ANNUAL REPORT

To:
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Brassica: companion planting for pest control

HortLINK project HL0174
HDC Project FV 251

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February 2008

Commercial - In Confidence

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

Project title:	Brassica: companion planting for pest control
Project number:	HL0174; FV 251
Project Leader:	Rosemary Collier Warwick HRI**,** Wellesbourne, Warwick CV35 9EF
Annual report:	2007 (year 2)
Previous reports:	None
Key workers:	Marian Elliott, Andrew Jukes, Geoff Clark, Carole Wright
Location of project:	Warwick HRI**,** Wellesbourne, Warwick CV35 9EF
Project co-ordinators:	Mel Miles/ Phillip Effingham
Date project commenced:	1 October 2005
Date project completed:	31 December 2009
Key words:	Companion planting, cabbage root fly, *Delia radicum*, cauliflower, pest

Signed on behalf of: Warwick HRI

Signature:…………Simon Bright……………… ***Date***: ………27 February 2008….
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Elsoms Seeds Ltd
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GROWER SUMMARY

Headline

- A number of companion plants show promise and are undergoing further investigation.
- Growers doing there own trials are advised that if cauliflowers are not 'presented' with a sufficient amount of alternative green surfaces (companion plants) then they are likely to be more susceptible to egg-laying by female cabbage root flies.

Background and expected deliverables

UK brassica crops currently occupy about 32,000 ha, with an annual marketed value of about £160M. Cabbage root fly and aphids are some of their most important pests. Three insecticides are approved currently for control of cabbage root fly on leafy brassica crops. They are chlorpyrifos (organophosphorus insecticide (OP)) and carbosulfan (carbamate) and spinosad (Tracer), which is a relatively new insecticide.

The use of pesticides, particularly OP insecticides, is a major concern for the horticultural industry and for the public. This is for environmental reasons, for operator safety and because of the possibility of residues in food. At present, most leafy brassica crops are treated prophylactically for cabbage root fly control using chlorpyrifos.

Many researchers have shown that the numbers of pest insects found on cruciferous and other crop plants are reduced considerably when they are grown with other plant species. Earlier attempts to develop commercially viable systems of polyculture in northern Europe have often failed. This is because the companion plants chosen were too competitive with the main crop, or to a lack of detailed understanding of how insects use not only chemical cues, but also visual cues, to find their host plants.

A new theory of host plant selection indicates that it is visual cues from companion plants, particularly the amount of green surfaces, rather than the volatile chemicals such plants release, that disrupt insects from finding their host plants. In particular, the protracted time spent on the non-host plants appears to be the underlying mechanism that disrupts insects from finding host plants in diverse plantings. Stimulated by this theory, some growers have investigated the use of companion planting to control the cabbage root fly and have obtained encouraging results, but consider that scientific input is now required to develop a system that consistently produces a commercially acceptable crop under all pest pressures. Whilst most of the recent experimental work has been done on brassicas and their pest insects, the approach is likely to be applicable to other non-cruciferous crops and their pests.

The aim of this project is to use companion plants instead of insecticides for controlling the cabbage root fly in conventional (ICM) production of leafy brassica crops. The technique will form a basis for development of an Integrated Pest Management (IPM) strategy that will be applicable to other pests, crops and production systems, including organics, and may also impact on weed and disease control, through increased plant species diversity within the crop.

Summary of the project and main conclusions

The experimental work done during 2007 (Year 2) addressed Objectives 5 and 6 of the project.

Objective 5 *Develop and refine robust systems for growing brassicas and companion plants together, so that the negative effects of competition are offset by the positive effects of reduced pest numbers.*

Eight field trials were done to evaluate the companion plant species/combinations identified in 2006. The trials were done at three times during the summer, targeted at periods of peak egg-laying by the three generations of cabbage root fly, and using three appropriate cauliflower varieties. Each trial was done at a minimum of two locations (8 trials in total).

The companion plant treatments (Table 1) were selected on the basis of the results from the field trials undertaken in 2006 to determine the effect of companion plant species and number on the yield and quality of cauliflower plants. Some of the more competitive companion plants were sown at a rate of 1 per module, whilst others were sown at a rate of 4 per module. There were two control treatments: 1) cauliflower sown alone and drenched with Dursban prior to planting (positive control) and 2) cauliflower sown alone and left untreated (negative control). The plants were machine-planted at one location (Elsoms (Spalding, Lincolnshire)) and hand-planted at the other sites (Marshalls, Kirton (both near Boston, Lincolnshire), Wellesbourne (Warwickshire)) (Table 2).

Table 1. Companion plant treatments used in 2007 - including control treatments

Treatment		No. companion plants per module	Treatment
1.	Cauliflower alone (control)	None	Drenched with Dursban
2.	Cauliflower alone (control)	None	No insecticide
3.	Chard	1	No insecticide
4.	Endive	1	No insecticide
5.	Lettuce	1	No insecticide
6.	Birds Foot Trefoil	4	No insecticide
7.	Carrot	4	No insecticide
8.	Chicory	4	No insecticide
9.	Sorrel	4	No insecticide
10.	Tarragon	4	No insecticide

Table 2. Locations of trials, planting dates and cauliflower varieties grown in 2007

Planting	Location	Planting date	Cauliflower variety
1	Elsoms	27-Apr	Jerez
1	Kirton	25-Apr	Jerez
1	Marshalls	27-Apr	Jerez
2	Elsoms	06-Jul	Skywalker
2	Kirton	19-Jul	Skywalker
3	Elsoms	02-Aug	Forward
3	Marshalls	07-Aug	Forward
3	Wellesbourne	08-Aug	Forward

Initially the programme of sowing and planting went according to schedule but it was then disrupted due to the very wet weather in June-July. This meant that Plantings 2 and 3 were planted later than originally planned and Planting 3 was harvested during December-January.

Assessments were made of cauliflower and companion plant survival after one cabbage root fly generation (generally about 6 weeks after planting) and larval feeding damage to the cauliflower roots and lower stem was also assessed at this stage. The cauliflowers were then left to grow to maturity when further assessments were made of maturity date, yield and curd quality.

It was difficult to achieve the correct density of companion plants in every module. To a certain extent this depended on the companion plant seed – both its size and viability. Even if the modules contained the correct number of companion plants prior to transplanting (every effort was made to ensure this) then some of them 'disappeared' either as a result of planting or for other reasons during the first few weeks of growth (Figure 1).

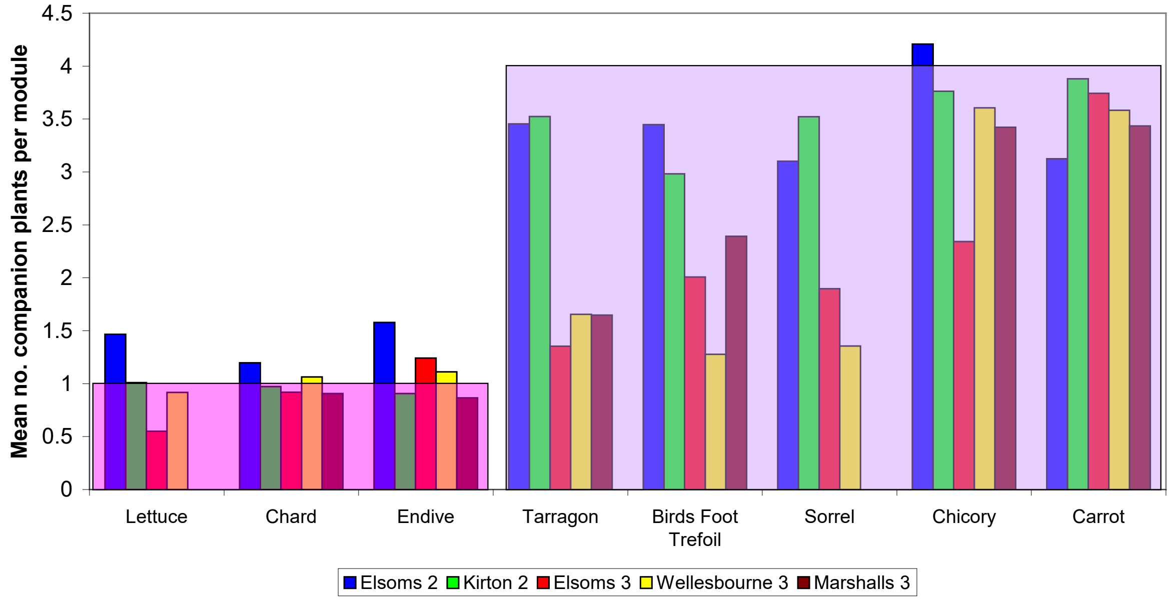

Figure 1. Comparisons between trials – mean number of companion plants per module after one generation of cabbage root fly. The coloured boxes show the target number of plants (1 or 4).

In general, the cauliflower plants treated with Dursban suffered the least larval feeding damage to the roots but none of the treatments were damaged severely by cabbage root fly (maximum score <3; score 3 represents 10-25% of damage to the surface area of the root (Figure 2)). However, the relative performance of the different companion plant treatments varied between trials.

