach i.e. can we evaluate the efficacy of treatments for virus control? For *Carrot red leaf virus* CtRLV, which is transmitted persistently, only the thiamethoxam seed treatment showed evidence of a reduction in virus. For *Carrot yellow leaf virus* (CYLV) which is transmitted in a semi-persistent manner there was evidence that the thiamethoxam seed treatment was more effective than the two other insecticide treatments, but levels were also consistently lower in the untreated control than in the sprayed plots. For *Carrot torrado virus-1 CaTV RNA1* levels were lowest in foliage from plots treated with the thiamethoxam seed treatment, but levels of virus were also lower than the untreated control in foliage from plots treated with the other two insecticides. Finally, samples of carrot roots (200/plot) were taken from untreated plots on 7 December and assessed for evidence of necrosis due to virus. Tip necrosis and internal browning have both been associated with virus in carrots. Up to 8% of roots showed tip necrosis and 6% internal browning.

Objective 2 Evaluate insecticide treatment programmes to control second, and potentially third, generation carrot fly.

Plots of carrot cv Nairobi were sown on 26 May 2015 to avoid infestation by the first generation of carrot fly. The trial consisted of 8 treatments x 4 replicates and all of the plots were sown with insecticide-free seed. The plots were subjected to treatment programmes shown in Table A. The timing of the first treatment was based on the forecast date of 10% emergence of carrot fly at Wellesbourne in 2015 (17 July).

Table A. Treatment programmes in Experiment 2. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); HDCI 087 (experimental treatment).

Weeks from predicted start of second generation		0	2	4	6	8	10
Date sprays applied		20 Jul	3 Aug	17 Aug	1 Sep	15 Sep	29 Sep
1	Untreated control						
2		H150	H100	H100	H100		
3		R	R				
4		R	R	H150	H100	H100	H100
5		R	R		H150	H100	H100
6		HDCI 087					
7		HDCI 087			H150	H100	H100
8		HDCI 087				H150	H100

The treatment programmes based on the experimental treatment (HDCI 087) were the most effective and indeed there was no difference in the levels of control whether additional sprays of Hallmark were applied subsequently or not (Figure B).

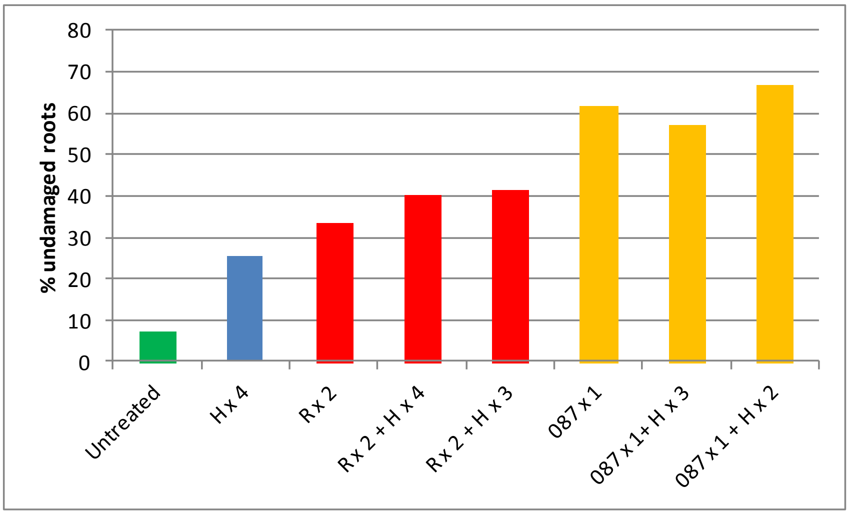

Figure B. The mean percentage of undamaged roots from each treatment. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); 087 = HDCI 087 (experimental treatment).

Finally, an un-replicated small-scale field trial was undertaken at Wellesbourne to assess the impact of third generation carrot flies on subsequent root damage. A small plot of carrots (cv Nairobi) was sown 26 May and part of this (3m x 4 rows) was covered with insect proof netting immediately after sowing to avoid damage by the second generation of carrot fly. An adjacent area in the same plot was left uncovered. The net was removed 21 September when second generation carrot flies were no longer present. The carrots were strawed down to protect them from frost and were harvested on 20 January 2016. The roots were washed and assessed for carrot fly damage. The roots from the plot covered with fine mesh netting until 21 September suffered a considerable amount of damage although they were not damaged as heavily as roots from the adjacent area which had been uncovered all the time. This suggests that the importance of the third generation of carrot fly, in terms of its impact on damage suffered by overwintered crops of carrot, should be re-investigated in more detail.

Financial Benefits

The carrot crop is Britain's major root vegetable, producing over 700,000 tonnes of carrots each year from 9,000 hectares and the sales value of British carrots is around £290 million (British Carrot Growers Association). The data from untreated plots in these trials indicates the considerable potential for loss in quality and yield, and thus sales value, as a result of infestation by aphids and the associated transmission of virus as well as by carrot fly. Whilst the impact of carrot fly is well known, the effect of poor aphid control on yield loss has been less well-documented – but in this study the yield from plots treated with the most effective treatment (thiamethoxam seed treatment) was twice that from the untreated control plots.

Action Points

- Growers should use seed treated with thiamethoxam to maximise control of virus transmission by willow-carrot aphid and associated reductions in yield.
- Growers should aim to use the most effective foliar spray treatments to provide additional control of willow-carrot and these treatments should be timed using careful crop monitoring.
- Growers should control second generation carrot fly using the treatments and approach recommended currently but be aware that the strategy may change once new products with different modes of action become available.

SCIENCE SECTION

Introduction

Carrot and related crops are infested by three ‘main’ pests; willow-carrot aphid, carrot fly and cutworm. The risk of infestation by all three pests varies with season and geographical location. Cutworms in particular are sporadic pests. Willow-carrot aphid (*Cavariella aegopodii*) usually infests carrot crops during May-June following the migration of overwintered aphids from their winter host, willow. Willow-carrot aphid provides a threat to crops through its presence, direct damage and the transmission of several viruses, which have been implicated in crop damage. In addition to the aphid monitoring data providing by the Rothamsted Insect Survey there are three ways in which growers can determine whether their crops are at risk: 1) day-degree forecast available through the AHDB Horticulture Pest Bulletin or they can run it themselves; 2) regular crop walking and 3) commercial monitoring services using water traps. Some insecticides are approved already for application of foliar sprays to control willow-carrot aphid and others have been identified in SCEPTRE, of which some are progressing towards approval. Growers are also able to import seed treated with thiamethoxam (Cruiser) to control aphids and this treatment may have activity against first generation carrot fly. Apart from direct efficacy of the aphicide treatments on aphid mortality there is an additional question about the control of virus transmission.

Until quite recently, control of carrot fly (*Psila rosae*), has relied on use of pyrethroid insecticides, applied either as seed treatments or foliar sprays (lambda-cyhalothrin, deltamethrin, tefluthrin seed treatments). Although there is no evidence that populations of carrot fly have become resistant to pyrethroids, the addition of a new active (Coragen®) has offered the industry another tool to control this pest and could reduce the risk of resistance developing through reliance on just one group of insecticides. Project FV 414 showed that a single spray of Coragen® can persist for at least 6 weeks but is insufficient, on its own, to provide more than about a 25% reduction in damage. However, two sprays of Coragen® timed 1 week before carrot fly emergence and 3 weeks after, or at 0 and 2 weeks after emergence, offered similar levels of damage reduction to a full pyrethroid programme. Timing of Coragen® applications may not be as critical as Hallmark applications but the current view is that they should be applied at the start of a programme to gain maximum benefit from these treatments.

It seems that despite the addition of a new active ingredient to their armoury, some growers have been finding it more difficult to control carrot fly in recent years (Howard Hinds, personal communication). This may be in part due to the unusual pattern of second generation emergence in 2013 and 2014 which occurred over a very long period and may have been the result of high temperatures. In addition, although work undertaken 15 years ago indicated that there was no need to control third generation carrot fly beyond the end of September (Julia Vincent, PhD project), as eggs laid after that did not lead to sufficiently large larvae to cause damage, this situation may be changing as a result of generally warmer weather in recent years. Changing conditions such as these may require some revision of the control strategy. Finally, the SCEPTRE project has identified a number of new active ingredients for control of vegetable pests. However, carrot fly was not considered as part of this project and so there is an opportunity to explore some of these insecticides for their performance against carrot fly.

The aim of this project is to evaluate a range of strategies for deploying approved products for aphid and carrot fly control to optimise timing and thereby efficacy and to determine how novel actives might be incorporated into programmes in future. Aphids of several species, including willow-carrot aphid, were particularly abundant in 2015 and led to virus problems in a number of crops, particularly carrot and lettuce crops.

