FINAL REPORT

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CARROT & PARSNIP: REVIEW OF CARROT FLY CONTROL STRATEGIES

FV 13e

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January 2006

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Grower Summary

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CARROT & PARSNIP: REVIEW OF CARROT FLY CONTROL STRATEGIES

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Project title:	Carrot & Parsnip: Review of carrot fly control strategies
Project number:	FV 13e
Project Leader:	Dr Rosemary Collier
Report:	Final report 2005
Previous reports:	
Key workers:	Dr Rosemary Collier
Location of project:	Warwick HRI, Wellesbourne, Warwick CV35 9EF
Project co-ordinators:	
Date project commenced:	1 May 2005
Date project completed:	31 December 2005
Key words:	Carrot fly, *Psila rosae*, insecticides, monitoring, forecasting, resistant cultivars, biological control, physical barriers, cultural control

Signed on behalf of: **Warwick HRI**

Signature:…………………………………………… ***Date***: ……………………………

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1. GROWER SUMMARY

1.1 Headline

- Since the mid-late 1990s, the carrot fly has been controlled effectively with pyrethroid insecticides applied either as seed treatments or foliar sprays.
- There is no evidence of insecticide resistance at present. However, complete reliance on insecticides from one chemical group is unlikely to be a sustainable strategy for pest control.
- In addition, as alternative active ingredients (especially organophosphates) are withdrawn as a result of ongoing UK/EU pesticides reviews, the use of pyrethroids is likely to increase on a wider range of crops. As these are broad-spectrum insecticides, this is likely to have an adverse effect on non-target species.
- This report contains a review of current and potential future strategies for carrot fly control. Potential management strategies that appear to be the most feasible are:
    - Alternative ‘novel’ insecticides applied either as seed treatments or foliar sprays. There are a number of active ingredients to try.
    - Physical barriers – including vertical ‘exclusion’ fences which require further practical and economic evaluation.
    - Entomopathogenic nematodes – these have not shown promise in previous trials, but such trials have been extremely limited.
    - Trap/sacrifice crops - it is possible that newly-emerged carrot flies could be arrested at the emergence site if a ‘sacrifice’ crop of young carrots was sown there. The crop could then be destroyed after the flies had laid their eggs, but before the larvae had completed their development. This technique has not been evaluated previously and it would be sensible to evaluate it on an experimental scale first. Trap or sacrifice crops could also be used in conjunction with vertical barriers – on the outer perimeter.
    - Intercropping – the practicalities of this approach should be considered. Again, previous trials have been quite limited.
    - An overall management strategy to identify crops or potential crops that are either ‘high risk’ or ‘low risk’ for carrot fly damage and to make modifications to reduce the risk where feasible. The tools are available to do this, but they need to be combined and tested in practical situations.

1.2 Background and expected deliverables

Since the mid-late 1990s, the carrot fly (*Psila rosae*) has been controlled with pyrethroid insecticides applied either as seed treatments (tefluthrin [Force]) or foliar sprays (lambda-cyhalothrin [Hallmark], deltamethrin [Decis]). Although the efficacy of the tefluthrin seed treatment has been questionable, there is no doubt that the foliar sprays have been extremely effective. In 2003, lambda-cyhalothrin accounted for 62% of the insecticide-treated area of carrot, parsnip and related crops, with an average of three applications at full label rate being used on 85% of the total area grown (Garthwaite *et al.,* 2003). Comparable figures for deltamethrin and cypermethrin respectively were 6% and 5% of the treated area and 17% and 26% of the total area grown.

Complete reliance on insecticides from one chemical group may not be a sustainable strategy for pest control. There is a significant risk of selecting for individuals resistant to pyrethroids, leading to reduced control efficacy and ultimately control failure if the selection pressure is sufficiently high. In addition, as alternative active ingredients (especially organophosphates (OPs)) are withdrawn as a result of ongoing UK/EU pesticides reviews, the use of pyrethroids is likely to increase on a wider range of crops. As these are broad-spectrum insecticides, this is likely to have an adverse effect on non-target species. In 2003, pyrethroids accounted to 51% of the area of vegetables treated with insecticide and use of lambda-cyhalothrin and deltamethrin had increased by 17% and 22% respectively since 1999.

Over the ten years since carrot fly control shifted to pyrethroids, new active ingredients have become available and have been evaluated against other fly pests such as the cabbage root fly (*Delia radicum*). There may also be new strategies of non-insecticidal control. It is therefore an opportune time to review current recommendations and evaluate new actives and non-insecticidal control strategies that might be deployed in the future.

The aim of the project is to provide an updated review of research and development on carrot fly and current strategies for carrot fly control. This should help to determine the feasibility of developing alternative strategies for carrot fly control. Evaluations of new active ingredients will indicate which products might be exploited for resistance management and to diversify chemical inputs available to control this important pest.

1.3 Summary of the project and main conclusions

Efforts have been made to obtain new information on approaches to carrot fly control in the UK and overseas. This has been done by standard searches of the scientific literature, web searches and by conversations with colleagues in Europe and North America. An extensive review of carrot fly control methods was done for Defra (then MAFF) in 1995, at the time that concerns arose about the use of OP insecticides in carrots. The new information obtained builds on this previous review.

1. Insecticides

Since the mid 1990s, carrot fly has been controlled in the UK with pyrethroid insecticides applied either as seed treatments (tefluthrin [Force]) or foliar sprays (lambda-cyhalothrin [Hallmark], deltamethrin [Decis]). In this respect, the UK differs from most other countries where carrot fly causes economic damage, since the majority appear to be continuing to use OP insecticides at present. Although insecticide trials at Wellesbourne have led us to question the efficacy of the tefluthrin seed treatment, there is no doubt that the foliar sprays of lambda-cyhalothrin and deltamethrin have been extremely effective. In many areas, carrot fly populations have declined considerably, although growers continue to be vigilant in applying insecticide treatments. Although OP insecticides are no longer used to control carrot fly, aldicarb (Temik) is still approved for control of aphids and nematodes in carrot and parsnip. Aldicarb may be providing a background level of carrot fly control in some crops. The final use date for this pesticide is 31 December 2007 and it will be interesting to see what impact its withdrawal has on carrot fly populations.

Complete reliance on insecticides from one chemical group may not be a sustainable strategy for pest control. There is a significant risk of selecting for individuals resistant to pyrethroids, leading to reduced control efficacy and ultimately control failure, if the selection pressure is sufficiently high. At present, limited assessments made by Syngenta Crop Protection indicate that carrot flies (at least from Wellesbourne) are fully susceptible to pyrethroids and the good levels of carrot fly control achieved in most insecticide-treated crops would support this.

However, over the ten years since carrot fly control became reliant on pyrethroids, new active ingredients have become available and have been evaluated against other fly pests, particularly the cabbage root fly. Insecticides evaluated for control of cabbage root fly include spinosad (Tracer), cyromazine (Trigard), fipronil (active ingredient in Vi-Nil), thiamethoxam (Cruiser), imidacloprid (Gaucho), diflubenzuron (Dimilin), teflubenzuron (Nemolt). Of these, only spinosad and cyromazine have been tested as foliar sprays against carrot fly, both at a single rate, in an HDC field trial on parsley. When applied in this way, neither insecticide was as effective as lambda-cyhalothrin (Hallmark). Fipronil and imidacloprid have been tested as seed treatments in HDC trials, but were ineffective at the rates tested. There has also been some recent research on seed treatments in the Netherlands and of the insecticides tested, both clothianidin (in the UK clothianidin is available in a mixture with beta-cyfluthrin called Poncho Beta) and thiamethoxam look promising.

Overall there is considerable potential to evaluate a number of foliar spray and seed treatments in the UK to identify treatments that could be used in conjunction with pyrethroids to provide alternative chemistry and reduce the 'selection' pressure from pyrethroids.

2. Treatment timing

As pyrethroids began to be used for carrot fly control, the HDC funded a project to help growers use them effectively. This culminated in a Factsheet (08/01 Insecticidal control of carrot fly), which is still applicable. It soon became clear that foliar sprays of pyrethroids killed adult carrot flies. This was in contrast to the OP insecticides used previously, which killed newly-hatched larvae in the soil. Key points regarding the application of foliar sprays of pyrethroids are:

- Pyrethroids should be applied from first emergence onwards, since the aim is to kill female flies before they lay eggs. Lambda-cyhalothrin (Hallmark) sprays applied one week before the HDC/HRI forecast for 10% (first) egg-laying gave better carrot fly control than when the first insecticide spray was triggered by the first capture of flies on sticky traps.
- If carrot flies are in the crop at the time it is sprayed with pyrethroids, they will be killed. Females have a diurnal pattern of activity, usually leaving the shelter of field boundaries to lay their eggs. To maximise the "knockdown" effect, sprays should be applied between 4-6 pm on warm days, as this is when most female flies are in the crop.
- Insecticide residues on foliage are also effective. In trials at Wellesbourne, on the day after lambda-cyhalothrin was sprayed, residues on the carrot foliage killed 95% of flies. Even after 18 days, the lambda-cyhalothrin residues still killed about 25% of flies. Therefore, because of this residual action, it is not crucial, but it is beneficial, to apply sprays in the late afternoon.
- Contrary to popular belief, the residues of pyrethroid sprays left on the foliage of carrot crops do not repel carrot flies, they kill them.
- In trials at Wellesbourne, under a wide range of different weather conditions, residues of lambda-cyhalothrin on carrot foliage killed more than 50% of the flies/day for at least 7 days. The length of time lambda-cyhalothrin residues remain effective on carrot foliage depends upon temperature. Residues of lambda-cyhalothrin on carrot foliage killed 50% of flies/day for 10 days at the time of the first fly generation (May max/min = 18ºC/8ºC) but only for 7 days during the warmer months (July/August max/min = 23ºC/11ºC) of the second fly generation. Sprays of lambda-cyhalothrin became “rainfast” as soon as they contacted the plant foliage. The insecticide was not washed off the plants even when irrigation was applied within 1 minute of applying the spray.

An understanding of the behaviour of adult carrot flies and of the way that the insecticide treatments act has led to clear recommendations for the application of pyrethroid sprays. If new active ingredients become available then it is important to obtain a similar understanding of how they work best.

There has been a considerable amount of research on spray thresholds for carrot fly in Europe and North America. However, this is more appropriate for control methods that are aimed at carrot fly larvae. It is important to remember that, unlike control using OP insecticides, once a pyrethroid spray regime is introduced, few, if any, flies should be caught on sticky traps. If they are, then alarm bells should ring.

3. Techniques for reducing the overall level of carrot fly attack

Insecticides kill only a percentage of the insects against which they are applied. Thus a treatment which is consistently efficient may be effective against a light to moderate pest attack, but will be ineffective against a severe infestation. Growers should be at least as concerned about the levels of the carrot fly population they are seeking to control as they are about the efficiency of the insecticides they use.

Resistant cultivars

There are no completely resistant carrot cultivars but some are certainly less susceptible to carrot fly than others. Seed companies still have an interest in breeding carrot cultivars that are resistant to carrot fly and commercially acceptable cultivars with higher levels of resistance may become available in the future.