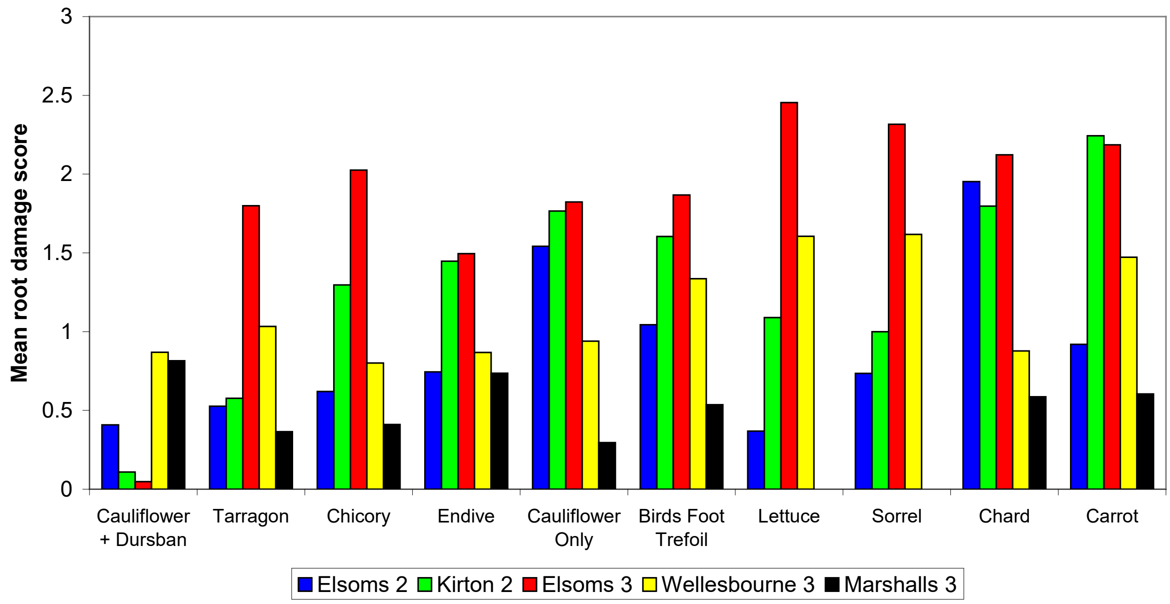

Figure 2. Comparisons between trials – mean root damage score after one generation of cabbage root fly. The damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage.

To try and understand why companion plant performance varied between trials, the mean root damage score was plotted against the mean number of companion plants (Figure 3). For the majority of companion plant types, the root damage score was inversely related to the number of companion plants, suggesting that the presence of a higher number of companion plants reduced cabbage root fly damage. Carrot and birds foot trefoil were the main exceptions.

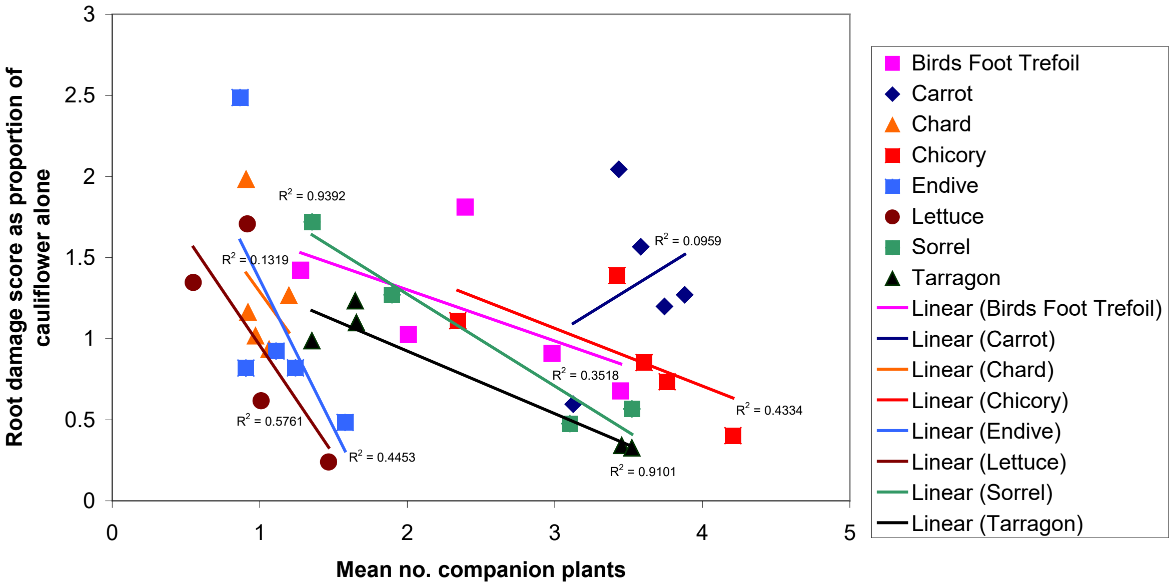

Figure 3. Comparisons between trials – relationship between mean root damage score and mean number of companion plants after one generation of cabbage root fly.

Damage to the lower stem varied between trials but was less variable between treatments than root damage (Figure 4).

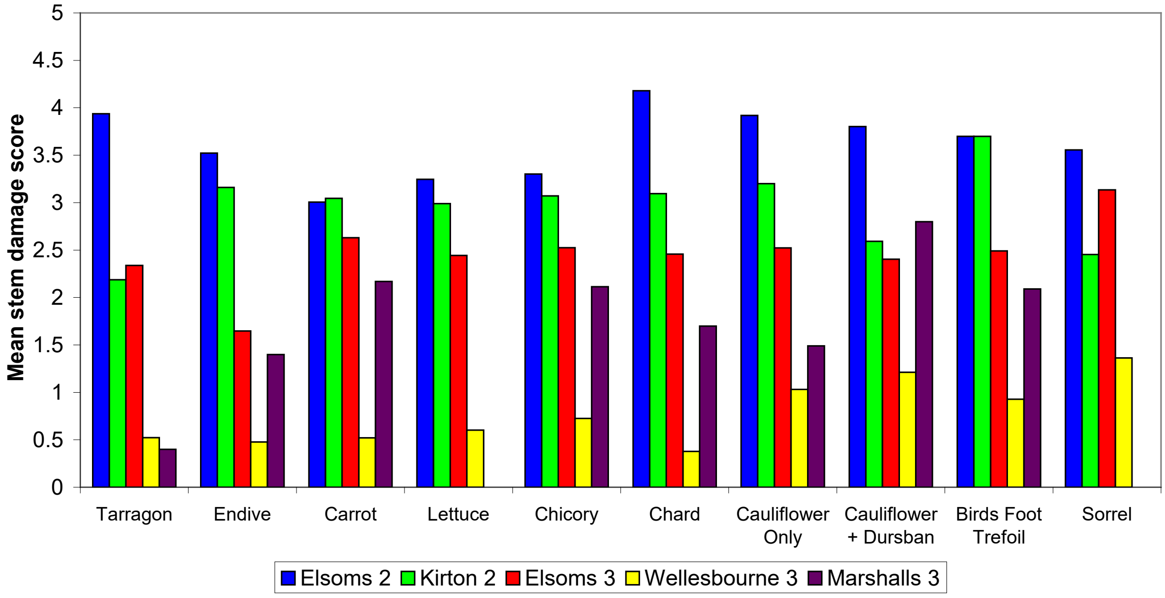

Figure 4. Comparisons between trials – mean stem damage score after one generation of cabbage root fly. The damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage.

There were also differences between treatments in the yield and quality of cauliflower curds at harvest but the differences between trials were often greater than the differences between treatments, possibly due to the extreme weather conditions that occurred during part of the summer (Figure 5).

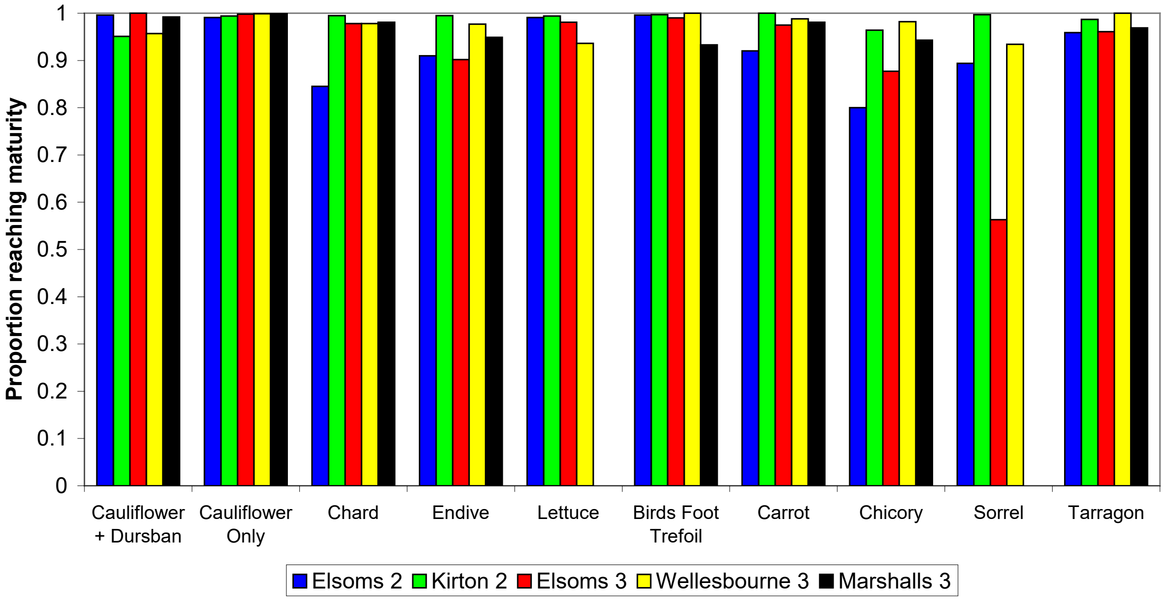

Figure 5. Comparisons between trials – mean proportion of first class curds.