Materials and methods

Pest monitoring

The numbers of carrot fly captured were recorded in a nearby carrot fly monitoring plot in Long Meadow Centre at Warwick Crop Centre using orange sticky traps (Rebell®). The traps were replaced twice a week. Winged willow-carrot aphids were captured in the Rothamsted suction trap located at Wellesbourne.

Objective 1 Evaluate insecticide treatment programmes applied to control willow-carrot aphid, their impact on virus transmission and their role in control of first generation carrot fly.

Experiment 1

Plots of carrot cv Nairobi were sown in the field known as Long Meadow West on 8 April 2015. The trial consisted of 8 treatments x 4 replicates with each plot being 3.5 m x 1 bed (1.83 m wide) in size. The seed was sown at a spacing of 100 seeds/m within rows and 0.35 m between rows. The plots were separated by 1 m along beds. The total area of the trial was 8 beds by 17 m. Most of the plots were sown with insecticide-free seed but one treatment (4 plots) was sown with seed treated with thiamethoxam (Cruiser) at the commercial rate (supplied by Syngenta).

The treatments are shown in Table 1. The majority of treatments are coded. All foliar spray treatments were applied in 300 l/ha water using a knapsack sprayer fitted with 3 x 02F110 nozzles.

Table 1. Treatments applied in Experiment 1. All foliar spray treatments were applied in 300l water/ha.

AHDB code	Product	Rate
Untreated		
Thiamethoxam seed treatment	Cruiser	8.6 g/100,000 seeds
HDCI 078		As recommended by manufacturer
HDCI 079		As recommended by manufacturer
HDCI 080		As recommended by manufacturer
HDCI 081		As recommended by manufacturer
HDCI 082		As recommended by manufacturer
HDCI 083		As recommended by manufacturer

Willow-carrot aphids started to migrate from mid-May and once aphids were relatively abundant in the crop the plots were sprayed on two occasions: 21 May and 4 June. The aim of the trial was to look at efficacy of treatments so insecticides were not used very early in crop life in an attempt to prevent transmission. The trial was sampled to record the numbers of aphids on three occasions: 1 June (1), 9 June (2), 25 June (3). The numbers of alate (winged) and wingless (adults and nymphs) aphids were counted on the foliage in 1m row, 50 plants and 40 plants per plot respectively on the three dates. For analysis, data were standardised to 50 plants per plot.

Plant counts were made on two occasions and a sample of roots (2 m row) was harvested, washed, assessed for carrot fly damage and weighed on 28 July 2015. Foliage samples were taken on 15 July from the four replicate plots of four of the treatments, the untreated control, two effective treatments (thiamethoxam seed treatment, HDCI078 (coded foliar spray)) and one less effective treatment (HDCI80 – coded foliar spray) and assessed for the presence of 3 viruses by Adrian Fox and his group at Fera to evaluate the approach i.e. can we evaluate the efficacy of treatments for virus control? Further to this, samples of carrot roots (200/plot) were taken from untreated plots on 7 December and assessed for evidence of necrosis due to virus. Tip necrosis and internal browning have both been associated with virus in carrots (FV 382a and FV 382b). The timing of the various activities is shown in Table 2.

Table 2. Timing of treatments and assessments in Experiment 1.

08-Apr	Trial drilled
13-May	Plant count
21-May	First sprays applied
01-Jun	Sample collected for aphid count
04-Jun	Second sprays applied
09-Jun	Sample collected for aphid count
25-Jun	Sample collected for aphid count
15-Jul	Foliage samples taken
28-Jul	Plant count
28-Jul	Trial harvested, root damage assessed
7-Dec	Untreated plots assessed for damage due to virus

The data were summarised in EXCEL and the majority of the data sets were subjected to Analysis of Variance by Andrew Mead and his team at Rothamsted Research using the Genstat programme.

Objective 2 Evaluate insecticide treatment programmes to control second, and potentially third, generation carrot fly.

Experiment 2

Plots of carrot cv Nairobi were sown in the field known as Long Meadow West on 26 May 2015 to avoid infestation by the first generation of carrot fly. The trial consisted of 8 treatments x 4 replicates with each plot being 3.5 m x 1 bed (1.83 m wide) in size. The seed was sown at a spacing of 100 seeds/m within rows and 0.35 m between rows. The plots were separated by 1 m along beds. The total area of the trial was 8 beds by 17 m. All of the plots were sown with insecticide-free seed.

The plots were subjected to treatment programmes shown in Table 3. All foliar spray treatments were applied in 300 l/ha water using a knapsack sprayer fitted with 3 x 02F110 nozzles. The timing of the first treatment was based on the forecast date of 10% emergence of carrot fly at Wellesbourne in 2015 (17 July). The timing of key events is summarised in Table 4.

A sample of roots (1.5 m row) was harvested, washed, assessed for carrot fly damage and weighed on 24 November 2015.

Table 3. Treatment programmes in Experiment 2. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); HDCI 087 (experimental treatment).

Weeks from predicted start of second generation		0	2	4	6	8	10
Date sprays applied		20 Jul	3 Aug	17 Aug	1 Sep	15 Sep	29 Sep
1	Untreated control						
2		H150	H100	H100	H100		
3		R	R				
4		R	R	H150	H100	H100	H100
5		R	R		H150	H100	H100
6		HDCI 087					
7		HDCI 087			H150	H100	H100
8		HDCI 087				H150	H100

Table 4. Timing of key events in Experiment 2.

Date	Event
26-May	Trial drilled
17-Jul	Predicted 10% emergence
20-Jul	First sprays applied
03-Aug	Second sprays applied
17-Aug	Third sprays applied
01-Sep	Fourth sprays applied
15-Sep	Fifth sprays applied
29-Sep	Sixth sprays applied
24-Nov	Trial harvested, root damage assessed

Experiment 3

Although work undertaken 15 years ago indicated that there was no need to control third generation carrot fly beyond the end of September (Julia Vincent, PhD project), as eggs laid after that did not lead to sufficiently large larvae to cause damage, this situation may be changing as a result of generally warmer weather in recent years. Changing conditions such as these may require some revision of the control strategy. An un-replicated small-scale field trial was undertaken at Wellesbourne to assess the impact of third generation carrot flies on subsequent root damage. A small plot of carrots (cv Nairobi) was sown 26 May and part of this (3m x 4 rows) was covered with insect proof netting immediately after sowing to avoid damage by the second generation of carrot fly. An adjacent area in the same plot was left uncovered. The net was removed 21 September when second generation carrot flies were no longer present. The carrots were strawed down to protect them from frost and were harvested (200 roots/plot) on 20 January 2016. The roots were washed and assessed for carrot fly damage.

Results

Pest monitoring

Figure 1 shows the numbers of adult carrot flies captured on sticky traps in Long Meadow Centre. There were clear periods of activity by the first and second generations. Third generation activity was less distinct. Figure 2 shows the numbers of winged willow-carrot aphid captured in the suction trap at Wellesbourne. Numbers were high from late May until early July.

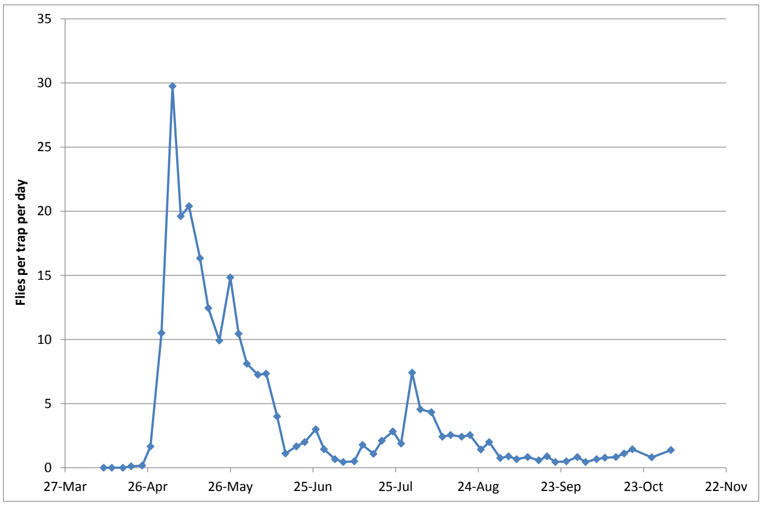

Figure 1. Numbers of adult carrot flies (*Psila rosae*) captured on sticky traps in Long Meadow Centre during 2015.