Crop rotation and isolation

When carrots are first grown on land remote from areas where they have been grown previously, carrot fly is unlikely to cause a problem for at least a few years, until numbers have built up, particularly if early and late crops are well-separated to break the sequence of host plants in the pest's life-cycle. Carrot fly is a relatively poor flier and recent research at Warwick HRI Wellesbourne showed that relatively few carrot flies moved more than 1 km from a previously infested crop and that numbers declined steadily, and predictably, with increasing distance from the 'source' of carrot fly.

The results of recent research on carrot fly dispersal and the distribution of carrot fly within infested crops have provided the tools to predict the number of carrot flies that might disperse from an infested crop to colonise a new crop grown in the locality. This is based on an estimate of fly damage in the old crop, the sizes and shapes of the two fields and the distance between them. This technique requires validation in a commercial situation, but could provide an effective and relatively simple tool for estimating the risk of carrot fly damage in new crops.

Manipulation of drilling and harvesting dates

Susceptibility to attack varies with sowing date of the crop. There have been a number of studies to demonstrate this. In a recent experiment at Wellesbourne, plots were sown at fortnightly intervals between mid March and mid June. The largest numbers of second generation flies (502/plot) emerged from the plots sown at the end of March, and the smallest numbers (13/plot) from the plots sown in mid-June. From the plots that were sown in mid-May, part-way through the first fly generation, a mean of 62 flies was caught/plot, which is equivalent to only 12% of the number of flies that emerged from the plots drilled in late March.

Early lifting of the entire crop cuts short the development of second generation carrot fly damage and prevents the carry over of large numbers of carrot fly larvae from one year to the next. In Sweden the development of carrot fly damage is predicted using pest monitoring and day - degree forecasts.

Growers may be prepared to lift carrots 'early' if they know that carrot fly damage is about to develop. The carrot fly forecast model developed at Warwick HRI was adapted in Defra project OF0179 to produce predictions of when damage symptoms appear in carrot crops. This was compared with a day-degree forecast of damage development that had been developed previously in Sweden. Neither forecast has been validated extensively in commercial crops and both require further testing to confirm that they are robust.

Assess the effectiveness of sacrifice crops grown at carrot fly emergence sites

When carrot flies emerge from the soil in the spring, the crop on which they developed in the previous summer has been harvested and they must disperse if they are to find a new host crop on which to lay their eggs.

It is possible that newly-emerged carrot flies could be arrested at the emergence site if a 'sacrifice' crop of young carrots was sown there. The crop could then be destroyed after the flies had laid their eggs, but before the larvae had completed their development. This technique has not been evaluated previously and it would be sensible to evaluate it on an experimental scale first.

Intercropping

Carrots have been intercropped with onions, lucerne, clover and other species, in an attempt to reduce colonisation by carrot fly. There is evidence of both a reduction in carrot fly numbers (although not on every occasion) and in yield due to competition between the carrots and the intercrop (again not on every occasion). In experiments in the Netherlands, undersowing with clover reduced carrot fly damage to a susceptible variety by 55-84% and to a 'carrot fly tolerant' variety by 45-72%. In general, crop yield and quality were maintained and the authors concluded that yield loss due to intercropping can be prevented, provided weeds are controlled until the clover covers the open area between the carrots and suppresses the weeds.

If intercropping were to be considered it should be approached in a more systematic manner to determine the characteristics of the intercrop that are necessary to reduce carrot fly colonisation without reducing crop yield. Such an approach is being taken for cabbage root fly in a current LINK project part-funded by the HDC.

Repellent chemicals

There has been some interest in treating crops with semiochemicals in the hope that these would mask attractive host plant odours and prevent pest insects entering the crop. This approach has been investigated for control of currant-lettuce aphid in salad crops and the use of foliar sprays of garlic extracts has been investigated in some detail for control of cabbage root fly in brassicas. Neither of these techniques was successful. This approach has not been tested experimentally for carrot fly.

Natural enemies/biological control

Carrot fly can be parastised by small wasps. However, parasitised carrot fly larvae complete feeding before the parasitoids kill them, so this does not reduce damage in the current crop, although parastioids might reduce the overall population size over time. The parasitoids are likely to be very susceptible to insecticides.

The fungus *Empusa* sp. can cause high adult carrot fly mortality in some years. In Denmark it was considered to be a potential agent for biological control. The difficulties of this approach are that fungal pathogens, which spread aerially, are usually costly to produce, are susceptible to environmental factors and only infect flies after they have laid most of their eggs.

The possibility of using entomopathogenic nematodes to control carrot fly has also been investigated on a small scale in the UK and in a larger trial in North America. No conclusive results were produced from any of the trials, at least in part because carrot fly numbers were low, and it would be valuable to evaluate nematodes against a more substantial carrot fly population.

Sterile male release

This technique has not been attempted with carrot fly although it has been used commercially in the Netherlands for onion fly control. Extremely large numbers of carrot fly would be required and a cost-effective rearing technique has not been perfected. Mass rearing techniques would need to be developed before sterile male release could be evaluated in the field.

4. *Techniques to avoid the use of insecticides*

Crop covers

Experimental work has shown that woven or non-woven covers can be used to prevent carrot fly attack. The covers can be applied at drilling or later, but must be applied before the flies start to lay eggs. Provided they are applied at the right time, the mesh size is sufficiently small and they stay intact, crop covers exclude all carrot fly. Crop covers are used extensively in the UK to control cabbage root fly on swede.

Vertical barriers

Scientists in North America, Norway, Switzerland and Germany have been investigating the use of vertical fences to prevent colonization by pest insects, including cabbage root fly and carrot fly. Fence heights range from 1.2 – 1.7 m and they are usually made of fine mesh netting. The fences also have an outward facing overhang of 17-35 cm which is to trap insects which walk up the outside of the fence. The fences are usually placed around the edges of the crop to completely enclose it, or in some cases they have been installed in a U-shape or as a linear barrier, when the source of the pest is known. With the exception of the German study, the results have been quite encouraging for both cabbage root fly and carrot fly. In a Canadian trial, vertical barriers reduced damage by 50-90% depending on when the roots were harvested and in one trial in Switzerland, the use of vertical fences reduced the percentage of damaged carrots from 8-9% to 1-2%. However, in a German study, there was no effect on carrot fly. Possible explanations for the failure of this control method against carrot fly were 1) that because carrot fly is a relatively weak flier there was passive drift of the insects into the enclosed area (a similar effect has been recorded for aphids in crops enclosed by barriers), 2) the carrot flies were walking over the overhang or 3) the carrot flies were flying down into the plots from nearby hedges that were taller than the fences.

The use of vertical barriers is a technique that could be evaluated in the UK, probably in the first instance for carrot fly control in organic crops. Factors that should be considered include the area that is cropped versus the height of the barrier, the effect of trees or shrubs on the field boundary (since carrot flies have been found several metres high in trees) and the use of 'trap crops', plants susceptible to carrot fly, on the outside of the barrier to arrest potential colonizers, perhaps in combination with bare soil or non-host strips. In more recent studies, researchers in Norway have been using fence netting that is impregnated with the pyrethroid insecticide deltamethrin and this appears to have been effective against adult cabbage root flies (which is surprising since pyrethroids have shown no effect against cabbage root fly in recent HDC projects) and are therefore very likely to be effective against adult carrot flies.

Early lifting and cold storage

In a previous review of methods of carrot fly control, there was a relatively large section on early lifting and cold storage of carrots, because it was suggested that, in the absence of OP insecticides, this might be one possible method of reducing carrot fly damage to overwintered carrots. Carrots are lifted early and kept in cold stores in some parts of Northern Europe and in North America. This is principally to prevent the crop being destroyed by frost but it also reduces or eliminates carrot fly damage to overwintered carrots.

At present, large scale cold storage of overwintered carrots does not appear to be an option in the UK. The main reasons for this are 1) the poor visual appearance of stored carrots due to a deterioration in skin finish and silvering of the skin, 2) the potential for rotting in store (difficult to estimate how this would compare with field conditions) and 3) the significant costs of building and running storage facilities.

1.4 Financial benefits

The UK carrot and parsnip crop is worth approximately £173M per year (value of home production marketed – Defra Basic Horticultural Statistics for 2005). The UK grows approximately 94% of carrots consumed in the UK. Without effective methods of carrot fly control then it is likely that damage levels would increase well beyond 5%, increasing the costs of production through wastage and higher grading costs.

1.5 Action points for growers

- Insecticide sprays of the pyrethroids lambda-cyhalothrin (Hallmark) and deltamethrin (Decis) continue to be effective methods of carrot fly control. There is no evidence that any UK carrot fly populations have developed resistance to these insecticides.
- The recommendations for use of foliar sprays of pyrethroids given in HDC Factsheet 08/01 are still relevant.
- The effectiveness of the tefluthrin (Force) seed treatment is more doubtful.
- Aldicarb (Temik) may be providing a background level of carrot fly control in some crops. However, the final use date for this pesticide is 31 December 2007.
- Pyrethroids are broad spectrum insecticides and every effort should be made to minimise their use both for environmental reasons and to reduce the selection pressure for insecticide resistance.
- The most effective way to reduce insecticide use is to employ management strategies that minimise the risk of carrot fly infestation. In particular, it is important to separate new crops from sources of carrot fly and a separation distance of 1 km should be sufficient to reduce the risk of carrot fly infestations considerably.

- Crop covers are an extremely effective method of excluding carrot fly from susceptible crops, provided the covers are applied before female carrot flies start to lay eggs and provided they are well-sealed.
- Other sorts of barriers, such as vertical fences, still have to be evaluated under UK conditions. Field size is likely to be a major consideration.

2. SCIENCE SECTION

2.1 Introduction

Carrot fly *(Psila rosae)* is a serious pest of umbelliferous crops such as carrot, parsnip, celery and parsley. The larvae cause damage by feeding on developing roots, rendering them unmarketable. Most carrot crops in the UK are vulnerable to carrot fly attacks and effective control of up to three generations of carrot fly is essential for the production of high quality, marketable roots.

In January 1995, the Pesticides Safety Directorate (PSD) announced a limit of three organophosphorus (OP) insecticide applications per carrot crop with a concession of four applications on soils with 10% or more organic matter. These restrictions arose from PSD taking action on their findings of unexpected and marked variation in OP insecticide residues between individual carrot roots. This lead to widespread consumer and retailer concern about OP residues in carrots, forcing the carrot industry to seek non-OP based carrot fly control programmes. This was a radical change, as OP insecticides were used widely to control both first and second generation carrot fly. The British Carrot Growers Association set a target of 100% OP-free production by 1998.

In spring 1995, following the restrictions on OP usage on carrots, Specific Off-Label Approvals were granted to the use of Hallmark (lambda-cyahlothrin) and Force (tefluthrin seed treatment) on carrots and parsnips. Later in the year, another SOLA was granted for the use of deltamethrin on carrots. When these SOLAs were granted, there was very little efficacy data available on these pyrethroids and the HDC funded a project to identify how best to use them (Blood Smyth & Finch, 1999). In addition, Defra (formerly MAFF) commissioned a review of possible methods of producing OP-free carrots (Collier, 1995). This previous review forms the starting point for the current review.