The preliminary conclusions drawn from the field trials are:

- It is sometimes difficult to achieve the correct density of companion plants in every module in an experimental trial on this scale. To a certain extent this depends on the companion plant seed – both its size and viability. This is obviously also a consideration for the development of a commercially-viable system of growing brassicas with companion plants.
- Even if the modules contain the correct number of companion plants prior to transplanting then some of them may 'disappear' either as a result of planting or for other reasons during the first few weeks of growth.
- If cauliflowers are not 'presented' with a sufficient amount of alternative green surfaces (companion plants) then they are likely to be more susceptible to egg-laying by female cabbage root flies. Thus when considering the effects of the 'treatments' it is also important to take into account how close companion plant numbers were to those intended.
- Generally the cauliflower plants treated with Dursban suffered lower levels of cabbage root fly feeding damage to the roots, but this was not true for damage to the lower stem area.
- Despite the different pressures that the different types of companion plant placed on the growing cauliflowers, many of the companion plant treatments in the trials yielded good quality curds. There were considerable differences between trials in the proportion of good quality curds produced and some of these are likely to be attributable to the very variable conditions under which the trials were grown in 2007.
- Future work should concentrate on producing cauliflower plants surrounded by a relatively large and consistent area of alternative green surfaces (companion plants) to disrupt egg-laying by the cabbage root fly.
- In these trials, the plots within a block were adjacent to one another (although their order was randomised) and they were relatively narrow, being 3 plants wide. In some cases, when the plants were well-established, the companion plants from one plot 'flowed' onto the adjacent plots. It is therefore important to make plots larger and more separate as the system is scaled-up, in order to avoid 'interference' between treatments.

Objective 6 Determine how the companion plant system developed for cabbage root fly control affects 1) other pest insects.

The aim of the work done in 2007 was to determine how the companion plant system developed for cabbage root fly control might affect other pests. The experiments with *Plutella xylostella* (diamond-back moth) and *Pieris brassicae* (large white butterfly) were done in a 'rotating' cage at Warwick HRI, Wellesbourne, using insects from the Warwick HRI cultures and cauliflower plants and companion plants (carrot, chard, birds foot trefoil, lettuce) that had been grown in a greenhouse. The experiments with *Brevicoryne brassicae* (cabbage aphid) were done in large Perspex cages.

Within each cage, the insects were presented with a choice of four treatments, which consisted of pots containing a cauliflower plant alone (the control treatment) or with companion plants. Once the plants were in place, fixed numbers of insects were released into each cage. After 24 hours, the plants were removed from the cages, labelled by treatment and the cauliflower and companion plants were inspected carefully to record the number of eggs laid (*Plutella xylostella*, *Pieris brassicae*) or the numbers of winged and wingless aphids (*Brevicoryne brassicae*).
Pieris brassicae females laid most of their eggs on the cauliflower plants, although, unusually, a few eggs were laid on the carrot companion plants in one of the experiments. On average, they laid more eggs on the cauliflower plants surrounded by bare soil than on those presented with companion plants.

Plutella xylostella females did not discriminate between cauliflower plants and companion plants as oviposition sites and in general, the cauliflower/companion plant combinations were preferred to the cauliflower plants surrounded by bare soil.

Brevicoryne brassicae females appeared to have an equal preference for the cauliflower plants whether or not they were presented with companion plants. They did not settle and reproduce on any of the companion plants themselves.

The behaviour of the three test insects was variable between replicates and further testing is required. The results for *Pieris brassicae* are consistent with a previous study (Finch & Kienegger, 1997), indicating that the egg-laying by this butterfly can be disrupted by the presence of companion plants. The results for *Plutella xylostella* are also consistent with previous observations, that it is one of the brassica pest species whose colonisation behaviour is least affected by the presence of companion plants (Finch & Kienegger, 1997; D. George and R. Collier, unpublished data) and which will lay its eggs on other surfaces apart from those of its brassica host plants (R. Collier, unpublished data). The results for *Brevicoryne brassicae* are more unexpected, since the study by Finch & Kienegger and a subsequent study at Warwick HRI presenting *B. brassicae* with cabbage plants in a background of weeds (R. Collier, unpublished data) showed that colonisation was disrupted considerably by the presence of alternative green surfaces.

Reference

Finch, S. & Kienegger, M. (1997). A behavioural study to help clarify how undersowing with clover affects host-plant selection by pest insects of brassica crops. *Entomologia experimentalis et applicata* **84**, 165-172.

Financial benefits

- UK brassica crops currently occupy about 32,000 ha, with an annual marketed value of about £160M. Without adequate insecticidal control, it is estimated that about 24% of the plants in field brassica crops would be rendered unmarketable by the cabbage root fly
- Companion planting costs depend on the cost of companion plant seed and the method used. In Marshalls' 2002 trials, companion planting with cauliflower cost £25-60/ha (4 companion plants/module), so costs could be less than Gigant seed treatment.
- There is likely to be little additional financial return compared with current prices. However, it is essential for growers to continue to seek methods of reducing pesticide usage, simply to remain competitive in the market.
- The other benefits of non-chemical insect control will far exceed any savings in production costs by maintaining and improving consumer confidence in the integrity of UK vegetable production and ensuring safe working conditions for operatives under Health and Safety legislation, particularly those working in glasshouses.
- If shown to be effective, the market potential of this technique is excellent, since it reduces the risk of insecticide residues in produce and has environmental benefits.
- If shown to be effective, then grower uptake of this technique could be very high and in theory it could be applied to all leafy brassica crops (32,000 ha). A reduction in the risk to propagators of using insecticides would be viewed very favourably. Customer acceptance of reduced pesticide use would also be high and such a technique should improve the market potential of crops grown in this way and could be used as a basis for promoting the purchase of brassica vegetables. This would have a beneficial effect on growers, propagators and seed producers.

Action points for growers

- These are the results from the second year of a four-year project to use companion plants for controlling the cabbage root fly in conventional (ICM) production of leafy brassica crops. They have confirmed that:
    - There are a number of plant species that could potentially be used as companion plants without affecting the yield, quality and maturity time of cauliflower adversely.
    - If cauliflowers are not 'presented' with a sufficient amount of alternative green surfaces (companion plants) then they are likely to be more susceptible to egg-laying by female cabbage root flies. Thus when considering the effects of the 'treatments' it is also important to take into account how complete the companion plant treatments were.

- Further work is required to refine the technique under field conditions and verify that companion plants are effective in this situation.

SCIENCE SECTION

Introduction

UK brassica crops currently occupy about 32,000 ha, with an annual marketed value of about £160M (Defra Basic Horticultural Statistics). Cabbage root fly and aphids are some of their most important pests. Three insecticides are approved currently for control of cabbage root fly on leafy brassica crops. They are chlorpyrifos (organophosphorus insecticide (OP)) and carbosulfan (carbamate) and spinosad (Tracer) which is a relatively new insecticide.

The use of pesticides, particularly OP insecticides, is a major concern for the horticultural industry and for the public. This is for environmental reasons, for operator safety and because of the possibility of residues in food. At present, most leafy brassica crops are treated prophylactically for cabbage root fly control using chlorpyrifos.

Many researchers have shown that the numbers of pest insects found on cruciferous and other crop plants are reduced considerably when they are grown with other plant species (Andow, 1991). Earlier attempts to develop commercially viable systems of polyculture in northern Europe have often failed. This is because the companion plants chosen were too competitive with the main crop, or to a lack of detailed understanding of how insects use not only chemical cues, but also visual cues, to find their host plants. A new theory of host plant selection (Finch & Collier, 2000), indicates that it is visual cues from companion plants, particularly the amount of green surfaces, rather than the volatile chemicals such plants release, that disrupt insects from finding their host plants. In particular, the protracted time spent on the non-host plants appears to be the underlying mechanism that disrupts insects from finding host plants in diverse plantings (Finch et al., 2003; Morley et al., 2005). Stimulated by this theory, growers have investigated the use of companion planting to control the cabbage root fly and have obtained encouraging results, but consider that scientific input is now required to develop a system that consistently produces a commercially acceptable crop under all pest pressures. Whilst most of the recent experimental work has been done on brassicas and their pest insects, the approach is likely to be applicable to other non-cruciferous crops and their pests.

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 (Andow, 1991). Several different hypotheses have been proposed and in 2000, following detailed studies of the behaviour of pest insects of cruciferous plants, Stan Finch and Rosemary Collier put forward their theory (Finch & Collier, 2000) 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.