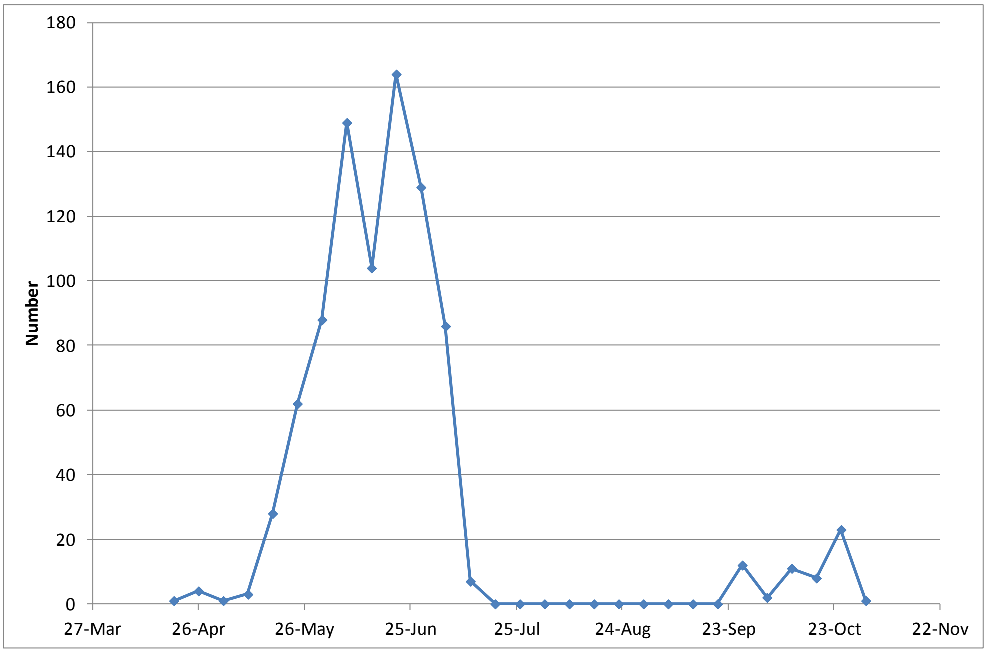

Figure 2. Rothamsted suction trap captures as numbers per week for 2015 - willow-carrot aphid (*Cavariella aegopodii*).

Objective 1 Evaluate insecticide treatment programmes applied to control willow-carrot aphid, their impact on virus transmission and their role in control of first generation carrot fly.

Experiment 1

Phytotoxicity

There was no evidence of phytotoxic effects due to any of the treatments in any of the trials; therefore no detailed data are presented.

Aphid counts

The data were natural log transformed before analysis. The numbers of winged and the total number of wingless aphids are presented in Figures 3 and 4 respectively. Figure 5 presents the difference between wingless adults and nymphs. The numbers of wingless aphids in particular continued to increase on the insecticide-free plots throughout the trial.

On 1 June (11 days after the first spray) all of the insecticide treatments provided a good level of control compared with the insecticide-free plots (Table 5). All treatments reduced numbers of wingless aphids (adults and nymphs) compared with the untreated control ($p<0.05$). When comparing the treatments the thiamethoxam seed treatment reduced numbers compared with all other treatments, HDCI 078 reduced numbers compared with HDCI 079 – 082 and HDCI 079 reduced numbers compared with HDCI 080 and HDCI 082 (p<0.05). Winged aphids were reduced by the thiamethoxam seed treatment compared with all other treatments (p<0.05).

Table 5. Experiment 1: the numbers of winged and wingless aphids on 1 June. Values followed by * are significantly different from the untreated control (p<0.05).

Treatment	**Total wingless**		**Winged**	
	Ln-trans	Back-trans	Ln-trans	Back-trans
Untreated	5.01	149.9	2.897	17.63
Thiamethoxam	-0.39*	0.18	0.806*	1.74
HDCI 078	1.02*	2.28	3.328	27.37
HDCI 079	2.24*	8.85	3.421	30.09
HDCI 080	3.53*	33.45	3.133	22.43
HDCI 081	2.73*	14.76	3.690	39.54
HDCI 082	3.46*	31.27	3.222	24.57
HDCI 083	1.11*	2.54	3.665	38.57
F-Value	29.51		38.65	
P-Value	<0.001		<0.001	
SED	0.447		0.212	
5% LSD	0.940		0.446	
Df	18		18	

On 9 June (5 days after the second spray) adult wingless aphids and nymphs were assessed separately and all insecticide treatments provided a good level of control of both life stages (Table 6). All treatments reduced numbers of both life stages compared with the untreated control (p<0.05). When comparing the treatments the thiamethoxam seed treatment, HDCI 078, HDCI 079, HDCI 081 and HDCI 083 all reduced both life stages compared with HDCI 080 and HDCI 082 (p<0.05) and the thiamethoxam seed treatment, HDCI 078 and HDCI 083 also reduced numbers of nymphs compared with HDCI 079 (p<0.05). The total numbers of wingless aphids followed the same pattern as the nymphs. No treatment reduced numbers of winged aphids compared with the untreated control (p<0.05).

Table 6. Experiment 1: the numbers of winged and wingless aphids on 9 June. Values followed by * are significantly different from the untreated control (p<0.05).

Treatment	Wingless						Winged	
	Adult		Nymph		Total			
	Ln trans	Back trans	Ln trans	Back trans	Ln trans	Back trans	Ln trans	Back trans
Untreated	4.28*	71.65	6.11*	451.86	6.38*	588.9	3.250	25.28
Thiamethoxam	-0.02*	0.48	-0.21*	0.31	0.18*	0.7	2.456	11.16
HDCI 078	-0.42*	0.16	-0.14*	0.37	0.13*	0.6	3.271	25.84
HDCI 079	-0.42*	0.16	1.6*	4.44	1.68*	4.9	2.877	17.26
HDCI 080	1.84*	5.80	4.29*	72.18	4.52*	91.1	3.891	48.45
HDCI 081	-0.42*	0.16	0.84*	1.82	0.86*	1.9	3.209	24.26
HDCI 082	2.36*	10.14	4.53*	91.92	4.76*	116.6	3.745	41.82
HDCI 083	-0.29*	0.25	-0.21*	0.31	0.20*	0.7	2.488	11.54
F-Value	13.12		34.47		31.09		3.67	
P-Value	<0.001		<0.001		<0.001		0.012	
SED	0.691		0.606		0.634		0.388	
5% LSD	1.451		1.273		1.331		0.814	
df	18		18		18		18	

On 25 June (21 days after the second spray) wingless adults and nymphs were assessed separately and all insecticide treatments continued to provide a good level of control of both life stages (Table 6). All treatments reduced numbers of both life stages compared with the untreated control (p<0.05). When comparing the treatments the thiamethoxam seed treatment and HDCI 078 all reduced the numbers of both life stages compared with HDCI 080 - 083 (p<0.05) and the thiamethoxam seed treatment and HDCI 078 also reduced the numbers of nymphs compared with HDCI 079 (p<0.05). The total numbers of wingless aphids followed the same pattern as the nymphs. There were very few winged aphids and the analysis was not significant (p<0.05).

Table 7. Experiment 1: the numbers of winged and wingless aphids on 25 June. Values followed by * are significantly different from the untreated control (p<0.05).

Treatment	**Wingless**						**Winged**	
	Adult		**Nymph**		**Total**			
	Ln trans	Back trans	Ln trans	Back trans	Ln trans	Back trans	Ln trans	Back trans
Untreated	4.50	89.10	6.24	510.2	6.51	669.2	1.08	2.46
Thiamethoxam	0.16*	0.67	1.24*	3.0	1.32*	3.2	1.08	2.46
HDCI 078	0.29*	0.84	0.83*	1.8	1.06*	2.4	0.78	1.69
HDCI 079	1.44*	3.70	3.97*	52.6	4.13*	61.9	0.52	1.18
HDCI 080	2.90*	17.70	4.60*	99.1	4.79*	120.3	0.16	0.67
HDCI 081	2.67*	13.94	4.36*	78.0	4.56*	95.4	0.52	1.18
HDCI 082	2.35*	9.97	3.54*	34.0	3.81*	44.8	0.07	0.57
HDCI 083	2.18*	8.34	4.30*	72.9	4.46*	86.4	0.54	1.22
F-Value	5.00		19.02		16.39		0.42	
P-Value	0.003		<0.001		<0.001		0.878	
SED	0.902		0.580		0.635		0.825	
5% LSD	1.896		1.219		1.334		1.733	
df	18		18		18		18	

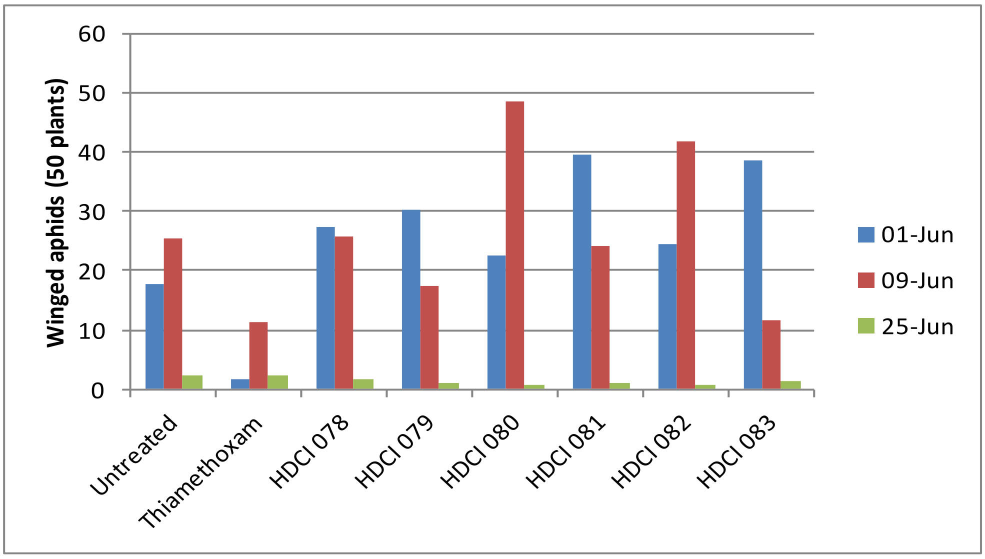

Figure 3. Experiment 1: mean numbers of winged willow-carrot aphid (50 plants) on 3 occasions.