There is no doubt that the foliar sprays of pyrethroids have been extremely effective and, since the mid-late 1990s, the carrot fly has been controlled with pyrethroid insecticides applied either as seed treatments or foliar sprays. The effectiveness of the tefluthrin (Force) seed treatment is more doubtful. In addition, aldicarb (Temik) may be providing a background level of carrot fly control in some crops. The final use date for this pesticide is 31 December 2007.

However, complete reliance on insecticides from one chemical group is unlikely to be a sustainable strategy for pest control. There is a significant risk of selecting for individuals resistant to pyrethroids, leading to reduced control efficacy and ultimately control failure if the selection pressure is sufficiently high. In addition, as alternative active ingredients are withdrawn as a result of ongoing UK/EU pesticides reviews, the use of pyrethroids is likely to increase on a wider range of crops. As pyrethroids are broad-spectrum insecticides, this is likely to have an adverse effect on non-target species. In 2003, pyrethroids accounted to 51% of the area of vegetables treated with insecticide and of this lambda-cyhalothrin accounted for 31% (Garthwaite *et al.*, 2003). The area treated with lambda-cyhalothrin and deltamethrin had increased by 17% and 22% respectively since 1999.

Over the ten years since carrot fly control has become reliant on pyrethroids, new active ingredients have become available and have been evaluated against other fly pests such as the cabbage root fly (*Delia radicum*). There may also be new strategies of non-insecticidal control. It is therefore an opportune time to review current recommendations and evaluate new actives and non-insecticidal control strategies that might be deployed in the future.

2.2 Insecticides

Since the mid-late 1990s, carrot fly has been controlled in the UK with pyrethroid insecticides applied either as seed treatments (tefluthrin [Force]) or foliar sprays (lambda-cyhalothrin [Hallmark], deltamethrin [Decis]). In this respect, the UK differs from most other countries where carrot fly causes economic damage, since the majority appear to be continuing to use OP insecticides.

Although insecticide trials at Wellesbourne have led us to question the efficacy of the tefluthrin seed treatment (Blood Smyth & Finch, 1999), there is no doubt that the foliar sprays of lambda-cyhalothrin and deltamethrin have been extremely effective. In many areas, carrot fly populations have declined considerably, although growers continue to be vigilant in applying insecticide treatments.

In 2003, lambda-cyhalothrin accounted for 62% of the insecticide-treated area of carrot, parsnip and related crops, with an average of three applications at full label rate being used on 85% of the total area grown (Garthwaite *et al.*, 2003). Comparable figures for deltamethrin and cypermethrin respectively were 6% and 5% of the treated area and 17% and 26% of the total area grown. Complete reliance on insecticides from one chemical group, such as the pyrethroids, may not be a sustainable strategy for pest control. There is a significant risk of selecting for individuals resistant to pyrethroids, leading to reduced control efficacy and ultimately control failure, if the selection pressure is sufficiently high. At present, limited assessments made by Syngenta Crop Protection in 2005 indicate that carrot flies (at least from Wellesbourne) are fully susceptible to pyrethroids (Russell Slater, personal communication) and the good levels of carrot fly control achieved in most insecticide-treated crops would support this. In addition, as alternative active ingredients are withdrawn as a result of ongoing UK/EU pesticides reviews, the use of pyrethroids is likely to increase on a wider range of crops. As these are broad-spectrum insecticides, this is likely to have an adverse effect on non-target species.

Although OP insecticides are no longer used to control carrot fly, aldicarb (Temik) is still approved for control of aphids and nematodes in carrot and parsnip and carbsosulfan is approved for the control of aphids. The most recent Pesticides Usage Survey Report (Garthwaite *et al.*, 2003) recorded that a total of 51% of the carrot and parsnip crop in the UK was treated with aldicarb, although usage may have declined since 2003 (S. Hockland, personal communication). Aldicarb may be providing a background level of carrot fly control in some crops. The final use date for this pesticide is 31 December 2007 and it will be interesting to see what impact its withdrawal has on carrot fly populations.

Over the ten years since carrot fly control became reliant on pyrethroids, new active ingredients have become available and have been evaluated against other fly pests, particularly the cabbage root fly (*Delia radicum*), in HDC projects (Jukes *et al*., 2000; 2001; 2002; 2003; 2004; 2005a). Insecticides evaluated for control of cabbage root fly include spinosad, cyromazine, fipronil, thiamethoxam, imidacloprid, diflubenzuron, teflubenzuron (Table 1). These insecticides were applied in a number of ways (as appropriate for each active ingredient and crop), either as seed treatments, pre- or post-planting drenches, or foliar sprays.

Table 1 Insecticides evaluated against cabbage root fly (Summarised from Jukes *et al*., 2000; 2001; 2002; 2003; 2004; 2005a)

Active ingredient	**Product name (e.g.)**	**Seed treatment**	**Drench treatment**	**Foliar spray**
Spinosad	Tracer	Effective	Effective	Ineffective
Thiamethoxam	Cruiser	Effective		
Cyromazine	Trigard	Effective	Ineffective	
Fipronil	Vi-Nil	Effective	Effective	Ineffective
Imidacloprid	Gaucho	Ineffective	Ineffective	
Teflubenzuron	Nemolt		Effective	
Diflubenzuron	Dimilin	Ineffective	Effective	
Thiacloprid	Calypso		Effective	
Lambda-cyhalothrin	Hallmark			Ineffective
Deltamethrin	Decis			Ineffective

<u>Foliar sprays</u>

In the HDC projects, none of the insecticides applied as foliar sprays have controlled adult cabbage root fly (Jukes *et al.,* 2000; 2004*)*. Indeed the projects showed that the results obtained for cabbage root fly may not be directly transferable to carrot fly, since both lambda-cyhalothrin and deltamethrin were ineffective against adult cabbage root flies in the field (Jukes *et al.*, 2000). To try to improve the efficacy of foliar sprays against adult cabbage root flies, 'baits' (sugar and protein) were incorporated into the spray solutions. Whilst this improved efficacy considerably in the laboratory (Jukes *et al*., 2003), such treatments did not control cabbage root fly effectively in the field (Jukes *et al*., 2004). In the case of spinosad, this may have been because the insecticide was not sufficiently persistent.

Control of carrot fly on parsley

Since the mid 1990's the HDC has funded a single insecticide trial on carrot fly. This was part of a project on herbs (PC 245) and was for control of carrot fly on parsley (Jukes & Collier, 2003). The parsley (cv. Champion Moss Curled) was drilled in 4-row beds at a rate of 100 seeds/m on 20 June 2002. The crop was covered with fleece on 16 July to promote growth and exclude carrot fly prior to spraying. The covers were removed on 1 August and the rows were divided into plots. Each plot was 1 bed wide x 2.5 m long and adjacent plots were separated by 1 m of bed. The first set of insecticide treatments was applied immediately after the plots were uncovered. The second set of treatments was applied on 15 August. There were four replicates of four treatments, which were:

1. Cyromazine (Trigard 75WP) (225 g a.i./ha)
2. Lambda-cyhalothrin (Hallmark Zeon) (15 g a.i./ha)
3. Spinosad (Tracer 480SC) (120 g a.i./ha)
4. Untreated control

The plots were sampled on 9 October by removing 0.7 m row from the middle two rows of each plot. The foliage was discarded and the roots were washed and assessed for damage. The numbers of mines (caused by larval feeding) on each root were recorded. The data were subjected to Analysis of Variance. The percentage data (percentage plants with more than one mine) were arcsine transformed prior to analysis.

Both lambda-cyhalothrin and cyromazine reduced the percentage of damaged parsley roots ($p<0.001$) (Figure 1). However, lambda-cyhalothrin was considerably more effective than cyromazine. Spinosad was ineffective. Similar treatment effects were observed for the mean number of mines per plant ($p=0.001$) (Figure 2). Treatment with lambda-cyhalothrin and cyromazine reduced the numbers of mines per plant by 86% and 41% respectively when compared with the insecticide-free control.

Figure 1. The percentage of parsley roots with more than one carrot fly mine (back-transformed means from Analysis of Variance).

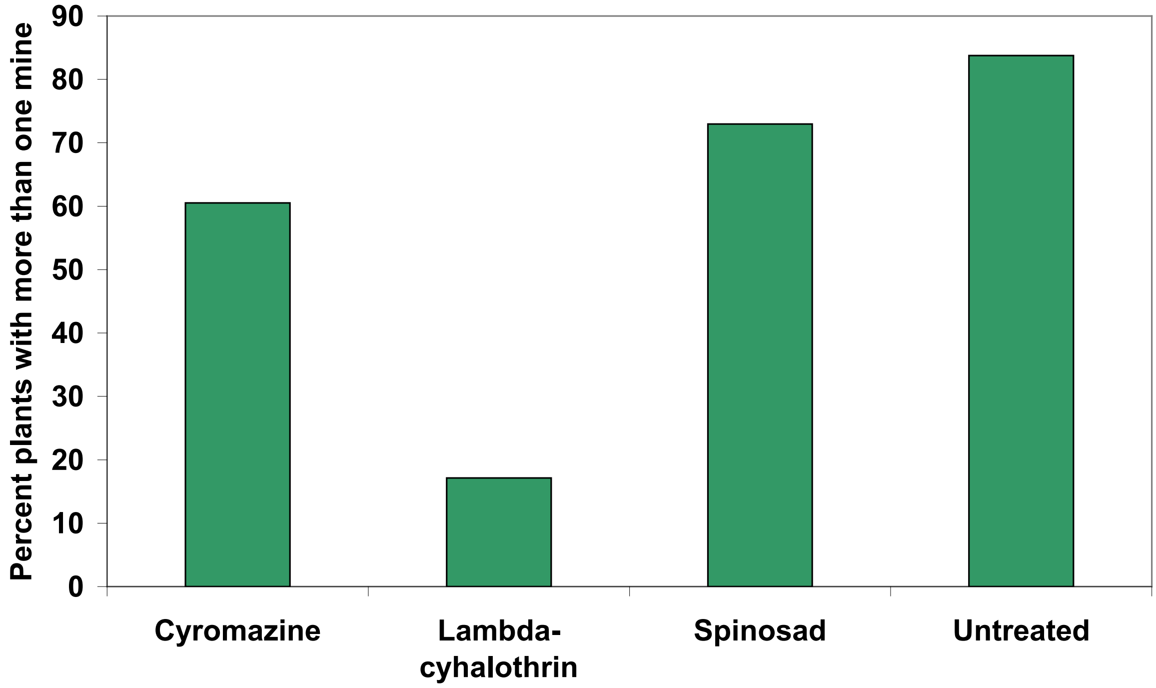
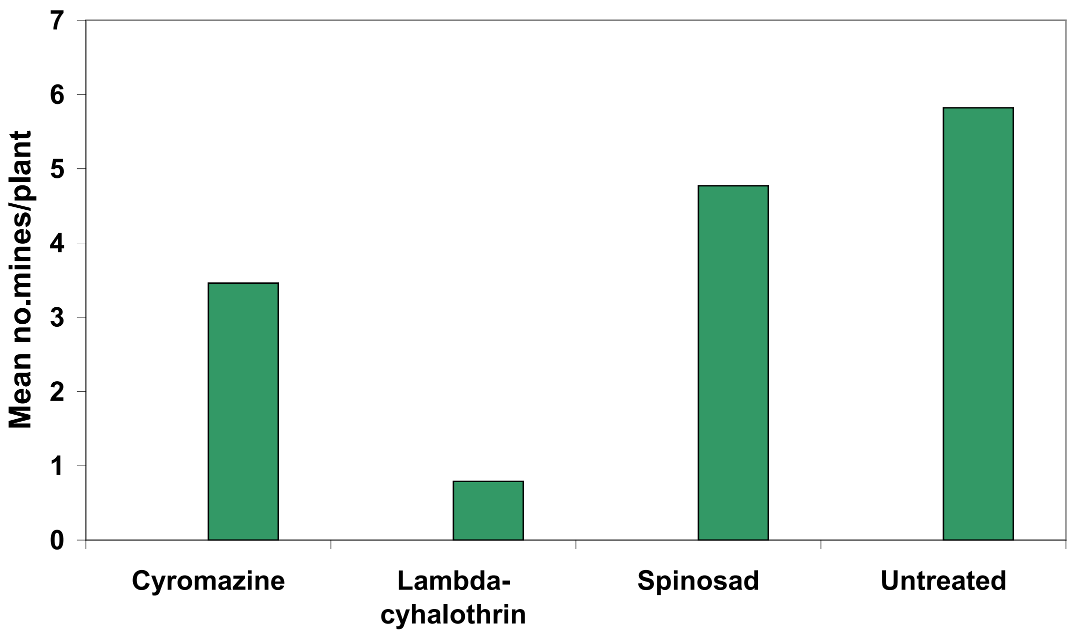


Figure 2. The mean numbers of carrot fly mines per parsley root.