Much of the evidence to support this theory was provided from insect behaviour studies done at Warwick HRI during collaborations between Stan Finch and three visiting workers/students. Although this work has been based on cruciferous plants and their pests, the results are relevant to crops from other plant families. Key findings to support this theory are that:

- Searching insects land on green surfaces, but avoid brown surfaces such as the soil.
- Artificial green plants or green paper (releasing no volatile chemicals) are as effective as companion plants as living green plants. The insects do not appear to discriminate between green surfaces on the basis of differences in colour or odour.
- Aromatic companion plants are no more effective than less pungent species and pest insects do not avoid the foliage of aromatic plants.

The theory proposes that the host plant selection process occurs as follows:

a) Plant odours stimulate searching insects to land.
b) The insects land on any green object (but avoid brown objects such as bare soil). Whilst landing, they do not differentiate between the greens, or the odours, of host and non-host plants. Therefore the insects may land on a host plant (appropriate landing) or on a non-host plant (inappropriate landing).
c) The insects that make inappropriate landings remain on the plant for some time and then fly off. They may repeat the process, or they simply leave the area.
d) Once an insect lands on a host plant it then assesses the suitability of the plant using chemical receptors on its feet and mouthparts. This may involve the insects making short flights from leaf to leaf. On plants surrounded by bare soil, most of the insects land back on the same plant (appropriate landing). On plants surrounded by non-host plants, some insects land on the non-host plants (inappropriate landing) and then leave.

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. Thus, although this study will focus on the visual aspects of host plant selection, it will take into account the possible contributory role of volatile and contact chemicals.

Increased plant diversity within the crop will also impact on the diversity and activity of the natural enemies of pest species. Some studies indicate that the effects of plant diversity on pests and their natural enemies are complementary, whilst others indicate that they are antagonistic (Andow, 1991). The proposed project should provide new information to determine whether diversity *per se* helps natural enemies to control pest insect species, as despite what many organic growers believe, this is still debatable. This can be achieved by fairly simple manipulative experiments, in which pest infested plants are placed in bare soil and diverse crop situations to monitor levels of parasitism (Richards, 1940). Similarly, by placing plants infested with pest insects into bare soil and diverse backgrounds it should be possible to determine whether predation is higher on infested plants surrounded by non-host plants than on plants surrounded by bare soil.

The aim of this project is to use companion plants instead of insecticides for controlling the cabbage root fly in conventional (ICM) production of leafy brassica crops. The technique will form a basis for development of an Integrated Pest Management (IPM) strategy that will be applicable to other pests, crops and production systems, including organics, and may also impact on weed and disease control, through increased plant species diversity within the crop. The two objectives addressed during this reporting period are:

5. Develop and refine robust systems for growing brassicas and companion plants together, so that the negative effects of competition are offset by the positive effects of reduced pest numbers.

6. Determine how the companion plant system developed for cabbage root fly control affects 1) other pest insects.

Experimental

5. Develop and refine robust systems for growing brassicas and companion plants together, so that the negative effects of competition are offset by the positive effects of reduced pest numbers.

The aim of these trials was to evaluate the companion plant species/combinations identified in 2006. The plan was to undertake trials at three times during the summer, using three appropriate cauliflower varieties and, if possible, to locate each trial at three sites (Table 3). The consortium members involved in this trial were Elsoms (Elsoms Seeds Ltd), Fountains (R. Fountain and Son) and Marshalls (Marshall Brothers (Butterwick) Limited)

Table 3. Target sowing and planting dates for the 2007 field trials.

Planting / fly generation	Sowing date	Planting date	Cauliflower variety	Potential sites
1	Early Feb	Late April	Jerez	Elsoms, Marshalls, Kirton
2	15 May	Late June	Skywalker	Elsoms, Marshalls, Kirton
3	Early June	Mid July	Forward	Elsoms, Marshalls, Kirton

The treatments are shown in Table 4. These were selected on the basis of the results from field trials undertaken in 2006 to determine the effect of companion plant type (species/variety) and number on the yield and quality of cauliflower plants. Some of the more competitive companion plants were sown at a rate of 1 per module, whilst others were sown at a rate of 4 per module. There were two control treatments: 1) cauliflower sown alone and drenched with Dursban prior to planting (positive control) and 2) cauliflower sown alone and left untreated (negative control). Appropriate varieties of cauliflower were chosen for the three sowing dates

The trays for all three trials were sown according to schedule by Elsoms. One 308 tray was sown per treatment per site per occasion. The plan was to pass the trays to Fountain's nursery once the seedlings had emerged, so that the plants could be raised according to commercial practice. This worked well until the wet weather arrived in June and then the nursery was very short of space for new plants, so some of the trays remained at Elsoms until they were ready to transplant.

Table 4. Companion plant treatments used in 2007 - including control treatments.

Treatment	No. companion plants per module	Treatment
11. Cauliflower alone (control)	None	Drenched with Dursban
12. Cauliflower alone (control)	None	No insecticide
13. Chard	1	No insecticide
14. Endive	1	No insecticide
15. Lettuce	1	No insecticide
16. Birds Foot Trefoil	4	No insecticide
17. Carrot	4	No insecticide
18. Chicory	4	No insecticide
19. Sorrel	4	No insecticide
20. Tarragon	4	No insecticide

Trial design

The trials were laid out as randomised blocks with 3 replicates of each treatment per site and each replicate consisted of 3 rows x 16 plants. Actual planting dates and trial locations are shown in Table 5.

Table 5. Actual planting dates and locations of trials in 2007.

Planting	Location	Planting date
1	Elsoms	27-Apr
1	Kirton	25-Apr
1	Marshalls	27-Apr
2	Elsoms	06-Jul
2	Kirton	19-Jul
3	Elsoms	02-Aug
3	Marshalls	07-Aug
3	Wellesbourne	08-Aug

Planting 1 went well and the three trials were planted on time at the three locations. Planting 2 was delayed due to the very wet weather and in the end was planted at two sites (Elsoms & Kirton), partly because of the weather and partly because of a shortage of plants with the correct number of companion plants in the trays. Planting 3 was delayed, again partly due to the weather, but also to separate it from Planting 2. In all cases, the plants were sorted prior to planting to ensure that the cauliflowers were planted with the correct number of companions of each plant type.

The trials at Elsoms were machine planted and the others were hand planted. The trials at Elsoms, Kirton and Wellesbourne were irrigated.

Assessments

Because of the weather-induced delays, cauliflower cutting continued until early January 2008. The assessments made are listed below.

At transplanting

- Numbers of companions/cauliflowers in each module in one tray

After one cabbage root fly generation (approximately 4-6 weeks from planting)

- Number of dead/wilting cauliflower plants
- Number of surviving cauliflower and companion plants
- Destructive sample to assess root damage (15 plants per plot)
- Weight of roots and foliage
- Assessment for the presence of other pests

At maturity

- Maturity date, size, condition of each curd and number of surviving companion plants (30 plants per plot)
- Assessment for the presence of other pests

Analysis

The companion planting trials were designed as partially balanced incomplete blocks and residual maximum likelihood (REML) has been used to analysis all variables. REML was chosen as it allows for use of the full blocking structure in the analysis. The treatment effects were tested with a Wald Statistic and a summary of the results is presented in the tables. Pair-wise comparisons were only calculated where a statistically significant treatment effect was identified.

Results

Figures 6-10 show different stages of the trials.

Figure 6. Cauliflower and carrot companion plants – April 2007

Figure 7. Planting the first trial at Elsoms on 26 April 2007.

Figure 8. Cauliflower and carrot companion plants at Elsoms on 26 April 2007.

Figure 9. Second trial at Elsoms on 26 July 2007

Figure 10. First trial at Kirton on 13 June 2007.

<u>Transplanting - numbers of companions/cauliflowers in each module in one tray</u>

Figure 11 shows the percentage of cells with the correct number of cauliflower and companion plants at Planting 2 (assessed on 28 June 2007). This demonstrates how difficult it was to achieve the 'correct' companion plant count in a cell.

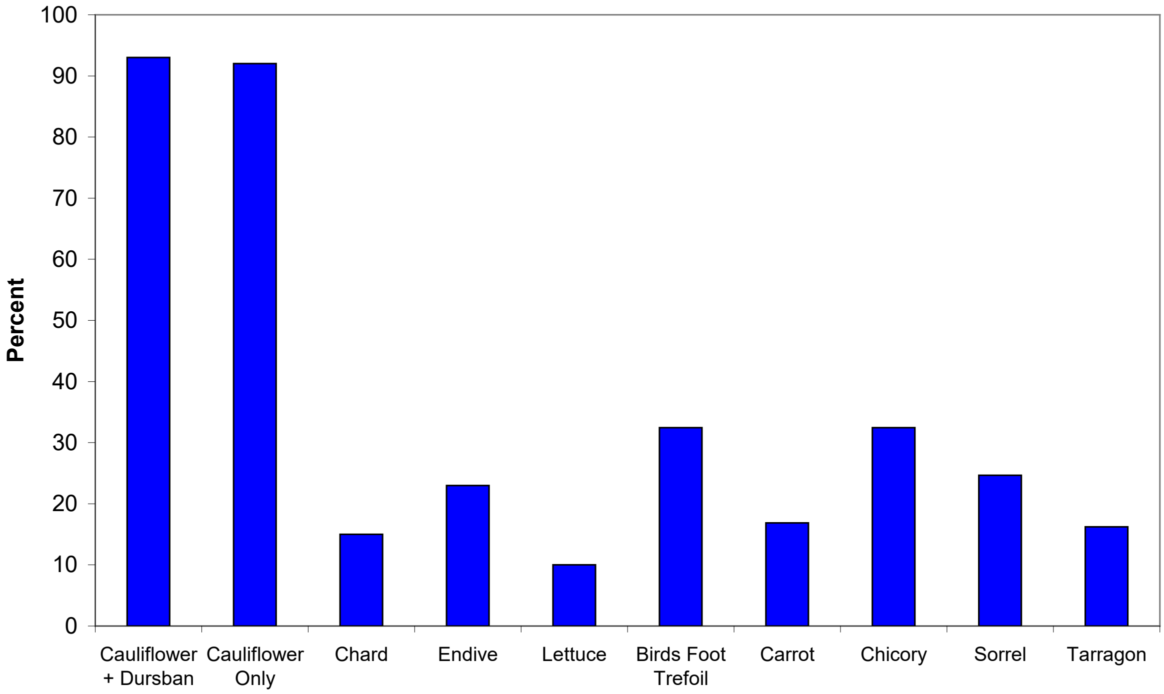

Figure 11. The percentage of cells in a 308 tray with the correct number of cauliflower and companion plants (Planting 2).