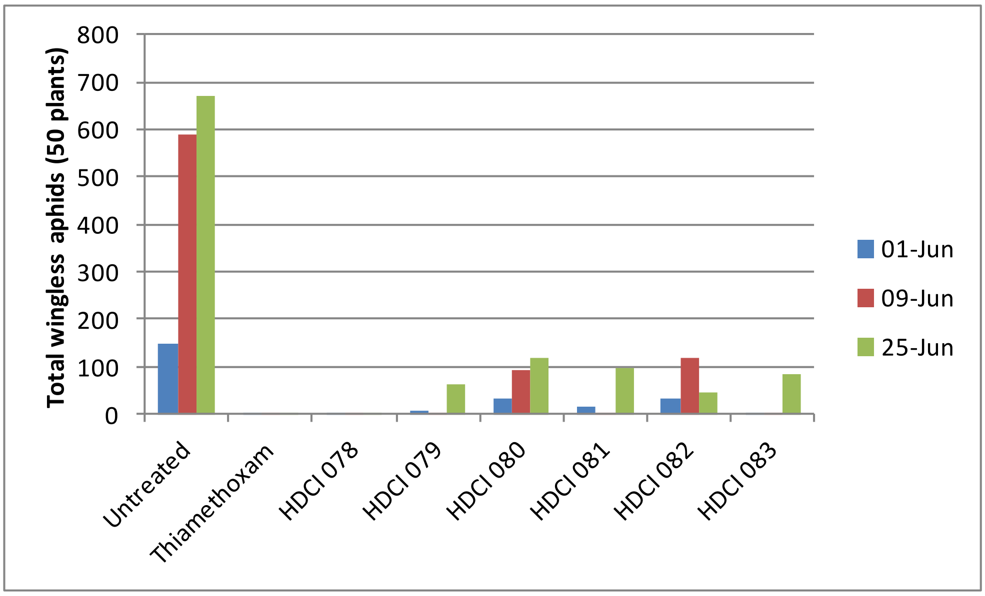

Figure 4. Experiment 1: mean numbers of wingless willow-carrot aphid (50 plants) on 3 occasions.

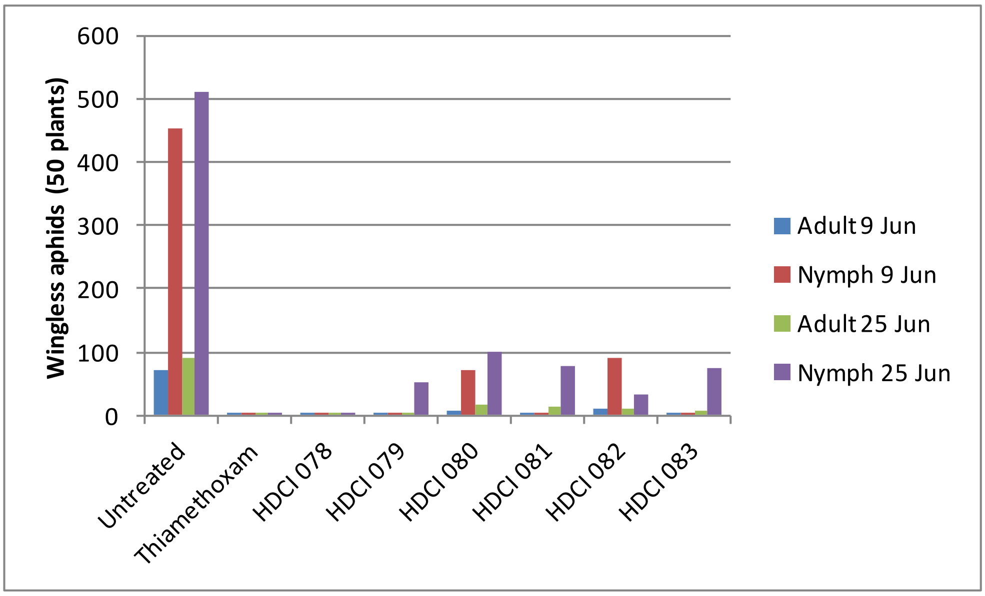

Figure 5. Experiment 1: mean numbers of wingless adults and nymphs of willow-carrot aphid (50 plants) on 2 occasions.

Harvest assessments

After washing, the harvested roots were classified into categories according to the extent of carrot fly damage. The mean damage score was calculated by giving each damage category a numeric value, which were: (0) - 0%, (1) - <5%, (2) - 5-10%, (3) - 10-25%, (4) - 25-50% and (5) - >50% damage. A mean damage score was then calculated for each plot. The mean damage score (Root Damage Index) was calculated for each plot using the following formula:

RDI (Root Damage Index) = $(1_n \times 1 + 2_n \times 2 + 3_n \times 3 + 4_n \times 4 + 5_n \times 5)/Total_n$

Where n was the number of roots in a particular category.

The roots in each damage category were weighed separately and the total weight in 1 m row and the mean root weight were calculated.

Statistical analyses were carried out on: the two plant counts and the percentage change between them, the percentage by number of carrots showing no damage, the cumulative percentage of carrots with less than 5% damage, the Root Damage Index, the total number of roots, weight of roots in 2 m row and the mean root weight. The percentage roots by number with no damage or less than 5% damage required an Angular transformation before analysis to ensure homogeneity of variance between treatments. The data were subjected to Analysis of Variance using the Genstat programme.

Table 8 shows the number of plants counted in 1 m row on two occasions and the percentage change between the two. None of the analyses were significant ($p>0.05$) suggesting that there was little or no seedling/plant mortality due to either carrot fly larvae or aphids.

Damage due to carrot fly larvae when the roots were harvested was relatively low. The percentage of roots with no damage, <5% damage and the Root Damage Index (RDI) are shown in Table 9. The analysis of the RDI was not significant ($p>0.05$), but the thiamethoxam seed treatment and HDCI 072 (two sprays) both reduced the percentage by number of roots with no and <5% damage ($p<0.05$) (Figure 6).

The number of roots harvested from a 2m length of row, the yield and the mean root weight are shown in Table 10. The analysis of the number of roots and the mean root weight were not significant ($p>0.05$). However, by comparing treatments using the 5% LSD, the mean root weight of roots from plots treated with the thiamethoxam seed treatment, HDCI 079 and HDCI 082 was greater than that of the roots from the untreated control and the roots from the plots treated with the thiamethoxam seed treatment were 61% heavier than those from the untreated control. The total yield from all the plots treated with insecticide was greater than from the untreated control ($p<0.05$) and the yield from the plots treated with the thiamethoxam seed treatment was significantly greater than the yield from any of the plots treated with foliar sprays of insecticide. The yield from the plots treated with the thiamethoxam seed treatment was twice that from the untreated control.

Table 8. Experiment 1: the number of plants on two occasions and the percentage change between the two

Treatment	**Number of plants**		
	13 May	**28 July**	**% change**
Untreated	78.2	75.0	-4.11
Thiamethoxam	87.2	90.5	3.73
HDCI 078	81.0	83.0	2.27
HDCI 079	74.2	73.0	-1.99
HDCI 080	81.8	84.5	3.61
HDCI 081	85.2	87.8	3.13
HDCI 082	74.5	78.5	5.43
HDCI 083	78.2	82.0	5.31
F-Value	1.38	1.61	0.63
P-Value	0.273	0.195	0.727
SED	5.64	6.71	6.132
5% LSD	11.85	14.10	12.882
df	18	18	18

Table 9. Experiment 1: the percentage roots with no or <5% damage and the Root Damage Index. Values followed by * are significantly different from the untreated control (p<0.05).