In addition to this single trial, which confirmed the effectiveness of lambda-cyhalothrin, commercially-funded confidential trials done at Wellesbourne indicate that there is at least one new insecticide that has activity against carrot fly which, if approved, would provide 'alternative chemistry' for control of this pest as part of a resistance management strategy.

Seed treatments

Experiments were done at Wellesbourne during the late 1990's to determine the efficacy of a number of insecticide seed treatments against carrot fly (Blood Smyth & Finch, 1999). Carrot seed film-coated with tefluthrin (Force), at the rate of 22g a.i./100,000 seeds, gave only slight control of a high carrot fly infestation. Carrot seed film-coated with fipronil at 18g and 39g a.i./100,000 seeds, or with imidacloprid, at 21g and 43g a.i./100,000 seeds, failed to control carrot fly. In contrast, carrot seed film-coated with the OP-insecticide chlorfenvinphos, at only 16g a.i./100,000 seeds, gave good control, even of a high carrot fly infestation. Overall, the chlorfenvinphos seed treatment was about three times as effective as the comparable tefluthrin (Force) treatment.

Insecticides that have proved effective as seed treatments against cabbage root fly include spinosad, thiamethoxam, cyromazine and fipronil (Table 1). Only fipronil has been tested against carrot fly in the UK (see above). However, in the Netherlands, seven 'new' insecticides have been evaluated as seed treatments for carrot fly control since 2003. These were spinosad, thiamethoxam, clothianidin, tefluthrin, semicarbazone, beta-cyfluthrin (in the UK beta-cyfluthrin and clothianidin are available in a mixture called Poncho Beta) and abamectin (Dynamec). These were applied to seed as single treatments or sometimes in combination. They were compared with chlorfenvinphos at a rate of 10g a.i./250,000 seeds. Clothianidin (24g a.i./250,000 seeds) and thiamethoxam (10g a.i./250,000 seeds) gave comparable or even better carrot fly control than the chlorfenvinphos standard treatment. However, both insecticide treatments were slightly phytotoxic (A. Ester, personal communication).

2.3 Treatment timing

The timing of insecticide applications is likely to be optimised only when the mode of action has been clarified answering the question 'where does the insecticide need to be, and for how long'? HDC-funded research (Blood Smyth & Finch, 1999) showed that pyrethroid sprays were effective against adult carrot fly but ineffective against carrot fly larvae in the soil. This led to the development of a control strategy, which is described in an HDC Factsheet (08/01 Insecticidal control of carrot fly).

There are two generations of carrot fly throughout the UK and a partial third generation occurs at warm sites towards the south of the UK. The timing of second generation carrot fly activity can vary by 3-5 weeks from region-to-region and year-to-year and the occurrence and timing of the third generation can also vary. In addition, the timing of activity in individual fields may be influenced by drilling date and by the proximity of the crop to a source of emerging carrot flies. The occurrence of adult carrot fly can be monitored using sticky traps or predicted in advance using a weather-based forecasting system.

Monitoring adult flies with sticky traps

Carrot flies can be monitored (Finch *et al*., 1999) using orange sticky traps, which are visually attractive to adult flies. Trap performance and selectivity can be improved by angling traps at 45° to the vertical (with the sticky surface facing downwards) (Finch & Collier, 1989). Trap performance, in terms of the numbers of flies trapped, might be improved by including a volatile attractant (Stevenson & Barszcz, 1997). However, the consistency of catches could then be affected adversely due to the differential effects of weather conditions on performance of the volatile chemical (Finch, 1989; 1990). This would be particularly important if traps were to be used to determine treatment thresholds. Larger catches might be obtained more simply by increasing the numbers of traps used and this would also have benefits in that a larger proportion of the crop would be sampled.

Adult carrot flies require a period to mature their eggs following emergence. The duration of this pre-oviposition period is determined by temperature (Collier & Finch, 1996). Carrot flies may be trapped close to the emergence site before they have laid their eggs or at the susceptible crop whilst egg-laying is occurring. The timing of treatments according to carrot fly trapping is always in retrospect since the traps must be left for a period of time (usually a week) before they are assessed. If low numbers of flies are trapped then information on the timing of activity will not be very accurate (Collier & Phelps, 1994).

Carrot fly forecasts

A computer program to forecast the timing of carrot fly activity was developed with HDC-funding (Collier & Finch, 1993; Phelps *et al*., 1993). Carrot fly forecasts are run using air and soil temperatures (Collier *et al.,* 1990; Collier *et al.,* 1992). They are analogous to weather forecasts and are used to predict, from several weeks in advance, when activity is likely to occur. They can be projected forwards using long-term-average weather data or weather data from a previous warm year (to give advanced warning). At present the forecasts are used to predict 10% and 50% egg-laying activity, but could be used to predict, for example, 5% emergence or any other stage in the population's life-cycle that was required. These forecasts do not predict the severity of attack as this will depend on the size of the local insect population. A similar carrot fly forecast has been developed in Germany (Hommes & Gebelein, 1996) and a further carrot fly forecast is available from a company (Dacom) that supplies pest and disease forecasting services in Europe.

The HDC forecasts are currently available free to HDC members as part of the MORPH decision support software (to be used with their own weather data) and are also available from mid-April until early October each year on the HDC Pest Bulletin web pages (forecasts produced using weather data provided by the Met Office). Each year a limited amount of monitoring has been undertaken at Warwick HRI sites (Wellesbourne and Kirton), and by volunteers, for continued forecast validation. Forecasts can be used to time treatments in the absence of carrot fly monitoring records (this will be far more accurate than starting to treat on a fixed calendar date such as 1 August) or they can be used to indicate when sticky traps should be deployed to monitor carrot fly numbers.

At some locations carrot fly activity has occurred later than forecast and this has often been related to drilling date. Second generation activity is often ‘delayed’ in a late-drilled crop, because such a crop only provides a suitable egg laying site for carrot flies that are active towards the end of the first generation.

Distance from a source of infestation may also determine the timing of activity in a susceptible crop. If the source of flies is very close to a susceptible crop then they may arrive soon after emergence, whereas flies may take several days to reach a more distant crop. If forecasts were to be produced for individual crops then these factors could be included in them, as well as using local, grower-collected weather data.

Timing of spray treatments

In the past, Defra-funded research indicated that the first mid-season OP treatment should be applied within one week of the start of egg-laying activity. This was because, although they are applied as foliar sprays, OPs actually control newly-hatched larvae in the soil, being most effective after the insecticide had been washed by rain or irrigation into the surface layers of the soil (Blood Smyth & Finch, 1999).

Pyrethroid spray treatments - timing the first application

Treatments that kill adult flies (e.g. pyrethroids) should be applied earlier than OP insecticides, from first emergence onwards. Lambda-cyhalothrin (Hallmark) sprays applied one week before the HDC/HRI forecast for 10% (first) egg-laying gave better carrot fly control than when the first insecticide spray was triggered by the first capture of flies on sticky traps (Blood Smyth & Finch, 1999). It is important to remember that, unlike control using OP insecticides, once a pyrethroid spray regime is introduced, few, if any, flies should be caught on sticky traps. If they are, then alarm bells should ring.

Time of day

If carrot flies are in the crop at the time it is sprayed with pyrethroids, they will be killed (Blood Smyth & Finch, 1999). Females have a diurnal pattern of activity, usually leaving the shelter of field boundaries to lay their eggs (see Dufault & Coaker, 1987). To maximise the "knockdown" effect, sprays should be applied between 4-6 pm on warm days, as this is when most female flies are in the crop (Blood Smyth & Finch, 1999). Insecticide residues are also effective. In trials at Wellesbourne, on the day after lambda-cyhalothrin was sprayed, residues on the carrot foliage killed 95% of flies (Blood Smyth & Finch, 1999). Even after 18 days, the lambda-cyhalothrin residues still killed about 25% of flies. Therefore, because of this residual action, it is not crucial, but beneficial, to apply sprays in the late afternoon. Contrary to popular belief, the residues of pyrethroid sprays left on the foliage of carrot crops do not repel carrot flies, they kill them.

Intervals between applications

In trials at Wellesbourne, under a wide range of different weather conditions, residues of lambda-cyhalothrin on carrot foliage killed more than 50% of the flies/day for at least 7 days (Blood Smyth & Finch, 1999). The length of time lambda-cyhalothrin residues remain effective on carrot foliage depends upon temperature. Residues of lambda-cyhalothrin on carrot foliage killed 50% of flies/day for 10 days at the time of the first fly generation (May max/min = 18ºC/8ºC) but only for 7 days during the warmer months (July/August max/min = 23ºC/11ºC) of the second fly generation. Sprays of lambda-cyhalothrin became "rainfast" as soon as they contacted the plant foliage. The insecticide was not washed off the plants even when irrigation was applied within 1 minute of applying the spray (Blood Smyth & Finch, 1999).

Control of damage to overwintering crops

In years when there is a partial third generation, carrot fly activity can extend over many weeks and viable eggs can be laid (Coppock, 1974). However, more recent research has shown that most damage to overwintering carrots results from larvae that hatch from eggs laid in late July/early August at the beginning of the second fly generation (Blood Smyth & Finch, 1999). Unless good control is achieved at this time, it is impossible to prevent damage on carrot crops increasing during the winter months. Usually, the damage done to overwintering crops is caused by larvae that hatch from eggs laid no later than the end of September (Blood Smyth & Finch, 1999).

At present there seems to be little risk of damage from third generation carrot fly in most regions of the UK. However, in very warm years, there may be a risk of some egg hatch and larval development in crops grown in the south of the country. Climate change may increase this risk. The HDC/HRI carrot fly forecast can be used to indicate the risk of damage due to third generation flies.