Plant counts and plant weights after one generation of cabbage root fly

A full analysis is presented for one of the trials, Elsoms 2, and then comparisons are made with some of the key results from the other trials in a later section.

Weight of companion plants

The mean weight of companion plants per module was calculated for each plot and $\log_{10}$ transformed before being analysed using REML. A coefficient of variation (CV) was also calculated for each plot based on the companion plant weights in each module. The CV is expressed as a percentage and calculated as the plot standard deviation divided by the plot mean and gives an indication of the variation of companion plant weights within each plot. Working with the CV rather than the standard deviation allows for the different mean weights of the companion plants.

The results are summarized in Table 6 and Figure 12. The results suggest that the weight of the birds foot trefoil plants was lower than all other companion plant treatments. The non-significant treatment effect for the CV analysis suggests the relative spread of weights was similar for each treatment.

Table 6. Elsoms 2 - mean weight of companion plants per module after one generation of cabbage root fly. Back-transformed means are shown in italics. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

Treatment	Companion plant weight			CV
Chard	1.875	d	*74.96*	75.04
Endive	1.877	d	*75.36*	85.69
Lettuce	1.868	d	*73.72*	87.23
Birds Foot Trefoil	1.081	a	*12.06*	92.28
Carrot	1.404	b	*25.38*	56.40
Chicory	1.859	d	*72.33*	50.71
Sorrel	1.780	cd	*60.22*	61.26
Tarragon	1.529	bc	*33.82*	82.48
χ- prob	<0.001			0.387
Wald Statistic	83.66			7.41
SED (average)	0.1202			22.32
LSD (average)	0.2578			47.87
df	7			7

Weight of cauliflower plants

The mean weight of the cauliflower plants in each plot is summarized in Table 7 and Figure 12.

Table 7. Elsoms 2 - mean weight of cauliflower plants after one generation of cabbage root fly. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

Treatment	Mean cauliflower weight		CV	
Cauliflower + Dursban	67.04	cd	40.72	a
Cauliflower alone	66.78	cd	64.50	ab
Chard	37.89	abc	56.12	ab
Endive	30.56	ab	54.98	ab
Lettuce	51.87	abcd	59.69	ab
Birds Foot Trefoil	78.99	d	48.65	a
Carrot	38.65	abc	80.29	b
Chicory	34.62	ab	80.22	b
Sorrel	27.16	a	65.49	ab
Tarragon	59.32	bcd	57.49	ab
χ- prob	<0.001		0.037	
Wald Statistic	28.70		17.83	
SED (average)	14.11		12.50	
LSD (average)	29.65		26.26	
df	9		9	

The significant treatment effect for the CV suggests that the carrot and chicory treatments had a higher level of variation relative to the mean of the weights than both the cauliflower + Dursban and birds foot trefoil treatments.

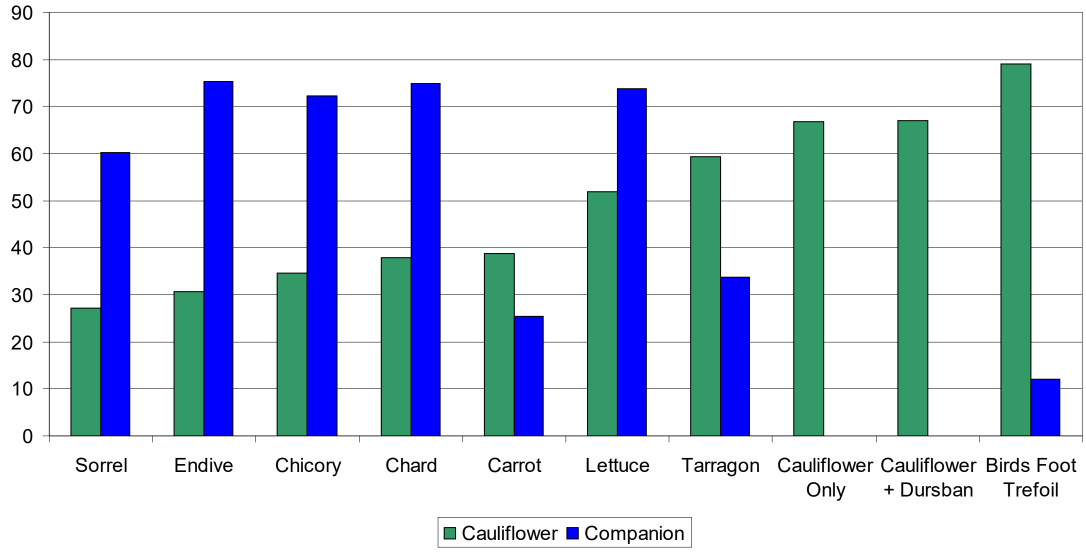

Figure 12. Elsoms 2 - the mean weight of cauliflower and companion plants after one generation of cabbage root fly.

Companion Plant Count

The mean number of companion plants per module was analysed using REML (Table 8, Figure 13). It was intended that the modules containing chard, endive and lettuce should have one companion plant, while the modules with birds foot trefoil, carrot, chicory, sorrel and tarragon would have 4 plants. The analysis showed that carrot and sorrel had significantly less plants than chicory, when the intention was for each of these treatments to have 4 plants. No statistically significant difference in the mean number of plants was found between chard, endive and lettuce. However, the CV was significantly higher for chard.

Table 8. Elsoms 2 - mean number of companion plants after one generation of cabbage root fly. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Mean Companion Plant Count		CV	
Chard	1.197	a	86.02	c
Endive	1.579	a	41.97	ab
Lettuce	1.467	a	50.40	ab
Birds Foot Trefoil	3.447	bc	45.18	ab
Carrot	3.125	b	25.83	a
Chicory	4.207	c	36.08	ab
Sorrel	3.102	b	44.13	ab
Tarragon	3.454	bc	66.67	bc
χ- prob	<0.001		0.002	
Wald Statistic	86.48		22.23	
SED (average)	0.4366		15.27	
LSD (average)	0.9365		32.75	
df	7		7	

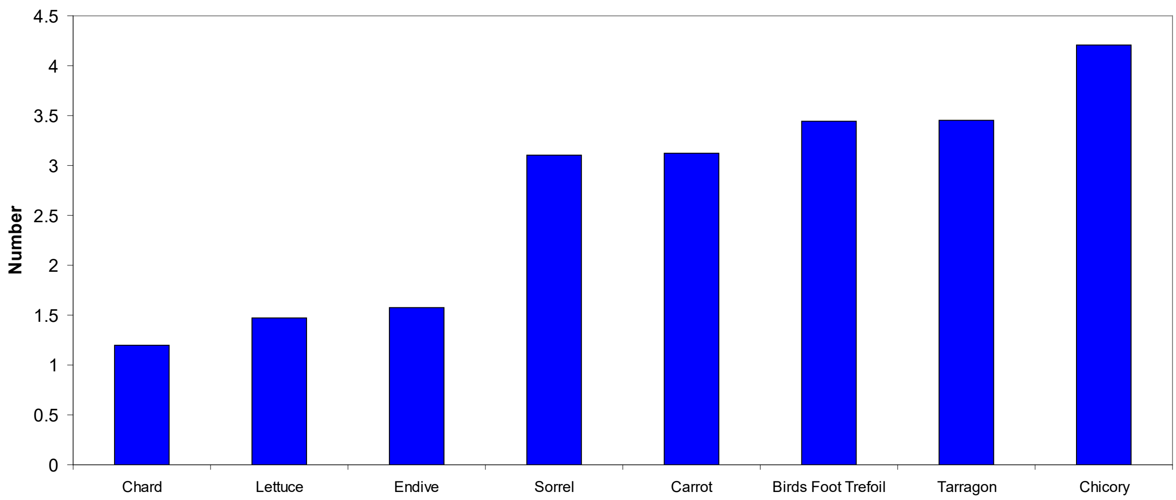

Figure 13. Elsoms 2 – the mean number of companion plants per module after one cabbage root fly generation.