Treatment	**% roots with no damage**		**% roots with < 5% damage**		**RDI**
	Ang-trans	Back-trans	Ang-trans	Back-trans	
Untreated	61.73	77.6	76.5	94.5	0.3
Thiamethoxam	78.74*	96.2	88.2*	99.9	0.1
HDCI 078	68.61	86.7	74.6	93.0	0.3
HDCI 079	65.66	83.0	75.6	93.8	0.3
HDCI 080	66.97	84.7	77.8	95.5	0.2
HDCI 081	66.36	83.9	73.8	92.2	0.3
HDCI 082	79.46*	96.7	87.6*	99.8	0.0
HDCI 083	67.37	85.2	74.9	93.2	0.3
F-Value	2.70		6.19		2.23
P-Value	0.042		<0.001		0.081
SED	5.45		3.321		0.11
5% LSD	11.45		6.977		0.22
df	18		18	18	18

Table 10. Experiment 1: the total number of roots, yield and mean root weight. Values followed by * are significantly different from the untreated control (p<0.05).

Treatment	Total Number	Total weight (g)	Mean root weight (g)
Untreated	140.2	1564	11.4
Thiamethoxam	170.5	3142*	18.4
HDCI 078	141.5	2055*	14.6
HDCI 079	140.2	2221*	16.4
HDCI 080	141.2	2111*	15.3
HDCI 081	156.0	2411*	15.6
HDCI 082	135.5	2338*	17.3
HDCI 083	141.0	2086*	15.3
F-Value	0.93	7.38	1.55
P-Value	0.511	<0.001	0.215
SED	17.07	231.4	2.36
5% LSD	35.87	486.2	4.96
df	18	18	18

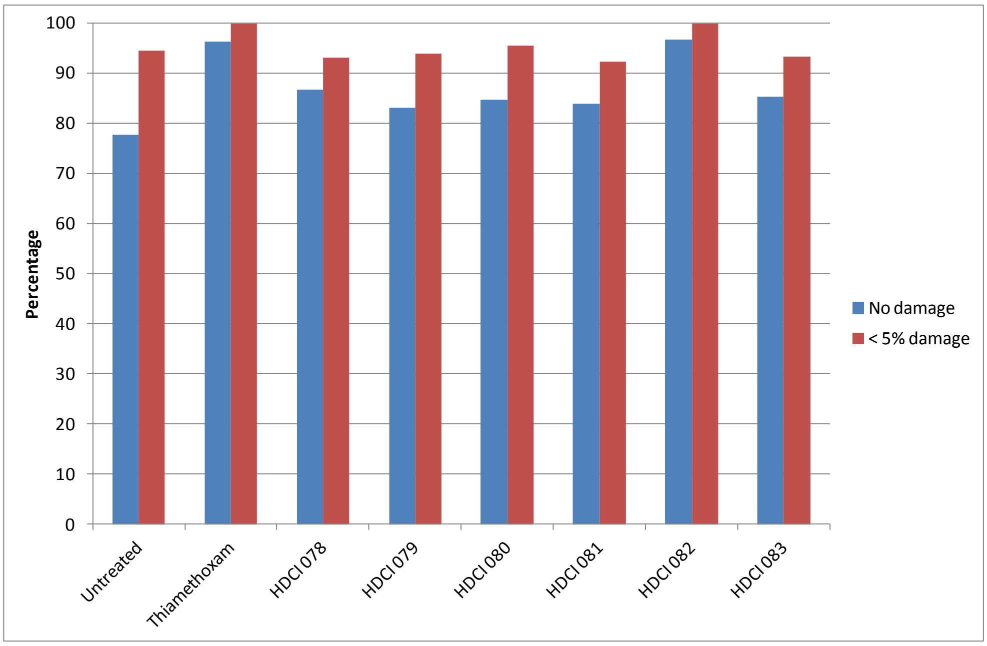

Figure 6. Experiment 1: the mean percentage of roots with no damage and < 5% damage from each treatment

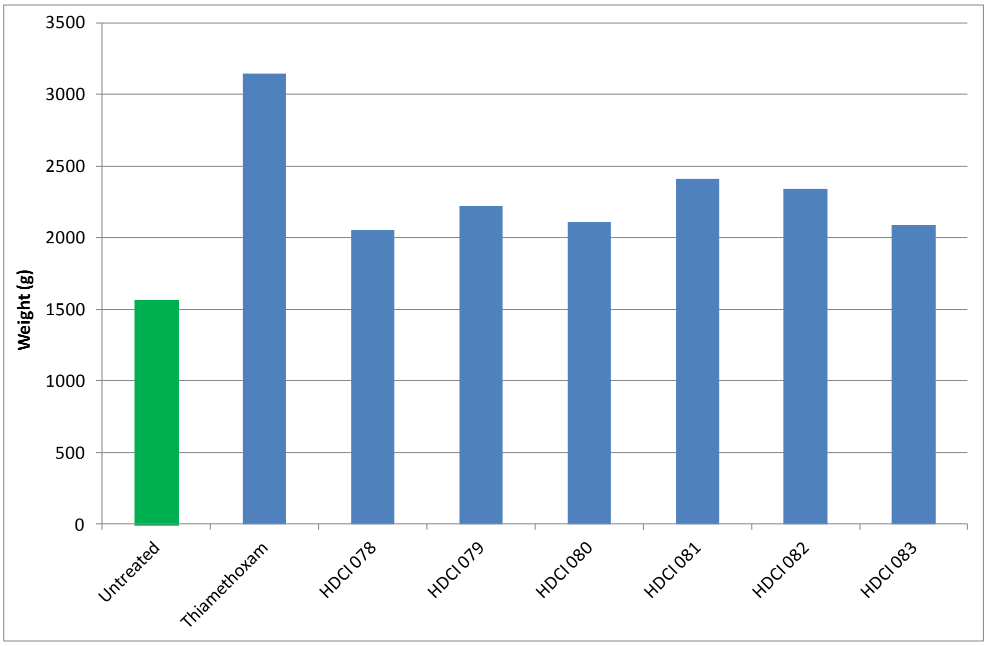

Figure 7. Experiment 1: the yield of roots (g/2 m row) from each treatment.

Virus assessments

Figures 8-10 show the percentage of plants containing virus from 4 replicate plots from the four treatments evaluated. The data for the replicate plots are presented separately as this is more informative than presenting a mean value as it illustrates clearly the amount of variation between replicates.

For *Carrot red leaf virus* CtRLV, which is transmitted persistently, only the thiamethoxam seed treatment showed evidence of a reduction in virus (Figure 8). For *Carrot yellow leaf virus* (CYLV) which is transmitted in a semi-persistent manner there was evidence that the thiamethoxam seed treatment was more effective than the two other insecticide treatments, but levels were also consistently lower in the untreated control than in the sprayed plots (Figure 9). For *Carrot torrado virus-1 CaTV RNA1* levels were lowest in foliage from plots treated with the thiamethoxam seed treatment, but levels of virus were also lower than the untreated control in foliage from plots treated with the other two insecticides (Figure 10).

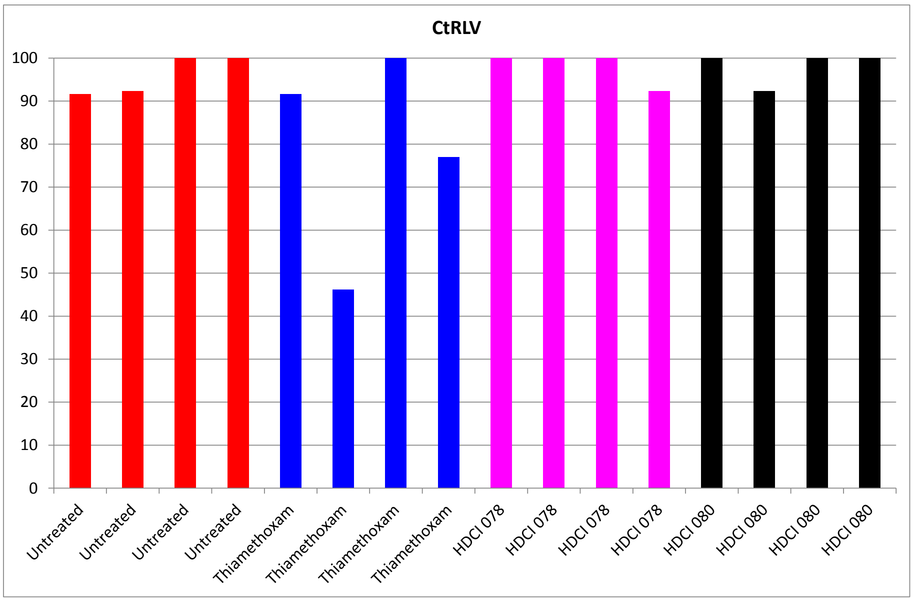

Figure 8. Experiment 1: levels of *Carrot red leaf virus* CtRLV in replicate plots of four of the treatments