<u>Carrot fly spray thresholds</u>

Carrot fly monitoring data could be used to inform growers whether a treatment was necessary or whether the pest population was too low to warrant treatment. Such treatment thresholds have been used in, for example, Denmark, the Netherlands and Canada (Esbjerg *et al.,* 1988; Ouden & Theunissen, 1988; Chaput, 1993) and are based on the numbers of carrot flies trapped per day or per week. For such a system to be effective there must be a good relationship between the numbers of flies trapped and the amount of damage the crop would suffer if left untreated. Trap placement to assess field populations accurately would be critical. Studies by Warwick HRI and others in the UK have shown that carrot fly numbers and subsequent damage are highest close to field margins and that sticky traps should be deployed taking this into account. It should be possible to use a relatively small number of traps to estimate the density and distribution of flies in a crop (Defra project HH1924TFV; R. Collier & K. Phelps, unpublished data).

2.4 Techniques for reducing the overall level of carrot fly attack

Insecticides kill only a percentage of the insects against which they are applied (Wheatley & Thompson, 1971; Bleasdale, 1981). Thus a treatment which is consistently efficient may be effective against a light to moderate pest attack but will be ineffective against a severe infestation. Growers should be at least as concerned about the levels of the carrot fly population they are seeking to control as they are about the efficiency of the insecticides they use.

The efficiency of a treatment largely determines how high the background level of damage can rise before the grower will not get the expected level of control, no matter how accurately he applies his treatments. As most growers wish to reduce crop damage to a maximum of 5% (because at levels above this the costs of grading out damaged roots would be prohibitive) there are limits above which damage to untreated carrots (i.e. the local fly infestation) cannot be allowed to rise. Wheatley & Freeman (1982) provided a nomogram relating the percentages of undamaged roots on treated and untreated carrots to the percent efficiency of treatments in reducing larval populations. Edmonds & Finch (1992) give examples for treatments of given efficiency (75-95%) of the maximum damage that an untreated crop could suffer to obtain 95 or 97% control. If, as Wheatley and Freeman (1982) suggest, carrot fly can consistently damage 40-60% of untreated carrots at a particular site, then an insecticide treatment would have to be 90-95 % efficient to give 95% fly control, and 97% control would probably be unachievable (Edmonds & Finch, 1992). The results of Defra field trials done during 1991-1993 indicated that the efficiency of mid-season OP spray treatments varied considerably and that they were, on average, only about 70% efficient.

Several techniques are available for reducing the size of the local carrot fly population and these include the use of host plant resistance, spatial separation of crops and manipulation of drilling dates. Wheatley & Thompson (1971) showed hypothetically how several of these factors could be integrated with insecticide treatments to improve the overall control of, in their case, two brassica pests. However, the same could be done on carrots and the principle has already been demonstrated experimentally by combining the effects of host plant resistance and drilling date (Ellis *et al.,* 1987*)* or resistance and reduced doses of insecticide (Thompson *et al.,* 1994*).*

Resistant cultivars

Partial levels of resistance to carrot fly exist in a number of commercially-acceptable carrot varieties. The most resistant varieties support about 50% of the insects and have about 50% of the damage compared with a very susceptible variety (Ellis *et al.,* 1984). Sytan was the most resistant variety identified initially and it performed consistently in a number of countries e.g. Finland (Kettunen *et al.,* 1988), Germany (Stein & Lehmann, 1984), Denmark, The Netherlands, Ireland, Poland (Ellis & Hardman, 1981) and New Zealand (Carpenter *et al.,* 1990).

Many of these trials have been in small plots where there is a 'choice' situation. However, Philipsen (1988) grew Danvers Half Long 126 (susceptible) and Sytan (resistant) in large field plots, closer to the normal field situation and found that varietal differences in susceptibility were maintained. He found that egg laying did not appear to be influenced by carrot variety, but that the distinct difference in the numbers of pupae produced indicated that partial resistance can be explained by antibiosis. Inoculation of different cultivars with carrot fly eggs also indicated that antibiosis was a major factor (Guerin *et aI*., 1981). Cole (1985) found that higher concentrations of chlorogenic acid in carrot roots correlated with increased susceptibility to larval damage. Chlorogenic acid may be important in the production of insect cuticle (Dufault & Coaker, 1987). Guerin & Ryan (1984) showed that non-preference resistance by ovipositing females also occurred with some varieties and Guerin & Stadler (1984) found that flies contacting foliage preferred Danvers to Sytan. Trials have shown no positive evidence of the existence of carrot fly populations (biotypes) with different responses to partially resistant carrot cultivars (Ellis & Hardman, 1981).

Sytan belongs to the Nantes group of carrots and derives its resistance from Touchon. Numerous varieties have been bred from Touchon, for example Prima-Touchon, and these appear to have inherited the same level of partial resistance. Although most of the partially-resistant varieties are Nantes types there are some carrots in this group which are very susceptible, for example, Nantes Express which is almost as susceptible as Danvers Half Long 126 (Ellis *et al.,* 1982; Ellis & Hardman, unpublished). There is considerable variation within every carrot group in varietal resistance and the resistance of new varieties should be assessed. The following varieties possess a level of resistance equal to Sytan: Ideal, Nandor, Nantucket, Prima, Fly Away, Tantal, Tip Top, Touchon, Vertou (Ellis, 1993).

About 130 species of wild umbellifer have been screened at HRI Wellesboume for their resistance to carrot fly. The most promising plants are certain wild *Daucus* species which include *D. capillifolius* from Libya. This is highly resistant to carrot fly and can be crossed easily with the cultivated carrot *D. carota.* Crosses were made between *D. capillifolius* and the carrot cultivars Sytan and Berlicum New Market Red Cored. This resulted in the production of breeding lines of several different carrot types which possessed good cropping qualities and a level of resistance 10% higher than Sytan. The breeding material was sold to commercial seed companies (Ellis, 1993). Since then, potentially carrot fly resistant carrot lines developed by some of the seed companies have been assessed at Wellesbourne. However, nothing has been evaluated at Wellesbourne in the last two years.

Commercial acceptability

Several partially-resistant varieties can be purchased by growers. Sytan last appeared on the NIAB list in 1981 and has been superseded by improved types. Fly Away was produced in the Joint Hybrid Scheme between Warwick HRI and Tozers Seeds and is similar to Sytan. It is now available to growers and gardeners. A further partially-resistant variety, Resistafly, is also available in the UK. Of those commercial varieties assessed, Nantucket, Fly Away and Nandor appeared to be the least susceptible. Narman also showed a certain amount of resistance whilst Narbonne and Nairobi were more susceptible. Information on susceptibility to carrot fly could be tied in with information from NIAB on other varietal characteristics.

Other cultural problems

There is no evidence of any problems which might arise from the use of partially-resistant varieties. Yield penalties or increased susceptibility to diseases or other pests have not been observed. Indeed in two field trials, Ellis & Hardman (Unpublished) observed that Sytan breeding lines were less infested with *Cavariella aegopodii,* the willow-carrot aphid, than many other carrot varieties.

Potential for reduced insecticide inputs

Experiments at Warwick HRI Wellesbourne have shown that the effects of a partially resistant variety and soil insecticide can be combined (Thompson *et al.,* 1994). The performance of soil-applied carbofuran and phorate was assessed on two varieties; Sytan (partially-resistant) and Danvers Half Long 126 (susceptible). In terms of carrot fly control, the effects of insecticides and partial resistance were additive. For example, when the two varieties were treated with phorate at the commercially recommended rate (60 mg a.i./m row) carrot fly damage was reduced on both varieties, but the level of attack on Danvers was still unacceptable. By using experimental continuous log-dose treatments it was shown that the dose of phorate required to give > 95 % control of carrot fly on Danvers was 80 mg a.i./m and on Sytan, 30 mg a.i./m, almost a third of the dose (Ellis *et al.,* 1990). Thus the use of partial resistance may offer opportunities for reduced doses of insecticide, or for the use of less efficient compounds, whilst still achieving comparable levels of control. In the Netherlands, in untreated plots, 94% of the susceptible variety Danvers was attacked whilst only 17% of the resistant variety, Vertou, was damaged. In plots treated with one third of the standard dose of dichlorfenvinfos the percentages of damaged roots were 74 and 2% respectively (Anon, 1986). Resistance also has the effect of delaying the build-up of damage, so a partially-resistant variety might be left in the field for a few weeks longer than a susceptible variety before damage exceeded the marketability threshold.

Crop rotation and spacing

When carrots are first grown on land remote from areas where they have been grown previously, carrot fly is unlikely to cause a problem for at least a few years, until numbers have built up, particularly if early and late crops are well-separated to break the sequence of host plants in the pest's life-cycle.

On farms where carrots are grown, about 5% of the crop is normally damaged by carrot fly during the first year of cropping (Bleasdale, 1981; Ellis, 1993). If farms continue to grow carrots the figure may rise to 15% by the second year and to more than 80% by the fifth year. Dabrowski & Legutskowa (1976) observed that when carrots were grown for two consecutive years in the same place, larval damage increased to 15% in the second year. With crop rotation only 2% of carrots were damaged.

Coaker & Hartley (1988) found that the distance of target crops from sources of carrot fly appeared to affect damage levels, indicating that flies do not travel far from the site of emergence. They suggested that the distances over which flies disperse are probably determined by features of the landscape, particularly trees, and the closeness of the subsequent crop. Crops at a distance greater than 250 m from a source field had less damage and Coaker & Hartley thought that this may be a direct consequence of trees close to the original source trapping out dispersing flies. There is other evidence (Stadler, 1972; Wainhouse, 1975) that most flies do not disperse over more than about 100 m. Some flies do travel over greater distances, as much as 4 km (Sant, 1961), but this type of dispersal may be wind-assisted. More recent research at Warwick HRI Wellesbourne (Finch & Collier, 2004) showed that relatively few carrot flies moved more than 1 km from a previously infested crop and that numbers declined steadily (and predictably) with increasing distance from the 'source' of carrot fly. Estimates of the fall-off in numbers of the carrot fly were obtained by using sticky traps to monitor changes in fly numbers in 11 small plots of carrots drilled 130–1300 m away from the site at which the flies emerged in the spring. A strong linear relationship was obtained between the $\log_{10}$ numbers of flies caught in each plot and the $\log_{10}$ distance the plot was from the emergence site. Few flies were caught more than 1 km from the emergence site. A linear relationship was also obtained between the date when 50% of the flies were caught in each plot and the distance the plot was from the emergence site. The date of 50% capture was delayed by 1 day for each 100 m the given plot was away from the emergence site. This suggests that when carrot flies move to find new crops, the population moves about 100 m per day.

Crop isolation as part of a management strategy was first considered at least 20 years ago. Wheatley & Percival (1974) suggested that consideration should be given to the possibility of moving crops more systematically from year to year, of zoning the production of early, main, and late-season crops and, especially, of avoiding a yearly overlap of carrot fly host crops in the same locality. Bleasdale (1981) indicated that it should be possible to maintain carrot fly populations at a relatively low level (5% damage) by rotating early and late crops on a farm scale. In the year following an early-harvested crop, additional reductions could be made by growing only late-drilled crops and it would be even more effective not to grow any carrots for one year thus introducing a complete break in the carrot fly life cycle. Other sources of carrot fly e.g. parsnips, should also be considered in this rotation.