The proportion of modules with the correct number of companion plants was analysed, together with the proportion of modules with fewer companion plants, and the proportion with more companion plants, than intended (Table 9). No transformation was required to analyse these proportions. The sum of these three proportions will not be one, as random block terms were included in the model, which resulted in adjustments to the proportions in each plot.

The mean proportion of modules with the correct number of companion plants was less than 0.5 (50%) for all treatments and lowest for sorrel with just 0.1. As may be expected, the treatments intended to have one companion plant tended to have a lower proportion with fewer than expected plants, and a higher proportion with more plants than intended.

Table 9. Elsoms 2 - mean proportion of modules with 1) the correct number of companion plants, 2) fewer or 3) more companion plants than intended (after one generation of cabbage root fly). Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Proportion with Correct Count		Proportion with Fewer Plants		Proportion with More Plants	
Chard	0.251	abc	0.349	c	0.460	bc
Endive	0.437	c	0.024	a	0.518	bc
Lettuce	0.412	c	0.099	ab	0.540	c
Birds Foot Trefoil	0.185	ab	0.593	d	0.201	ab
Carrot	0.387	c	0.609	d	0.024	a
Chicory	0.309	bc	0.278	bc	0.364	bc
Sorrel	0.102	a	0.700	d	0.200	a
Tarragon	0.211	ab	0.488	cd	0.311	abc
χ- prob	<0.001		<0.001		0.010	
Wald Statistic	34.88		70.51		18.47	
SED (average)	0.0763		0.1114		0.1526	
LSD (average)	0.1634		0.2389		0.3273	
df	7		7		7	

Root weight

The total weight of cauliflower roots (including the lower part of the stem) per plot was recorded. The analysis showed that the cauliflower + Dursban and birds foot trefoil treatments had high root weights, but these were not significantly higher ($p<0.05$) than the weights of roots from the cauliflower alone, lettuce and tarragon treatments (Table 10; Figure 14).

Table 10. Elsoms 2 - the total weight of cauliflower roots (including the lower part of the stem) per plot after one generation of cabbage root fly. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Cauliflower root weight per plot	
Cauliflower + Dursban	57.97	e
Cauliflower alone	52.10	de
Chard	27.99	ab
Endive	26.42	a
Lettuce	50.86	cde
Birds Foot Trefoil	57.00	e
Carrot	30.72	abcd
Chicory	29.07	abc
Sorrel	21.49	a
Tarragon	49.34	bcde
χ- prob	<0.001	
Wald Statistic	32.33	
SED (average)	10.50	
LSD (average)	22.06	
df	9	

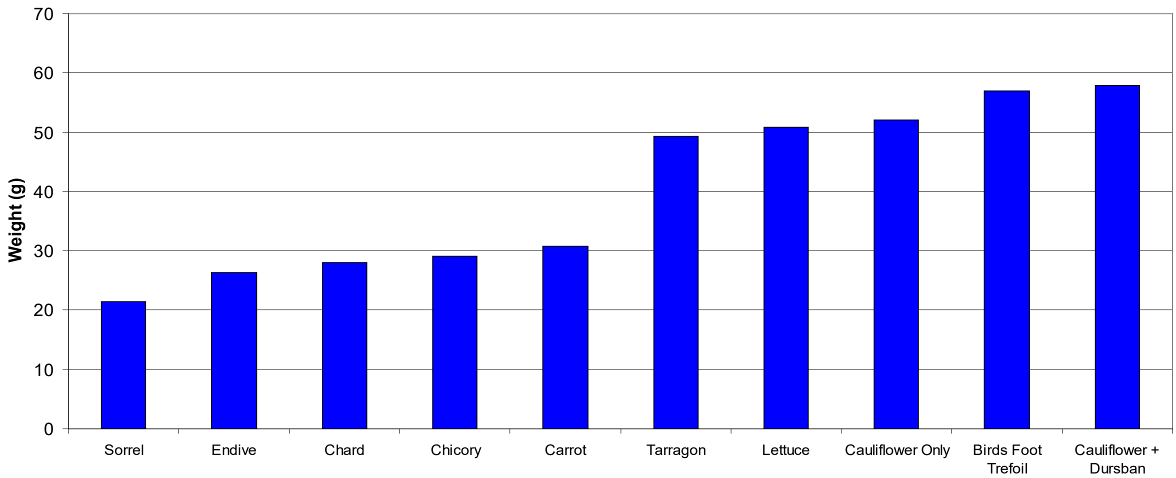

Figure 14. Elsoms 2 - the total weight of cauliflower roots (including the lower stem area) per plot after one generation of cabbage root fly.

Damage to the cauliflower stems

Cabbage root fly feeding damage to the lower stem area on each plant was scored on a scale of 0-5. The stem damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage. These data were analysed, together with the cumulative proportion of stem damage. An angular transformation was required for the cumulative proportions.

No statistically significant treatment effects were identified for the higher damage scores and the results suggest that a higher proportion of cauliflowers grown with carrots showed no sign of stem damage (Table 11).

Table 11. Elsoms 2 - the proportion of cauliflowers per plot with damage to the lower stem. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Proportion with Stem Damage =								
	0		1	2		3		4	5
Cauliflower + Dursban	0.000	a	0.123	0.026	ab	0.261	e	0.158	0.422
Cauliflower alone	0.000	a	0.023	0.172	bcd	0.142	abcd	0.167	0.444
Chard	0.000	a	0.030	0.130	abcd	0.220	cde	0.113	0.597
Endive	0.026	a	0.032	0.214	cd	0.253	de	0.179	0.323
Lettuce	0.079	ab	0.090	0.129	abcd	0.214	bcde	0.223	0.300
Birds Foot Trefoil	0.072	ab	0.020	0.152	abcd	0.098	a	0.173	0.499
Carrot	0.177	b	0.087	0.107	abc	0.128	abc	0.101	0.356
Chicory	0.034	a	0.090	0.168	abcd	0.150	abcde	0.272	0.247
Sorrel	0.020	a	0.063	0.280	d	0.101	ab	0.105	0.460
Tarragon	0.043	a	0.060	0.015	a	0.182	abcde	0.152	0.540
χ- prob	0.005		0.831	0.018		0.005		0.209	0.276
Wald Statistic	23.40		5.04	19.95		23.87		12.08	10.99
SED (average)	0.0527		0.0672	0.0745		0.0538		0.0669	0.1433
LSD (average)	0.1127		0.1412	0.1565		0.1129		0.1405	0.3011
df	9		9	9		9		9	9

Analyses of the cumulative proportions of cauliflowers with stem damage showed no statistically significant differences between the companion plant treatments (Table 12).

Table 12. Elsoms 2 - the cumulative proportion of cauliflowers per plot with damage to the lower stem. Back-transformed means are shown in italics.

Treatment	Cumulative proportion with stem damage							
	<= 1		<= 2		<= 3		<= 4	
Cauliflower + Dursban	14.255	*0.061*	18.418	*0.100*	38.041	*0.380*	50.183	*0.590*
Cauliflower alone	4.749	*0.007*	25.571	*0.186*	34.968	*0.328*	49.004	*0.570*
Chard	4.934	*0.007*	21.882	*0.139*	34.937	*0.328*	37.891	*0.377*
Endive	12.432	*0.046*	28.826	*0.232*	43.852	*0.480*	56.378	*0.693*
Lettuce	21.943	*0.140*	31.952	*0.280*	46.090	*0.519*	57.771	*0.716*
Birds Foot Trefoil	17.063	*0.086*	27.309	*0.210*	35.791	*0.342*	45.136	*0.502*
Carrot	29.408	*0.241*	37.547	*0.371*	46.354	*0.524*	58.731	*0.731*
Chicory	16.814	*0.084*	33.654	*0.307*	43.347	*0.471*	60.282	*0.754*
Sorrel	13.249	*0.053*	37.411	*0.369*	42.425	*0.455*	46.338	*0.523*
Tarragon	14.422	*0.062*	16.210	*0.078*	33.653	*0.307*	43.250	*0.469*
χ- prob	0.314		0.167		0.504		0.234	
Wald Statistic	10.46		12.91		8.30		11.64	
SED (average)	9.612		8.839		7.413		9.503	
LSD (average)	20.194		18.570		15.574		19.965	
df	9		9		9		9	

A mean stem damage score was calculated and no statistically significant differences were found between the ten treatments (Table 13).

Table 13. Elsoms 2 - the mean damage score for cauliflowers with damage to the lower stem.

Treatment	Mean stem damage score
Cauliflower + Dursban	3.803
Cauliflower alone	3.920
Chard	4.180
Endive	3.522
Lettuce	3.245
Birds Foot Trefoil	3.698
Carrot	3.006
Chicory	3.301
Sorrel	3.556
Tarragon	3.938
χ- prob	0.172
Wald Statistic	12.79
SED (average)	0.4400
LSD (average)	0.9244
Df	9

Damage to the cauliflower roots

Cabbage root fly feeding damage to the root of each plant was scored on a scale of 0-5. The damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage. The analysis of the root damage scores is summarized in Table 14 and suggests that the chard treatment had a significantly lower proportion of cauliflowers with no root damage than the other treatments. Only two plots contained plants with a root damage score of 4, therefore this category has been combined with a root damage score of 5. An angular transformation was used for the cumulative proportion of plants.