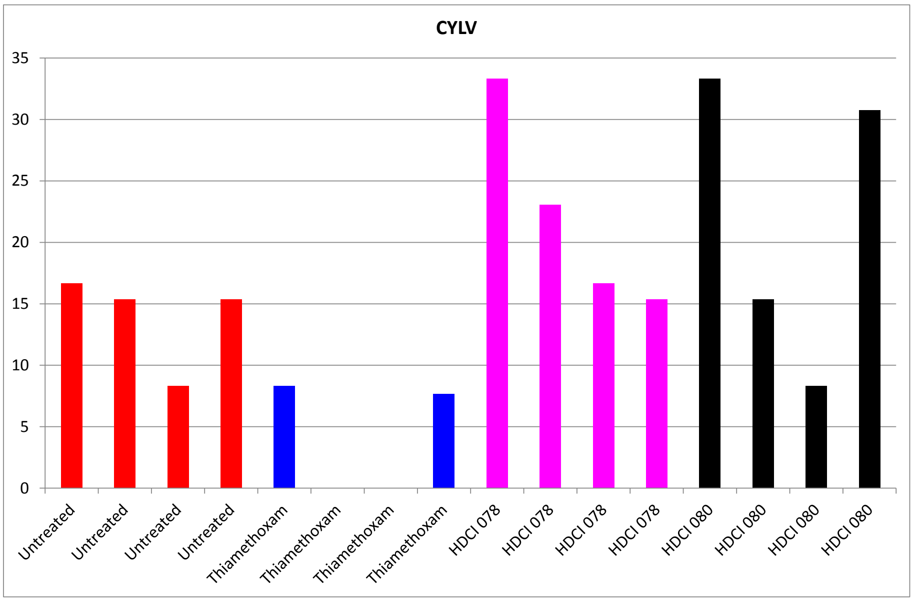

Figure 9. Experiment 1: levels of *Carrot yellow leaf virus* (CYLV) in replicate plots of four of the treatments

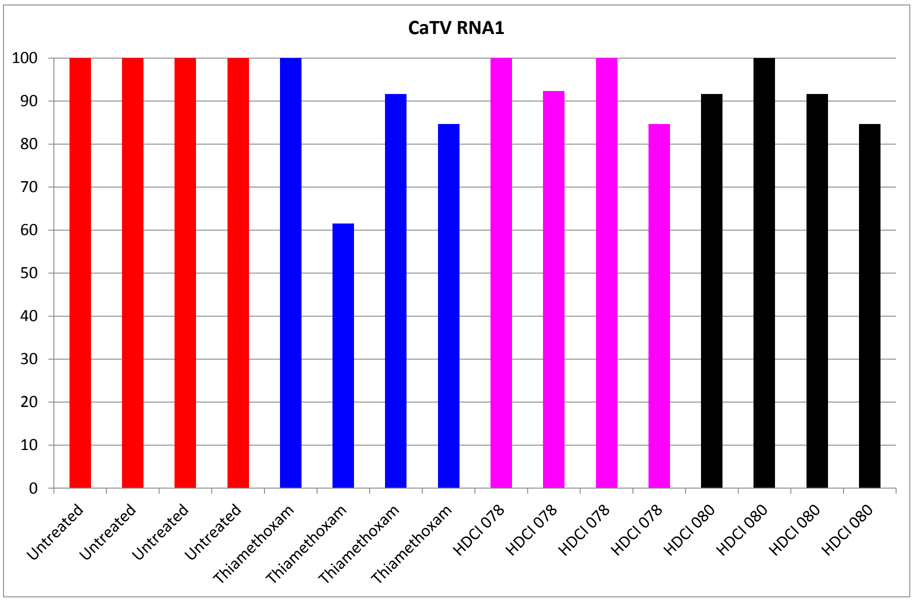

Figure 10. Experiment 1: levels of *Carrot torrado virus-1 CaTV RNA1* in replicate plots of four of the treatments.

Table 11 shows the levels of damage to carrot roots potentially due to viruses from the four replicate plots of the untreated control. Up to 8% of roots showed tip necrosis and 6% internal browning.

Table 11. Experiment 1: levels of damage to carrot roots potentially due to viruses

	% plants with	
Plot	Tip necrosis	Internal browning
5	6.5	2.0
11	8.0	1.0
23	5.5	3.0
25	6.5	6.0

Objective 2 Evaluate insecticide treatment programmes to control second, and potentially third, generation carrot fly.

Experiment 2

Harvest assessments

After washing, the harvested roots were classified into categories according to the extent of carrot fly damage. The mean damage score was calculated by giving each damage category a numeric value, which were: (0) - 0%, (1) - <5%, (2) - 5-10%, (3) - 10-25%, (4) -

25-50% and (5) - >50% damage. A mean damage score was then calculated for each plot. The mean damage score (Root Damage Index) was calculated for each plot using the following formula:

RDI (Root Damage Index) = $(1_n \times 1 + 2_n \times 2 + 3_n \times 3 + 4_n \times 4 + 5_n \times 5)/Total_n$

Where n was the number of roots in a particular category.

The roots in each damage category were weighed separately and the total weight in 1.5 m row and the mean root weight were calculated.

Analyses were carried out on: the percentage by number of carrots showing no damage, the cumulative percentage of carrots with less than 5% damage, the Root Damage Index, the total number of roots, weight of roots in 1.5 m row and the mean root weight. The percentage roots by number with no damage or less than 5% damage required an Angular transformation before analysis to ensure homogeneity of variance between treatments. The data were subjected to Analysis of Variance using the Genstat programme.

When the roots were harvested damage due to carrot fly larvae was relatively high. The percentage of roots with no damage (Figure 11), <5% damage (Figure 12) and the Root Damage Index (Figure 13) are shown in Table 12. The analyses were all significant ($p<0.05$) and by all three measures all treatments reduced damage compared with the untreated control ($p<0.05$). When comparing treatments, addition of Hallmark sprays to either the Coragen programmes or the HDC 087 programmes had no effect on carrot fly control. All programmes containing Coragen or HDCI 087 were more effective ($p<0.05$) than Hallmark alone and one spray of HDCI 087 was more effective ($p<0.05$) than two sprays of Coragen.

The number of roots harvested from a 1.5 m length of row, the yield and the mean root weight are shown in Table 13. The analysis of the number of roots and the mean root weight (Figure 15) were not significant ($p>0.05$). However, all treatments produced heavier roots than the untreated control. The total yield (Figure 14) from all the plots treated with insecticide was greater than from the untreated control but this was only significant ($p<0.05$) with the Hallmark programme and two of the programmes containing HDCI 087 (T6 and T7). Further to this, T7 also had a higher yield ($p<0.5$) than T3, T5 and T8. Overall the suggestion is that the carrot fly had more impact on damage than it had on yield.

Table 12. Experiment 2: the percentage roots with no or <5% damage and the Root Damage Index. Values followed by * are significantly different from the untreated control (p<0.05).

Code	**Treatment**	**% roots with no damage**		**% roots with < 5% damage**		**RDI**
		Ang-trans	Back-trans	Ang-trans	Back-trans	
1	Untreated	15.29	7.0	23.02	15.3	2.9
2	Hallmark	30.22*	25.3	39.32*	40.2	1.8*
3	Coragen	35.34*	33.5	46.30*	52.3	1.4*
4	Coragen + Hallmark x 4	39.35*	40.2	50.96*	60.3	1.2*
5	Coragen + Hallmark x 3	40.02*	41.4	51.06*	60.5	1.2*
6	HDCI 087	51.76*	61.7	63.04*	79.4	0.7*
7	HDCI 087 + Hallmark x 3	49.02*	57.0	61.06*	76.6	0.8*
8	HDCI 087 + Hallmark x 2	54.93*	67.0	66.75*	84.4	0.6*
	F-Value	33.13		43.38		78.02
	P-Value	<0.001		<0.001		<0.001
	SED	3.175		3.069		0.12
	5% LSD	6.670		6.448		0.25
	df	18		18	18	18

Table 13. Experiment 2: the total number of roots, yield and mean root weight. Values followed by * are significantly different from the untreated control (p<0.05).