Influence of wild umbellifers

More than 100 species and sub-species of umbellifer have been tested as potential carrot fly hosts (Hardman *et al.,* 1990). Less than 20% of these failed to support any carrot flies at all. Most wild species were less susceptible to carrot fly than the standard cultivated carrot and would support fewer carrot flies per plant (e.g. cow parsley, *Anthriscus sylvestris,* which supported 6% of flies compared with the standard cultivated carrot). However, one species, fools parsley, *Aethusa cynapium,* produced more carrot flies.

It is not known what contribution carrot fly populations living on wild hosts would make to carrot fly numbers in any locality although it is thought that carrot and parsnip crops are still the main sources of the pest (Bleasdale, 1981). Efforts to find carrot fly pupae around wild umbellifers growing on the edges of carrot crops were unsuccessful (S. Finch, personal communication). However, Wainhouse & Coaker (1981) estimated that emergence of flies from hemlock, *Conium maculatum,* contributed about 10% of the total population of carrot fly emerging in three fields in Norfolk in 1973.

Planning and management tools

Since, in contrast to many pest insects, adult carrot flies move relatively short distances, there is the opportunity to develop management strategies based on the isolation of new crops from sources of carrot fly. As a result of previous Defra-funded work at Warwick HRI (some in the late 70's and more recently in project Defra project HH1924TFV), there is now sufficient information to be able to estimate the risk of damage to new crops from flies leaving old crops. This information could be used to develop a planning tool for growers. The planning tool would be based on three mathematical relationships derived from the Defra-funded work:

a. An equation to estimate the total numbers of carrot fly within a field (old crop) based on a relatively small number of samples of damaged roots (HH1924TFV).

b. An equation relating carrot fly mining damage to numbers of larvae (old crop) (Wheatley & Freeman, 1982).
c. An equation to estimate the fall off in the numbers of dispersing carrot fly adults with increasing distance from an emergence site (old crop) (Finch & Collier, 2004).

These three equations could be combined in a single piece of software and used in conjunction with targeted field sampling to estimate the risk of migration of carrot fly from sources of infestation. In practice, a grower or consultant would:

- Take samples of roots from each potential source of carrot fly – using a pre-determined sampling plan. This would be a relatively small number of samples.
- Assess carrot fly damage to the roots.
- Input information into the planning software on the
    - size and location of each potential source of carrot fly (old crops)
    - amount of damage to each sample from an old crop and its position in the field
    - proposed locations and sizes of new crops

The software would then estimate the numbers of carrot fly likely to reach each new location. The technique would be applicable to all crops susceptible to carrot fly – whether grown according to organic or conventional protocols.

In theory, locating new carrot crops in areas outside the normal areas of carrot production should obviate the need for carrot fly control. However, several wild species of umbellifer are also hosts to carrot fly. Previous Defra-funded research at Warwick HRI provided an indication of the relative susceptibility of wild and cultivated umbellifers to carrot fly attack when they were exposed to carrot fly under controlled conditions. However, there is little information on natural levels of infestation in wild hosts and the risks they pose to new crops. One approach would be to:

- Survey new localities for the occurrence of wild host plants and estimate the numbers of carrot fly larvae/pupae infesting them.
- Use the planning tool described above to predict how many carrot flies will infest a new 'test' site.
- Validate predictions by planting indicator carrot crops at the test sites and monitoring fly abundance.
- Refine the crop planning tool based on findings.

<u>Influence of field margins</u>
Large numbers of carrot flies often occur in non-crop habitats around carrot fields (Baker *et al.,* 1942; Barnes, 1942; Petherbridge & Wright, 1943; Judd *et al.,* 1985) and result in high levels of damage to adjacent carrots. Legutskowa (1984) and Legutskowa & Plaskota (1986)

classified carrot crops according to the presence of various features and found the highest levels of infestation in fields with hedges/trees or with banks/ditches, and the least near agricultural horticultural crops and meadows/pastures. In British Columbia, Judd *et al.* (1985) found that populations and damage were greater in smaller or more sheltered fields and that damage was usually concentrated around field edges.

For some time, trees and bushes had been considered important (Baker *et al.,* 1942; Stadler, 1972; Brunel, 1977) for carrot fly aggregation. Then Wainhouse & Coaker (1981) examined the effect of floral content of field margins on the distribution of flies. They concluded that the herbaceous layer provided the most important physical shelter for flies and that the presence of nettles, *Urtica dioica,* was particularly critical. More recently, Coaker & Hartley (1988) confirmed that trees were of overriding importance for aggregation, mating and shelter and indicated that 'sheltered' fields (with a woodland strip along one side, or tree boundaries of any description along two sides), suffer approximately twice as much damage as 'open' fields bounded by ditches alone. Small populations of carrot flies are also found in the herbaceous vegetation of field boundaries without trees. However, their attraction to herbaceous vegetation to use food resources such as nectar in flowers does not seem to be important. Thus in addition to choosing fields well away from previously infested ones, growers should also select exposed, rather than sheltered, fields for late-lifted crops.

Management of field margins

Removal of herbage from field boundaries may lead to a reduction in damage in certain circumstances by affecting the distribution of adult carrot flies (Coaker & Hartley, 1988). However, in practice the removal of herbage is subject to severe restrictions although it is regular practice to mow along ditches. The removal of herbage from under windbreaks or woodland strips would require the use of selective herbicides and would have a major impact on non-target species.

Since carrot fly damage is usually most severe around the edges of the crop, growers may need to consider the margins and the centre of the field as two separate crops and treat them differently. The centre of the field would require fewer insecticidal treatments than the margins and early lifting of the margins would be a way of limiting damage to this part of the crop (Jonsson, 1992). On the basis that large numbers of carrot flies are concentrated at the edges of the field, some growers selectively treat field margins and/or crop headlands. The headlands, planted with a particularly carrot fly susceptible carrot variety or species of umbellifer, could be used as a trap crop and destroyed once they had become infested. The information collected at Warwick HRI Wellesbourne by Bob Ellis and colleagues on the susceptibility of wild and cultivated hosts to carrot fly could be used to identify particularly susceptible species. Of cultivated carrots, Danvers or Royal Chantenay Elite, would be two of the most susceptible cultivars. There are several other species of umbellifer which support large numbers of carrot fly including *Aethusa cynapium* (fool's parsley) (Hardman *et aI, 1990). Apium nodijlorum* (fool's watercress) has been used as an alternative to Danvers for maintaining carrot fly populations in the field at Wellesbourne and supported large numbers of insects (P.R. Ellis, personal communication). However, effective use of trap crops would involve the sacrifice of an area of productive land and the crop would require complete destruction at the appropriate time. Failure to do this would only exacerbate the carrot fly problem. The feasibility of such a technique and the relative area required should be investigated thoroughly before resources are expended in selecting or breeding more attractive varieties.

<u>Manipulation of drilling dates</u>
Susceptibility to attack varies with sowing date of the crop. Legutskowa (1984) and Legutskowa & Plaskota (1986) estimated levels of carrot fly infestation in crops drilled in Poland in March, April or May. Crops drilled in May suffered the least damage because they avoided the majority of first generation carrot fly attack.

In the UK, Coaker & Hartley (1988) showed that early sowing in March coupled with harvesting after September resulted in high levels of damage. Early sown crops became attractive to first generation adults earlier in the season and had larger roots to support larval development. Earlier sowing also affected the level of second generation damage since adults emerging from the first generation generally remain in the vicinity of the crop. In one year, a March sown crop suffered >20% damage, whilst a May sown crop 100-200m away suffered less than 5% damage at harvest, in April the following year.

Ellis *et al.* (1987) looked at the complementary effects of partial host plant resistance and the choice of sowing and harvest times using the susceptible variety, Danvers and the partially-resistant variety, Sytan. They showed that an early June sowing of both cultivars at Wellesbourne provided roots of a marketable size with least attack. Nine combinations of sowing and lifting dates provided more than 75% marketable roots of Sytan compared with only three combinations of dates for Danvers. However, none of the January or February harvests produced more than 70% undamaged roots and often considerably less.

To determine the effects of sowing date on the timing of emergence of the second generation of flies, small plots of carrots cv Nairobi were sown every two weeks from mid-March until mid-June 1999 at Warwick HRI Wellesbourne. These plots were sited close to the area containing the overwintering population of carrot fly. There were 7 treatments in total, replicated three times, and the plots were arranged in a randomised block design. Individual plots were separated by an area of bare soil of at least 4 m. Because of heavy rainfall at the end of May, the late May sowing was not made. Instead, the remaining six plots were sown on 15 June (the last sowing date).

The plots were exposed to infestation by the local population of carrot fly. The first adult carrot fly was captured between 26 and 29 April and the largest numbers of flies (>3 flies/trap/day) were captured in the period 4-27 May. In mid-July, prior to the start of the second fly generation, part of each plot (3 beds x 3 m) was enclosed within a fine-mesh netting (Enviromesh®) cage, supported by metal hoops, to record the numbers of flies that emerged from the various plots. Flies were captured between mid-July and early November on orange sticky traps (Rebell®, Swiss Federal Research Station) placed within these emergence cages. The traps were inspected every 3-4 days and replaced as necessary.

The largest numbers of flies (502/plot) emerged from the plots sown at the end of March, and the smallest numbers (13/plot) from the plots sown in mid-June. From the plots that were sown in mid-May, part-way through the first fly generation, a mean of 62 flies was caught/plot, which is equivalent to only 12% of the number of flies that emerged from the plots drilled in late March.

The timing of emergence by flies of the second generation was affected also by the date the crop was sown. The later the plots were sown, the greater the delay in emergence of the second fly generation

The carrot fly forecast (Phelps *et al.*, 1993) was adapted to account for the effect of sowing date on subsequent second generation fly emergence. It was assumed that flies will not lay eggs on a crop until at least 50% seedlings have emerged. The date of 50% seedling emergence was estimated (190 day-degrees > 0ºC; Finch-Savage, 1990) for each sowing date in the 1999 experiment, and was used to provide input to the model. Estimated seedling emergence times ranged from 20 (March) to 12 (June) days from sowing. As expected, the forecast predicted that lower numbers of second generation flies would emerge from the plots as the sowing date was delayed. There was a strong correlation between observed and forecast dates.

<u>Manipulation of lifting/strawing dates</u>
Early lifting of the entire crop cuts short the development of second generation carrot fly damage and prevents the carry over of large numbers of carrot fly larvae from one year to the next. In the UK this would probably have to be in October as work at ADAS`Arthur Rickwood suggested that November would be too late (Runham, 1993; 1994). Crops lifted before October could suffer as little as 1 % damage (Coaker & Hartley, 1988).

The carrot fly forecast model developed at Warwick HRI (Collier *et al.*, 1992) was adapted in Defra project OF0179 to produce predictions of when damage symptoms appear in carrot crops. This was compared with a day-degree forecast of damage development that had been developed previously in Sweden. Neither forecast has been validated extensively in commercial crops and both require further testing to confirm that they are robust.