Table 14. Elsoms 2 - the proportion of cauliflowers per plot with root damage. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

Treatment	Proportion with root damage score =						
	0		1	2	3		4+5	
Cauliflower + Dursban	0.747	cd	0.116	0.135	0.000	a	0.001	a
Cauliflower alone	0.435	b	0.194	0.091	0.085	bcd	0.168	b
Chard	0.106	a	0.285	0.375	0.091	cd	0.115	ab
Endive	0.672	bcd	0.150	0.096	0.018	ab	0.089	ab
Lettuce	0.752	d	0.116	0.171	0.002	a	0.001	a
Birds Foot Trefoil	0.500	bc	0.195	0.157	0.100	d	0.050	ab
Carrot	0.578	bcd	0.140	0.213	0.000	a	0.080	ab
Chicory	0.680	bcd	0.119	0.117	0.066	abcd	0.004	a
Sorrel	0.702	cd	0.091	0.018	0.051	abcd	0.090	ab
Tarragon	0.599	bcd	0.321	0.119	0.024	abc	0.010	a
χ- prob	<0.001		0.211	0.627	<0.001		0.026	
Wald Statistic	46.34		12.04	7.10	40.75		18.91	
SED (average)	0.1199		0.0939	0.1497	0.0344		0.0563	
LSD (average)	0.2519		0.1973	0.3145	0.0722		0.1183	
df	9		9	9	9		9	

Unlike the analysis of cumulative stem damage, statistically significant differences were found in the analysis of cumulative root damage (Table 15). The cauliflower + Dursban treatment had a higher proportion of plants with less root damage, while the cauliflower alone and chard treatments appeared to have a lower proportion with root damage scores of 0, 1, 2 and 3. This is reflected in Table 13 in the results for categories 4 and 5.

Table 15. Elsoms 2 - the cumulative proportion of cauliflowers per plot with damage to the root. Back-transformed means are shown in italics. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

Treatment	Cumulative proportion with root damage								
	<= 1			<= 2			<= 3		
Cauliflower + Dursban	74.288	d	*0.927*	89.360	d	*1.000*	89.297	b	*1.000*
Cauliflower alone	54.667	abc	*0.666*	60.352	a	*0.755*	67.212	a	*0.850*
Chard	43.072	a	*0.466*	64.662	ab	*0.817*	70.424	a	*0.888*
Endive	66.257	bcd	*0.838*	76.133	bcd	*0.943*	75.964	ab	*0.941*
Lettuce	68.700	cd	*0.868*	89.324	d	*1.000*	84.439	b	*1.000*
Birds Foot Trefoil	50.645	ab	*0.598*	67.174	ab	*0.850*	79.856	ab	*0.969*
Carrot	55.860	abc	*0.685*	76.155	bcd	*0.943*	77.056	ab	*0.950*
Chicory	67.208	bcd	*0.850*	78.348	bcd	*0.959*	89.680	b	*1.000*
Sorrel	67.463	bcd	*0.853*	69.939	abc	*0.882*	76.574	ab	*0.946*
Tarragon	70.325	cd	*0.887*	83.354	cd	*0.987*	88.308	b	*0.999*
χ- prob	<0.001			<0.001			<0.001		
Wald Statistic	31.31			39.04			29.95		
SED (average)	8.281			6.765			6.562		
LSD (average)	17.398			14.213			13.786		
df	9			9			9		

An analysis of the mean root damage score (Table 16, Figure 15) showed that the cauliflower alone treatment and the chard treatment resulted in a significantly higher mean root damage score.

Table 16. Elsoms 2 - the mean root damage score for cauliflowers. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

Treatment	Mean root damage score	
Cauliflower + Dursban	0.408	a
Cauliflower alone	1.542	d
Chard	1.952	d
Endive	0.745	abc
Lettuce	0.369	a
Birds Foot Trefoil	1.044	c
Carrot	0.919	bc
Chicory	0.620	abc
Sorrel	0.735	abc
Tarragon	0.527	ab
χ- prob	<0.001	
Wald Statistic	89.63	
SED (average)	0.2242	
LSD (average)	0.4710	
df	9	

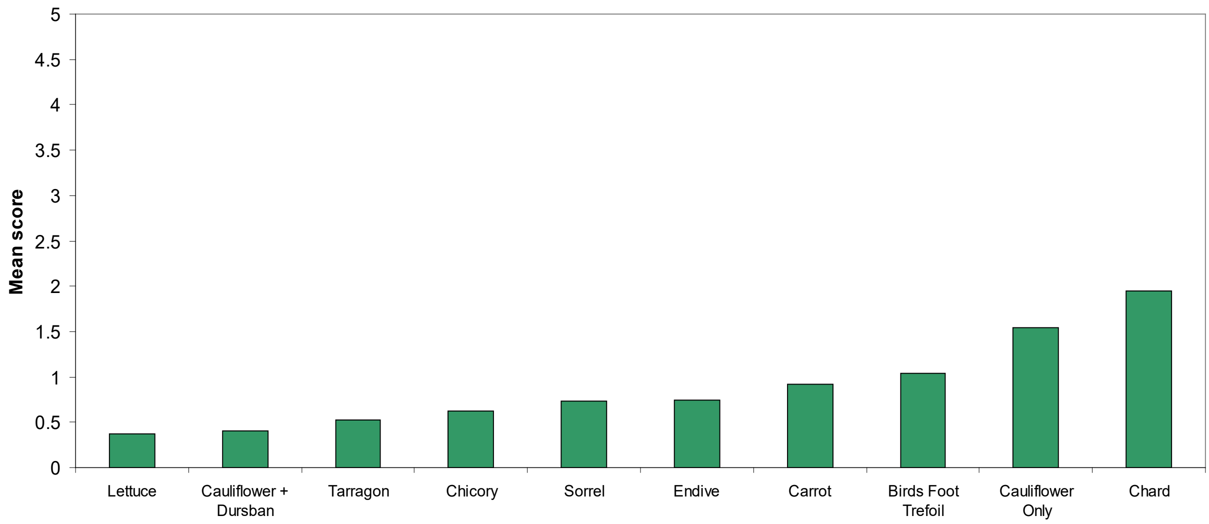

Figure 15. Elsoms 2 - the mean root damage score for cauliflowers after one generation of cabbage root fly. The damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage.

<u>Harvest data</u>

A full analysis is presented for one of the trials, Elsoms 2, and then comparisons are made with some of the key results from the other trials in a subsequent section.

Two subsets of the harvest data were analysed –

1. All harvest data included in the analysis
2. Only data with both surviving cauliflowers and companion plants included

Curd Quality

Cauliflower plants were graded for curd quality on a three point scale – 1st Class, 2nd Class and Unmarketable. Any blind cauliflowers were included in the unmarketable class. The proportion of cauliflowers in each grade in each plot was analysed by REML and an angular transformation was required. The results for all harvested plants are summarized In Table 17, where the means in italics are the back-transformed means. Removing data where no companion plants survived had very little effect on the results.

A lower proportion of cauliflowers surrounded by endive were recorded as 1st Class quality and a higher proportion were classed as Unmarketable. Birds foot trefoil companions tended to result in more cauliflowers graded as 1st Class and fewer as Unmarketable.

Table 17. Elsoms 2 - The proportion of cauliflowers in each curd quality class. The means in italics are the back-transformed means. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Proportion in Each Curd Quality Class							
	1st			2nd		Unmarketable		
Cauliflower + Dursban	35.287	de	*0.334*	36.535	*0.354*	32.028	ab	*0.281*
Cauliflower alone	33.061	d	*0.298*	32.523	*0.289*	39.190	abc	*0.399*
Chard	13.432	abc	*0.054*	20.672	*0.125*	59.909	de	*0.749*
Endive	4.191	a	*0.005*	25.974	*0.192*	65.065	e	*0.822*
Lettuce	22.287	bcd	*0.144*	30.417	*0.256*	47.984	bcde	*0.552*
Birds Foot Trefoil	46.991	e	*0.535*	33.996	*0.313*	20.230	a	*0.120*
Carrot	10.870	ab	*0.036*	23.298	*0.156*	62.475	e	*0.786*
Chicory	18.308	bc	*0.099*	22.459	*0.146*	60.445	de	*0.757*
Sorrel	22.833	bcd	*0.151*	25.776	*0.189*	55.867	cde	*0.685*
Tarragon	26.513	cd	*0.199*	34.080	*0.314*	42.565	bcd	*0.458*
χ- prob	<0.001			0.179		<0.001		
Wald Statistic	78.21			12.65		47.82		
SED (average)	6.521			6.634		9.425		
LSD (average)	13.701			13.938		19.802		
df	9			9		9		

Maturity

The estimated maturity date has been converted to the estimated number of days from planting to maturity. The Elsoms 2 trial was planted on 6 July 2007. The mean, median and inter-quartile range (IQR = 75th percentile – 25th percentile) of the estimated days to maturity have been analysed as well as the proportion of plants which reached maturity. The proportion which reached maturity required an angular transformation and the back-transformed means are given in italics (Table 18).

The results suggest that cauliflowers surrounded by birds toot trefoil or with no companion plants are some of the quickest to reach maturity, have the smallest IQR in maturity time and also one of the highest proportions reaching maturity. ‘Chicory’ resulted in one of the later maturity times and had a lower proportion of cauliflowers which reached maturity.