Code	**Treatment**	Total Number	Total weight (g)	Mean root weight (g)
1	Untreated	109	3688	33.8
2	Hallmark x 4	108	4346*	40.6
3	Coragen x 2	107	3964	37.1
4	Coragen x 2 + Hallmark x 4	105	4242	40.7
5	Coragen x 2 + Hallmark x 3	105	4122	39.3
6	HDCI 087 x 1	112	4480*	40.5
7	HDCI 087 x 1+ Hallmark x 3	108	4824*	45.8
8	HDCI 087 x 1 + Hallmark x 2	103	3956	38.7
	F-Value	0.34	3.12	1.57
	P-Value	0.926	0.024	0.206
	SED	6.92	282.7	3.87
	5% LSD	14.53	593.9	8.14
	df	18	18	18

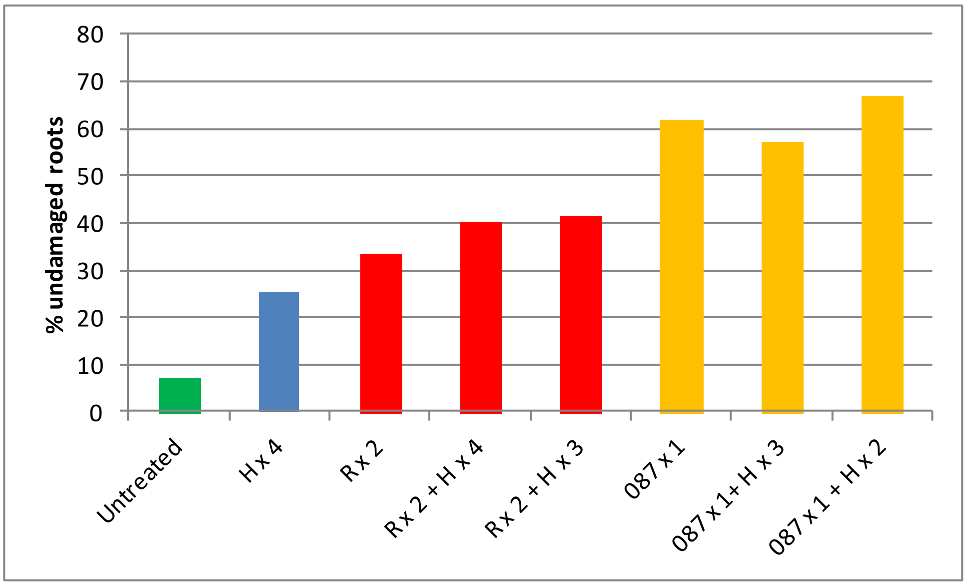

Figure 11. Experiment 2: the mean percentage of undamaged roots from each treatment. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); 087 = HDCI 087 (experimental treatment).

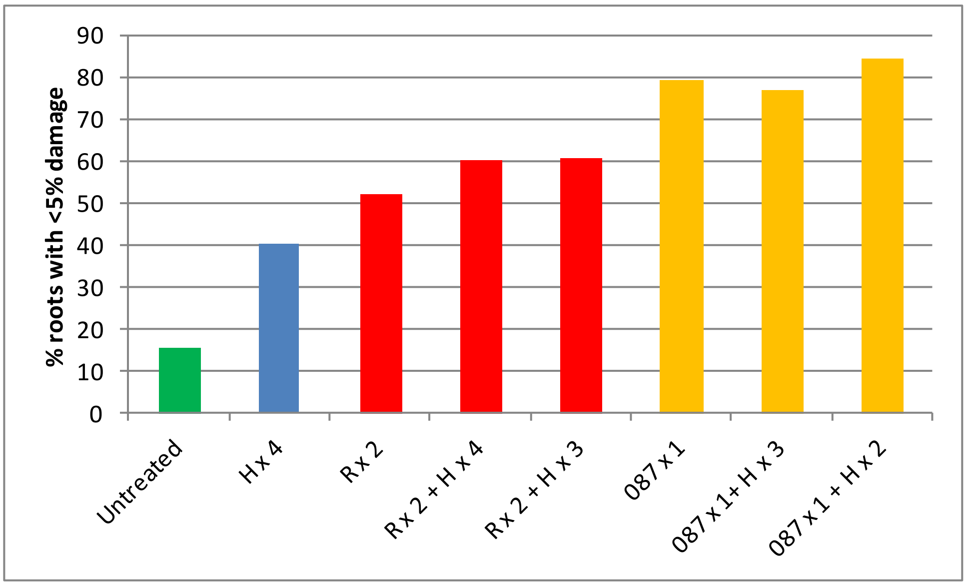

Figure 12. Experiment 2: the mean percentage of roots with <5% damage from each treatment. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); 087 = HDCI 087 (experimental treatment).

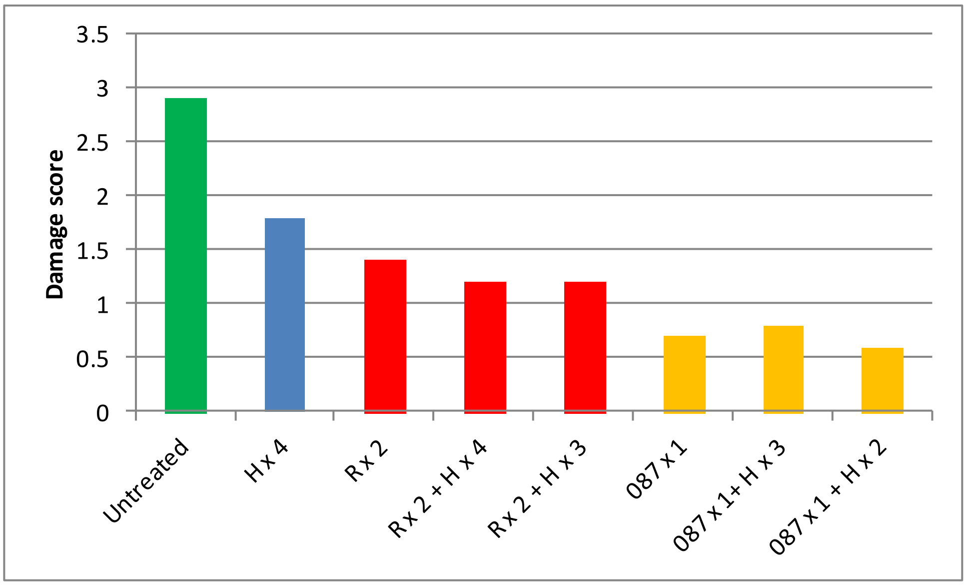

Figure 13. Experiment 2: the mean damage score. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); 087 = HDCI 087 (experimental treatment).

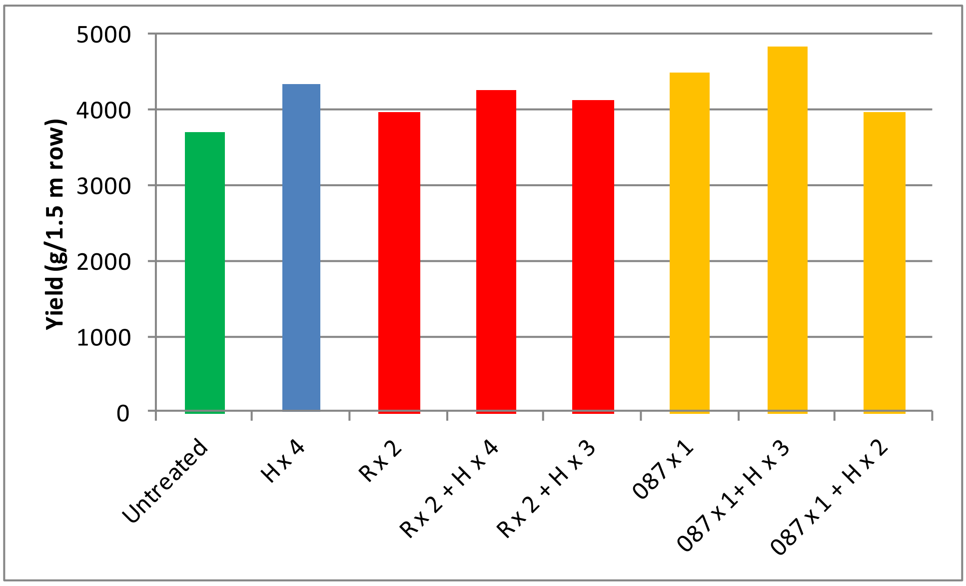

Figure 14. Experiment 2: the total weight of roots. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); 087 = HDCI 087 (experimental treatment).