Sometimes parts of the crop which are likely to be most heavily damaged are lifted earlier than the majority. Partially resistant varieties may be left in the ground longer than more susceptible ones.

Disposal of infested crops

Growers should not plough in heavily infested carrots; this will allow larvae to complete their life cycle and provide a source of infestation for subsequent crops. Carrots would need to be covered with at least 30 cm of soil to be sure that no carrot fly could emerge from them and ploughing would not provide this degree of cover (Bleasdale, 1981). Heavily infested crops should be lifted by November and fed to livestock (Gratwick, 1992).

Sacrifice crops grown at carrot fly emergence sites.

When carrot flies emerge from the soil in the spring, the crop on which they developed in the previous summer has been harvested and they must disperse if they are to find a new host crop on which to lay their eggs. It is possible that newly-emerged carrot flies could be arrested at the emergence site if a 'sacrifice' crop of young carrots was sown there. The crop could then be destroyed after the flies had laid their eggs, but before the larvae had completed their development. This technique has not been evaluated previously and it would be sensible to evaluate it on an experimental scale first.

Intercropping and companion planting

Many studies have shown that the numbers of pest insects found on crop plants are reduced considerably when plant diversity is increased within the crop. Several different hypotheses have been proposed, and following detailed studies of the behaviour of pest insects of cruciferous plants, Finch & Collier (2000) put forward a theory to explain this phenomenon. This theory proposes that the colour, size and shape of companion plants, rather than the volatile chemicals they release, determine their effectiveness in reducing insect colonisation. Although the colour, size and shape of companion plants, rather than the volatile chemicals they release, appear to determine their effectiveness in reducing insect colonisation, it is likely that volatile chemicals provide the initial stimulus to land in the vicinity of a host plant. In addition, the final decision to accept a host plant for egg laying or as a feeding site is based on contact chemical stimuli.

Results of intercropping carrots with onions have been inconsistent. Several workers were unable to demonstrate any effect on carrot fly damage (see Dufault & Coaker, 1987; Kuttunen *et al,,* 1988). Details of some of the more successful experiments are lacking (Dufault & Coaker, 1987). Uvah & Coaker (1984) obtained maximum reduction in carrot fly damage when onions were young, although levels of control were not acceptable commercially. This method was effective only against the first generation and became ineffective once the onions had begun to bulb. Intercropping carrots with French marigold (*Tagetes patula*) was ineffective. More recently, Mateeva *et al*. (2002) found that intercropping carrots with onion repelled carrot fly.

Ramert (1993) attempted intercropping carrots with lucerne *(Medicago littoralis*) and this reduced damage at two out of three sites, but also caused a reduction in yield. In a further study (Ramert & Ekbom, 1996), the lucerne and the carrots were sown at the same time, with the lucerne sown between the carrot rows. Carrot fly damage was substantially higher in the monoculture control plots than in the intercropped plots in two of the four trials. Cage experiments in a greenhouse using cultured carrot flies showed that the highest numbers of carrot fly eggs were laid in the monoculture plots in 7 out of 8 experiments. Ramert and Ekbom suggested that one approach to carrot fly control would be to sow carrots as a monoculture around the perimeter of a field and intercrop the central area. This might concentrate damage in an area where carrots could be harvested earlier to minimise damage effects.

In the Netherlands, trials were done over four years to determine whether undersowing carrots with subterranean clover (*Trifolium subterraneum*) would suppress both carrot fly and cavity spot (Theunissen & Schelling, 2000). The carrots were sown in May-June (depending on the year of the trial) and the clover seed was broadcast (15 kg per ha), either at the same time as the carrot seed was sown or up to one month later. The carrots were harvested in September (1 trial) or November (3 trials). Undersowing with clover reduced carrot fly damage to a susceptible variety by 55-84% and to a 'carrot fly tolerant' variety by 45-72%. In general, crop yield and quality were maintained and the authors concluded that yield loss due to intercropping can be prevented, provided weeds are controlled until the clover covers the open area between the carrots and suppresses the weeds.

At Washington State University, carrots were intercropped with one of five different cover crops (crimson clover (*Trifolium incarnatum*), lucerne, subterranean clover, vetch (*Vicia sativa*), white clover (*Trifolium repens*)) to determine their effects on carrot fly infestation and on crop yield (Muehleisen *et al*., 2003; Miles *et al*., 2003). The carrots were sown on 23 May in single rows spaced 2 foot apart and the cover crops were broadcase seeded over the tops of the carrots on 19 August. Adult carrot fly numbers were monitored using yellow sticky traps and from the data presented by Muehleisen *et al.,* carrot flies were active from mid June until mid September, with a distinct peak of activity in the second part of August. Therefore, it is questionable whether the cover crops would have grown sufficiently to have an impact on the majority of the infestation. Unfortunately there was no carrot fly damage to any of the plots, so it was not possible to compare treatments. However, the intercropping had no adverse effect on the carrot yield, which is perhaps understandable because the cover crops were sown so late.

Repellents

Kettunen *et al* (1988) sprinkled wood ash on the ground around carrot plants as a method for carrot fly control. Ash was spread to a depth of 0.5 cm twice during the growing period and reduced egg numbers to approximately a third of those laid on untreated carrots. Ramert (1993) tried mulching with grass or bark but these treatments were unsuccessful. Pine oil was used with little effect in New Zealand (Carpenter *et al*., 1990).

There has been some interest in treating crops with semiochemicals in the hope that these would mask attractive host plant odours, or act as repellents, and prevent pest insets entering the crop. This approach has been investigated for control of currant-lettuce aphid in salad crops (Tatchell, 2001) and the use of foliar sprays of garlic extracts has been investigated in some detail for control of cabbage root fly in brassica crops (Jukes *et al.,* 2005b). Neither of these techniques was successful, although further experiments showed that garlic granules were toxic to cabbage root fly eggs/larvae if they were placed close to the base of brassica plants (Jukes *et al*., 2005b). The experiments indicated that the relatively short persistence of this treatment was the factor likely to limit its efficacy in the field. Although garlic has been promoted as a control method for carrot fly there does not appear to be any data available from replicated trials to indicate its efficacy.

Natural enemies/biological control

The two most important parasitoids are *Chorebus gracilis* and *Basalys tritoma.* Levels of from 4-63% parasitism by *C. gracilis* have been recorded (see Dufault & Coaker, 1987). However, parasitised larvae complete feeding before the parasitoids emerge so this does not reduce damage in the current crop, although parastioids might reduce the overall population size over time. Rearing methods for both species of parasitoid have been developed (Maybee, 1956; Naton, 1968) but an attempt at introducing parasitoids in Canada was unsuccessful (Maybee, 1954). The parasitoids are likely to be very susceptible to insecticides.

The fungus *Empusa* sp. can cause high adult carrot fly mortality in some years. *Empusa muscae* is the most common species, causing up to three epizootics per year and infecting up to 60% of flies. In Denmark it was considered to be a potential agent for biological control (Eilenberg, 1983; 1988). The difficulties of this approach are that these fungal pathogens, which spread aerially, are usually costly to produce, are susceptible to environmental factors (Eilenberg & Philipsen, 1988) and only infect flies after they have laid most of their eggs (Finch, 1993).

The possibility of using entomopathogenic nematodes to control carrot fly has also been investigated on a small scale in the UK (Cyrille Verdun, personal communication). It seems that in these unreplicated trials, the differences between treated and untreated areas were not great enough to stimulate further work. Nematodes are being considered currently for the control of other horticultural pests; slugs in brassica and salad crops (G. Gowling, personal communication) and thrips in leek (current project at Warwick HRI funded by Defra).

In a study conducted by Washington State University in 2003, cover crop treatments were combined with applications of either the entomopathogenic fungus *Beauveria bassiana* or the entomopathogenic nematode *Steinernema feltiae* (Miles et al., 2003). Carrots were sown on 15 May in single rows 2 feet apart and crimson clover was drilled on 8 August in a single row between the carrots. The treatments were: fungus, nematodes, crimson clover, crimson clover + fungus, crimson clover + nematodes and an untreated control. The fungus and nematode treatments were applied on 8 August with a back-pack sprayer. The numbers of carrot flies were monitored using sticky traps. A similar trial was done at a commercial carrot farm but in this case there were additional treatments where the application timings of the fungus and the application timing and rates of the nematodes were varied. When the carrots at Washington State University were harvested, the greatest amount of carrot fly damage was in the control plots whilst the least damage occurred in plots treated with clover + fungus or clover + nematodes. However, these differences were not statistically significant. In the commercial crop, carrot fly damage was greatest in the plots treated with fungus alone at planting, whilst it was least in plots with clover alone. However, once again these differences were not statistically significant. The carrot fly infestation was very low overall and so this in itself made it difficult to distinguish between treatments.

Sterile male release

This technique has not been attempted with carrot fly although it has been used commercially in the Netherlands for onion fly control (Loosjes, 1976). Extremely large numbers of carrot fly would be required and a cost-effective rearing technique has not been perfected. Mass rearing techniques would need to be developed before sterile male release could be evaluated in the field.

Carrot flies can be reared in the laboratory and have been reared at Wellesboume, Cambridge University and in Switzerland. However, rearing conditions have not been optimised and further research would be required to develop an effective technique. This could probably be achieved in three years (S. Finch, personal communication). However, it is believed that for sterile male release to be effective the ratio of sterile: wild males would have to be 30: 1 (S. Finch, personal communication) which would require the release of extremely large numbers of insects. If, as appears likely, carrot fly cannot be reared at a density much higher than it occurs naturally (S. Finch, personal communication), extremely large volumes of carrots or rearing medium would be required and the technique would not be cost-effective.

2.5 Techniques to avoid the use of insecticides

<u>Crop covers</u>

Experimental work has shown that woven (e.g. fine mesh of polyethylene fibre) or non-woven covers (fleeces) can be used to prevent carrot fly attack (Eichin *et al.,* 1987; Haseli & Konrad, 1987a,b; 1988; Antill *et al.,* 1990; Antill & Davies, 1990). The covers can be applied at drilling or later, but must be applied before the flies start to lay eggs. Provided they are applied at the right time, the mesh size is sufficiently small and they stay intact, crop covers exclude all carrot fly. If covers are not applied until the start of the second generation then first generation carrot fly must be controlled effectively with insecticides, otherwise the use of covers may exacerbate the problem. Crop covers have been used regularly in experiments at Wellesbourne, either to exclude carrot fly from plots or confine them within certain areas. They have proved to be extremely effective.

Crop covers are now used widely to exclude cabbage root fly from swede crops, since there is no effective insecticide treatment available for cabbage root fly control on swede. The down-side of crop covers is their management and cost. The costs of netting are in the region of £3,000/ha, allowing enough surplus net for securing at the edges and for plant growth. In terms of capital cost, the net will last for up to 10 years (Ian Campbell, Wondermesh, personal communication).

Practicality especially if re-used and methods of disposal

In theory it should be possible to re-use woven crop covers (e.g. Enviromesh) many times. In trials at Hamburg University, Enviromesh remained undamaged after five years exposure to field conditions whereas non-woven fleece materials had all broken down (Anon, 1991). However, although cover re-use is feasible and is practiced by organic growers in the UK, it may not be appropriate for large scale carrot or parsnip production. Machines for lifting and re-winding crop covers are available in France and Germany (Anon, 1991). Wondermesh also make a machine to unroll and roll up the netting. Ian Campbell of Wondermesh estimates £200 per ha for putting the netting on and removing it at the end of the season.

Disposal of crop covers may be a problem. Plastics should be re-cycled or disposed of to the local authority or commercial land-fill sites. If pesticide were to be sprayed through covers then they would become contaminated and would require appropriate disposal.

Durability

Huber (1989) considered that non-woven crop covers were fragile and required careful handling whilst woven covers were stronger and did not flap in windy conditions. On the other hand, Antill & Davies (1990) thought non-woven Agryl P17 (17g/m2) to be sufficiently durable on carrots. However, experiments with this material on carrots in Defra-funded work at Arthur Rickwood demonstrated that it would tear under very windy conditions (S. Runham, personal communication). Because of this, carrot fly control was reduced. Other types of non-woven cover may be more durable and it would be worth examining those available currently.

Effect on yield and quality

Depending on when, and for how long, they are applied, crop covers may be detrimental to yield. Non-woven, Agryl P17 covers used to exclude carrot fly, from drilling or from late July, reduced yield compared with plots treated with a standard insecticide programme (Antill & Davies, 1990) and similar results were obtained from further Defra-funded work during 1992 and 1993 at Arthur Rickwood (Runham, 1993; 1994). In 1992, covers were applied from drilling and it appeared that abrasion damage to the seedlings reduced plant populations.

Woven crop covers may have less effect on yield because of better ventilation (Anon, 1991). Their effects on carrot yields have not been evaluated in the UK. However, Haseli & Konrad (1987a, b; 1988) showed that woven covers increased both total and marketable yield as well as preventing carrot fly damage. In Switzerland covers are removed two weeks before harvest to allow the crop to recover (J. Freuler, personal communication).

Effect on incidence of weeds. diseases and pests other than carrot fly

The use of crop covers encourages the germination and growth of naturally-occurring weeds. However, most work has been concerned with the effect of polyethylene covers, used to promote earliness, and these increased the number and fresh weight of naturally-occurring weeds (Bond & Burch, 1989; Bond & Walker, 1989). Peacock (1991) used Agryl P17 to protect carrots from first generation carrot fly attack and found no difference between the total weight of weeds from non-weeded plots whether they were covered or uncovered.

Crop covers will exclude other carrot pests such as cutworms and aphids provided the plants are uninfested when the covers are applied and provided the mesh size is sufficiently small. Slugs will not be excluded by crop covers. Vertebrate pests, such as birds and rabbits, are usually excluded by woven covers but not by, for example, Agryl. Eichin *et al.* (1987) found non-woven covers unsuitable for carrots, owing to the increased incidence of diseases. In Defra-funded trials at ADAS Arthur Rickwood during 1992 and 1993 there was some evidence that Agryl P17 covers increased the incidence of cavity spot (Runham, 1993; 1994).

Other pesticide applications

Once again, for weed control, the work has been done with polyethylene covers. The simplest technique is to apply pre-emergence residual herbicides prior to covering the crop. The performance of a number of herbicides used on carrots, in terms of percentage reduction in weed number and weed fresh weight, was similar under polyethylene covers and in the open (Bond & Walker, 1989). The most effective weed control under the polyethylene was achieved with broad spectrum herbicides, since surviving weed seedlings grew rapidly in the protected environment.

Measurement of the distribution of herbicide residues in the soil demonstrated that persistence was increased and movement in the soil decreased by polyethylene covers due to reduced levels of soil moisture. Increased persistence appears to offset reduced soil moisture levels so that the relative effectiveness of the herbicides is not affected. However, in other circumstances, the covered environment may affect the persistence, distribution, and activity of such chemicals.

In Defra-funded work, a very small study of phorate residues was undertaken (Mason & Paxton, 1994). Samples were taken to test whether the microclimate provided by a covered treatment (Agryl P17) had any effect on phorate residues in carrots. Samples were taken from covered and uncovered plots at Arthur Rickwood. The covers were applied at drilling and the samples were taken at harvest (8 November). There appeared to be no difference in residue levels between the covered and uncovered treatments.

The efficacy of products applied through covers has not been established and sprays may not penetrate covers effectively. Ester *et al.* (1994) investigated the influence of woven crop covers on spray penetration. They found that with application volumes of 200 l/ha, at least 50 % of the spray was intercepted by the cover. For the standard mesh size of 1.35 mm, the interception could be reduced to 20%, either by the use of air assistance, or by increasing the volume to 600 l/ha with a large droplet size. To achieve acceptable penetration on finer mesh sizes it was advisable to use 600 l/ha with air assistance.

Herbicides were used on film-covered crops of celery in an HDC-funded trial at ADAS Arthur Rickwood. Treatments applied through the cover at first emergence of weed seedlings provided better control than treatments applied at planting (Greenfield, 1989). In ADAS trials during 1992 and 1993, herbicides were applied to early carrots grown under Agryl P17 on peat soil. The herbicides were applied through the covers at 60 psi (double nonnal pressure) and all gave good weed control. However, under the covers, some treatments tended to be phytotoxic to carrots (Sally Runham, personal communication). There appears to have been no work undertaken on the application of fungicides through crop covers.

Vertical barriers

Over the years, many gardening experts have advocated the use of vertical barriers to prevent carrot fly adults invading their carrot plots. For example Lawrence Hills, the founder of Henry Doubleday Research Association, indicated that carrot flies could be deterred by erecting a fence-like barrier around three or four rows of carrots and that the barrier should be at least 70 cm high and enclose an area that is no more than 1 m wide. Suitable coverings are either fine mesh netting or polythene.

Obviously, there is a question of scale when comparing a commercial carrot crop with a few rows of carrots in a garden. However, scientists in North America and Norway have been investigating the use of vertical fences to prevent colonization by pest insets, particularly cabbage root fly (Päts & Vernon, 1999; Bomford *et al.,* 2000; Meadow & Johansen, 2005), and the technique has also been evaluated in Canada (Vernon & McGregor, 1999) and Switzerland (Wyss, 2003) for carrot fly control.

In the Canadian studies, fenced enclosures (8 x 8m) were surrounded by panels of mesh nylon window screen 1.2 m high and with a 25 cm overhang on either side. Control enclosures were left unfenced. Although the number of first generation carrot fly adults captured on yellow sticky traps was not significantly different between control and fenced enclosures, the number of second generation adults emerging within enclosures was significantly higher in control enclosures than in fenced enclosures. Vertical barriers reduced damage by 50-90%, depending on when the roots were harvested.

In the Swiss studies, the fences were 1.4 m high with an overhang of 30 cm. Such fences are made of netting and are usually placed around the edges of the crop to completely enclose it, or in some cases they have been installed in a U-shape or as a linear barrier, when the source of the pest is known. In one trial, the use of vertical fences reduced the percentage of damaged carrots from 8-9% to 1-2%.

The use of exclusion fences was evaluated further in Germany in 2004-5 (G. Siekmann, personal communication). In 2004, the fences were made of 0.8 x 0.8 mm mesh and were 1.7 m high with a 17 cm outward-facing overhang held at an angle of 45º. The fenced area was 20 x 25 m and contained plots of both radish and carrot. These fences did not reduce carrot fly damage to the carrots, nor did they reduce cabbage root fly damage to the radish when compared with the unfenced control plots. The experiment was repeated in 2005, but in this instance the overhang was lengthened to 35 cm. Again there was no effect on carrot fly damage compared with the unfenced control plots. However, cabbage root fly damage to the radish plots was reduced by 55%. Possible explanations for the failure of this control method against carrot fly were 1) that because carrot fly is a relatively weak flier there was passive drift of the insects into the enclosed area (a similar effect has been recorded for aphids in crops enclosed by barriers), 2) the carrot flies were walking over the overhang or 3) the carrot flies were flying down into the plots from nearby hedges that were > 1.7m tall (Meadow & Johansen, 1995). The latter is certainly feasible since adult carrot flies aggregate in field boundaries that contain trees (Coaker & Hartley, 1988) and were captured in relatively high numbers on sticky traps placed 6-10 m high close to trees (Freuler & Collier, 1999).

This is certainly a technique that could be evaluated, probably in the first instance for carrot fly control in organic crops. Factors that should be considered include the area that is cropped versus the height of the barrier, the effect of trees or shrubs on the field boundary (since carrot flies have been found several metres high in trees) and the use of 'trap crops', plants susceptible to carrot fly, on the outside of the barrier to arrest potential colonizers, perhaps in combination with bare soil or non-host strips. In more recent studies, researchers in Norway have been using fence netting that is impregnated with the pyrethroid insecticide deltamethrin (R. Meadow, personal communication) and this appears to have been effective against adult cabbage root flies (which is surprising since previous observations of pyrethroids have shown no effect against cabbage root fly in recent HDC projects) and are therefore very likely to be effective against adult carrot flies.

Meadow & Johansen (2005) attempted a theoretical costing for control of cabbage root fly with fences versus insecticides (Table 2).

Table 2
Comparison of costs of cabbage root fly control with exclusion fences or insecticides. The calculation is based on a 0.5 ha enclosure. The larger the area, the cheaper the fence per ha (from Meadow & Johansen, 2005). Originally costed in Euros.

Cost	
Fence	**Insecticide**
Linear metre netting = £1.17	£549.92 per ha
Fence post = £2.52	
4 years re-use of netting and poles	
0.5 ha enclosure = £251.59 per ha	

<u>Early lifting and cold storage</u>
In a previous review of methods of carrot fly control (Collier, 1995) there was a relatively large section on early lifting and cold storage of carrots, because it was suggested that, in the absence of OP insecticides, this might be one possible method of reducing carrot fly damage to overwintered carrots. Carrots are lifted early and kept in cold stores in some parts of Northern Europe and in North America. This is principally to prevent the crop being destroyed by frost but it also reduces or eliminates carrot fly damage to overwintered carrots.

Cold storage is not used widely in France but the possibility has been investigated (Villeneuve & Leteinturier, 1992).

In Sweden, a method, based on accumulated day-degrees, was developed for predicting when carrot fly damage will start to show in infested crops, so that growers could be advised of when to lift infested fields or the most heavily-infested parts of fields (usually the edges) before carrot fly larvae reduced crop quality (Jonsson, 1992). The timing of the development of carrot fly damage will vary from region to region and year to year since the rate of carrot fly development is dependent on temperature. Some preliminary work on the effects of cold storage on carrot fly control and other factors was done with Defra-funding at Arthur Rickwood (Runham, 1993; 1994). Carrots were lifted in November, which was after second generation damage had started to develop, and not all damage was avoided. However, cold storage did reduce subsequent carrot fly damage when compared with field storage under straw.

At present, large scale cold storage of overwintered carrots does not appear to be an option in the UK. The main reasons for this are 1) the poor visual appearance of stored carrots (Runham, Davies & Rickard, 1992) due to a deterioration in skin finish and silvering of the skin, 2) the potential for rotting in store (difficult to estimate how this would compare with field conditions) and 3) the significant costs of building and running storage facilities.

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