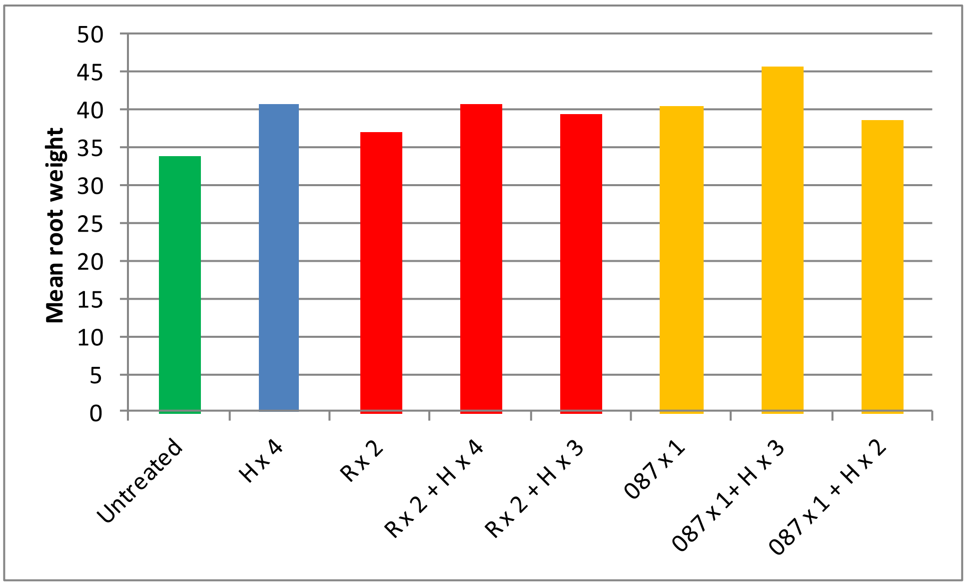

Figure 15. Experiment 2: the mean weight of individual roots from each treatment. H = Hallmark (lambda-cyhalothrin) at 100 or 150 ml/ha; R = Coragen (Rynaxypyr); 087 = HDCI 087 (experimental treatment).

The treatment programmes based on the experimental treatment (HDCI 087) were the most effective and indeed there was no difference in the levels of control whether additional sprays of Hallmark were applied subsequently or not.

Experiment 3

The numbers of carrots in each damage category are presented in Table 12. Damage was severe in the plot left uncovered throughout the trial (exposed to 2nd and 3rd generation flies) but there was still extensive, albeit less, damage in the plot covered throughout the flight of the second generation flies (exposed to 3rd generation flies only).

Table 12. The numbers of roots in six damage categories taken from one plot exposed to second and third generation carrot flies and one plot only exposed to third generation flies

Plot	Damage category (% surface area damaged)					
	0	0-5	5-10	10-25	25-50	>50
2nd + 3rd Generation flies	0	2	9	49	77	63
3rd generation flies only	42	31	56	39	29	3

Discussion

Experiment 1

Winged willow-carrot aphids started to enter the first trial from mid-April and were captured in the suction trap at Wellesbourne between the week ending 19th April and the week ending 12th July (13 weeks). The trial was undertaken as an efficacy trial and no attempt was made to protect the crop at the start of the season or for the entire migration period, with the last sprays being applied on 4th June. At the times the crop was assessed, all of the treatments provided control of wingless aphids and nymphs (last assessment on 25th June) compared with the insecticide-free control. Numbers of winged adults were only reduced by insecticide treatment on the first sampling occasion and this was by the thiamethoxam seed treatment. By the time of the last assessment the thiamethoxam seed treatment had been exposed to field conditions for just over 6 weeks.

In Trial 1 the total yield from all the plots treated with insecticide was greater than from the untreated control plots ($p<0.05$) and the yield from the plots treated with the thiamethoxam seed treatment was significantly greater than the yield from any of the plots treated with foliar sprays of insecticide. Indeed the yield from the plots treated with the thiamethoxam seed treatment was twice that from the untreated control. It appears that the effect on yield may be through an effect on both the number of roots and their size, although the analyses for each of these effects were not statistically significant. For example, comparing the thiamethoxam seed treatment with the untreated control shows that there were 20% more roots, they were 61% heavier on average and that the total yield was doubled.

The aim of the virus assessments was to determine whether this approach could be used to evaluate the efficacy of insecticide treatments for virus control. All three viruses assessed were present in the plots to varying degrees and there was an indication that some of the insecticide treatments, particularly the thiamethoxam seed treatment, had reduced the virus load. The insecticide-free plants were generally most highly infected, with the exception of *Carrot yellow leaf virus* (CYLV) where the plots treated with foliar sprays were more infected. This is hard to explain. However, it is worth noting that comparison of the two foliar spray treatments showed them to be remarkably consistent. The results indicate that there is considerable potential to use this approach to evaluate the efficacy of insecticide programmes for virus control; the only constraint being the cost of analysis for the presence of virus. The variability between the replicates (12 or 13 plants) highlights the need to take replicate samples within a plot, and so to assess a complete trial adequately would be extremely expensive. However, it appears that there may also be a relationship between virus load and yield, so root weight may be a good proxy for virus load when assessing trials, backed up by virus sampling data.

Finally, both the thiamethoxam seed treatment and HDCI 072 (two sprays) reduced the percentage by number of roots damaged by first generation carrot fly and so may have additional benefits in this respect depending on the relative timing of colonisation by carrot fly, in relation to sowing date in the case of the thiamethoxam seed treatment, and spray dates in the case of HDCI 072. It is likely also that HDCI 072 might be useful for control of second generation carrot fly, in which case, if application number is restricted, a decision would need to be made about when best to apply it.

Experiment 2

The treatment programmes based on a single spray of the experimental treatment (HDCI 087) were more effective than those based on two sprays of Coragen, which was in turn more effective than Hallmark alone. In fact there was no difference in the levels of control whether additional sprays of Hallmark were applied subsequently or not to either HDCI 087 or Coragen. This indicates that one well-timed spray of HDCI 087 may be all that is required to control second generation carrot fly.

Experiment 3

In the 'look-see' experiment on the importance of third generation carrot fly, the roots from the plot covered with fine mesh netting until 21 September suffered damage although they were not damaged as heavily as roots from the adjacent area which had been uncovered all the time. This suggests that the importance of the third generation of carrot fly in terms of its impact on damage suffered by overwintered crops of carrot should be re-investigated in more detail.

Conclusions

- Treatment of seed with thiamethoxam was the most effective way of reducing the numbers of wingless adult willow-carrot aphids and nymphs on carrot plots colonised in May-June. This treatment was less effective against winged aphids.
- Foliar sprays of six coded treatments were also effective against wingless adult willow-carrot aphids and nymphs to varying degrees but were ineffective against winged aphids.
- In the first trial, the total yield from all the plots treated with insecticide was greater than from the untreated control plots and the yield from the plots grown from seed treated with thiamethoxam was significantly greater than the yield from any of the plots treated with

foliar sprays of insecticide. The yield from the plots treated with the thiamethoxam seed treatment was twice that from the untreated control.

- There is considerable potential to use the analysis of the virus load of samples of foliage from treated plots to evaluate the efficacy of insecticide programmes for virus control as all three viruses assessed were present in the plots to varying degrees and there was an indication that some of the insecticide treatments, particularly the thiamethoxam seed treatment, had reduced the virus load.
- There may also be a relationship between virus load and yield, so root weight may be a good proxy for virus load when assessing trials, backed up by virus sampling data.
- Both the thiamethoxam seed treatment and HDCI 072 (two sprays) reduced the percentage by number of roots damaged by first generation carrot fly and so may have additional benefits in this respect depending on the relative timing of colonisation by carrot fly, in relation to sowing date in the case of the thiamethoxam seed treatment, and spray dates in the case of HDCI 072.
- For control of second generation carrot fly the treatment programmes based on the experimental treatment (HDCI 087) were the most effective and indeed there was no difference in the levels of control whether additional sprays of Hallmark were applied subsequently or not.
- The importance of the third generation of carrot fly in terms of its impact on damage suffered by overwintered crops of carrot should be re-investigated in more detail.

Knowledge and Technology Transfer

- Presentation at British Carrot Growers R & D Committee meeting on 24th June 2015.
- Poster at Carrot Conference on 5th November 2015.
- Presentation at Syngenta meeting at Newark Showground for growers and advisors on 25th February 2016.
- Poster planned for AHDB Horticulture/BCGA Carrot Technical Seminar on 22 March 2016.
- Information on the abundance of carrot fly and willow-carrot aphid at Wellesbourne was made available, together with forecasts of carrot fly activity, on the Syngenta website as part of the AHDB/Syngenta Pest Bulletin and also on the AHDB Pest Blog.

References

AHDB Project FV 414 - Carrots: Optimising carrot fly control using pyrethroids and Coragen (2013-2014).

AHDB Project FV 382a - Internal browning of carrot: investigating a link with the viral diseases PYFV and CMD.
AHDB Project FV 382b - Carrots: The Epidemiology of Carrot yellow leaf virus (CYLV) - the development of a decision support system for the management of carrot viruses in the UK.
Vincent, J. (1999). Studies on the biology and mortality of the carrot fly, Psila rosae F. (Diptera:Psilidae). PhD Thesis, University of Birmingham.