Table 18. Elsoms 2 - The estimated number of days to maturity - all plants. The back-transformed means are given in italics. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment

means with a letter in common are said to be not significantly different. N.B. IQR = inter-quartile range.

	Estimated Number of Days to Maturity – All Plants								
	Mean		Median		IQR		Proportion Reached Maturity		
Cauliflower + Dursban	103.44	ab	100.87	ab	8.40	abc	86.47	d	*0.996*
Cauliflower alone	102.68	ab	101.44	ab	4.28	a	84.69	cd	*0.991*
Chard	107.16	bcd	108.52	bc	14.65	bc	66.81	ab	*0.845*
Endive	106.53	bcd	108.45	bc	14.11	bc	72.56	abc	*0.910*
Lettuce	107.39	bcd	108.60	bc	12.52	bc	84.61	cd	*0.991*
Birds Foot Trefoil	101.62	a	99.18	a	4.09	a	86.15	d	*0.996*
Carrot	110.81	d	110.81	c	8.00	ab	73.55	abcd	*0.920*
Chicory	108.26	cd	108.63	bc	11.56	bc	63.43	a	*0.800*
Sorrel	107.22	bcd	105.79	abc	11.23	bc	70.96	ab	*0.894*
Tarragon	105.55	abc	105.38	abc	15.16	c	78.35	bcd	*0.959*
χ- prob	<0.001		0.014		<0.001		<0.001		
Wald Statistic	28.73		20.76		30.22		33.32		
SED (average)	2.251		3.828		3.230		6.244		
LSD (average)	4.729		8.042		6.786		13.118		
df	9		9		9		9		

Since there was a weak effect of shortened time to maturity for cauliflowers without companion plants, the data were re-analysed excluding the cauliflower plants which had no surviving companion plants (subset 2 described above). No change was made to the overall results by excluding these plants. However the results are presented in Table 19.

Table 19. Elsoms 2 - The estimated number of days to maturity – cauliflowers with surviving companion plants. The back-transformed means are given in italics. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different. N.B. IQR = inter-quartile range.

	Estimated number of days to maturity - excluding cauliflowers with no companion plants									
	Mean		Median		IQR		Proportion Reached Maturity			
Cauliflower + Dursban	103.48	abc	100.84	ab	8.71	ab	86.51	c	*0.996*
Cauliflower alone	102.65	ab	101.31	ab	3.38	a	84.67	c	*0.991*
Chard	107.37	bcd	108.79	bc	15.30	c	66.48	ab	*0.841*
Endive	106.79	bcd	108.32	bc	14.01	bc	73.02	abc	*0.915*
Lettuce	107.78	cd	108.47	bc	12.80	bc	84.02	c	*0.989*
Birds Foot Trefoil	101.69	a	99.45	a	3.64	a	86.14	c	*0.995*
Carrot	110.76	d	110.68	c	8.62	ab	73.55	abc	*0.920*
Chicory	108.42	cd	108.65	bc	11.59	bc	63.70	a	*0.804*
Sorrel	107.64	bcd	105.79	abc	12.95	bc	70.19	ab	*0.885*
Tarragon	105.14	abc	103.04	abc	13.99	bc	78.04	bc	*0.957*
χ- prob	0.002		0.011		<0.001		<0.001		
Wald Statistic	26.48		21.51		41.35		31.30		
SED (average)	2.389		3.815		3.012		6.420		
LSD (average)	5.019		8.015		6.328		13.488		
df	9		9		9		9		

Curd Diameter

Table 20 shows an analysis of curd diameter. The cauliflower treatments with no companion plants had a higher curd diameter ($p<0.05$) than the other treatments, excluding birds foot trefoil. Based on this observation, the data were re-analyzed excluding cauliflowers where the companion plants had not survived. In addition, the proportion of cauliflowers with a curd diameter less than 10 cm is also shown. Again, excluding plants with no companion plants had little effect on the results.

Table 20. Elsoms 2 – mean curd diameter. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Curd Diameter				Proportion < 10 cm diameter			
	All Plants		Excluding cauliflowers where companion plants lost		All Plants		Excluding cauliflowers where companion plants lost	
Cauliflower + Dursban	10.30	c	10.23	cd	0.390	ab	0.390	ab
Cauliflower alone	9.80	c	9.78	bcd	0.371	ab	0.373	ab
Chard	5.99	ab	5.68	a	0.744	cd	0.765	d
Endive	5.31	a	5.16	a	0.797	d	0.802	d
Lettuce	6.99	ab	6.93	ab	0.667	cd	0.690	cd
Birds Foot Trefoil	10.85	c	10.93	d	0.214	a	0.212	a
Carrot	5.00	a	5.05	a	0.797	d	0.794	d
Chicory	6.19	ab	6.03	a	0.515	bc	0.517	bc
Sorrel	6.98	ab	6.83	ab	0.705	cd	0.726	cd
Tarragon	7.66	b	7.74	abc	0.592	bcd	0.583	bcd
χ- prob	<0.001		<0.001		<0.001		<0.001	
Wald Statistic	99.53		99.76		48.42		54.42	
SED (average)	0.953		0.973		0.1220		0.1175	
LSD (average)	2.002		3.043		0.2563		0.2469	
df	9		9		9		9	

Companion Plant Counts

The proportion of cauliflower plants within each plot with the correct number of companion plants is shown in Table 21. The target for chard, endive and lettuce was one companion plant per module, whilst the remaining five companion plants were to have a density of 4 plants per module. Less than 35% of the cauliflowers planted with carrots had the correct number of companions present at harvest. At the 6 week assessment, a high proportion of 'carrot modules' had more than 4 carrot plants.

Table 21. Elsoms 2 – the proportion of cauliflower plants within each plot with the correct number of companion plants. The back-transformed means are given in italics. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

Treatment	Proportion cauliflower plants with correct number of companion plants		
Chard	75.05	b	*0.933*
Endive	70.90	b	*0.893*
Lettuce	80.03	b	*0.970*
Birds Foot Trefoil	75.69	b	*0.939*
Carrot	35.17	a	*0.332*
Chicory	78.81	b	*0.962*
Sorrel	71.47	b	*0.899*
Tarragon	75.54	b	*0.938*
χ- prob	<0.001		
Wald Statistic	58.67		
SED (average)	7.137		
LSD (average)	15.309		
df	7		

Damage Categories

Each cauliflower harvested was assessed for damage and the most frequently occurring categories were button, rot, loose, yellow, water soaked, caterpillars, aphid and the occasional plant was classed as purple, blind or slug damaged (Table 22). Where enough non-zero data were present the total number of affected plants in each plot has been analysed. An individual plant can be identified as having more than one type of damage. The categories of caterpillar and aphid damage have been combined into a single insect category.

Statistically significant differences between the treatments were found for the number of cauliflowers classed as 'button' and with insect damage. Cauliflower alone with and without Dursban and with birds foot trefoil had a lower number of button cauliflowers.

Table 22. Elsoms 2 – The proportion of mature cauliflower plants with damage. The back-transformed means are given in italics. Statistically significant differences in the treatment means are shown by the letters next to each mean. Treatment means with a letter in common are said to be not significantly different.

	Proportion of mature cauliflowers with damage											
	Button			Rot		Loose		Water-soaked		Insects		
Cauliflower + Dursban	10.35	a	*0.032*	13.01	*0.051*	41.43	*0.438*	9.02	*0.025*	16.63	ab	*0.082*
Cauliflower alone	13.74	ab	*0.056*	10.19	*0.031*	48.03	*0.553*	3.68	*0.004*	23.33	b	*0.157*
Chard	37.68	cd	*0.374*	18.16	*0.097*	39.61	*0.406*	3.73	*0.004*	13.15	ab	*0.052*
Endive	40.05	cd	*0.414*	17.89	*0.094*	40.80	*0.427*	6.12	*0.011*	4.96	a	*0.007*
Lettuce	35.33	cd	*0.334*	10.23	*0.032*	37.71	*0.374*	3.92	*0.005*	19.78	b	*0.115*
Birds Foot Trefoil	12.49	a	*0.047*	4.69	*0.007*	38.31	*0.384*	3.67	*0.004*	21.87	b	*0.139*
Carrot	48.51	d	*0.561*	5.10	*0.008*	26.44	*0.198*	15.10	*0.068*	11.42	ab	*0.039*
Chicory	35.18	cd	*0.332*	3.90	*0.005*	34.07	*0.314*	3.69	*0.004*	11.46	ab	*0.039*
Sorrel	33.41	c	*0.303*	12.92	*0.050*	38.08	*0.380*	3.70	*0.004*	20.48	b	*0.122*
Tarragon	27.33	bc	*0.211*	12.22	*0.045*	41.26	*0.435*	0.00	*0.000*	4.99	a	*0.008*
χ- prob	<0.001			0.623		0.080		0.323		0.002		
Wald Statistic	74.05			7.14		15.43		10.35		25.55		
SED (average)	6.680			7.445		5.951		5.447		5.744		
LSD (average)	14.034			15.641		12.502		11.444		12.068		
df	9			9		9		9		9		

Comparisons between trials

This section compares the results from the different trials that have been analysed to date.

The mean weight of companion plants per module is shown in Figure 16. Birds foot trefoil (target sowing of 4 plants) was consistently lighter than the other companion plants and in general carrot and tarragon were also 'light' plants.

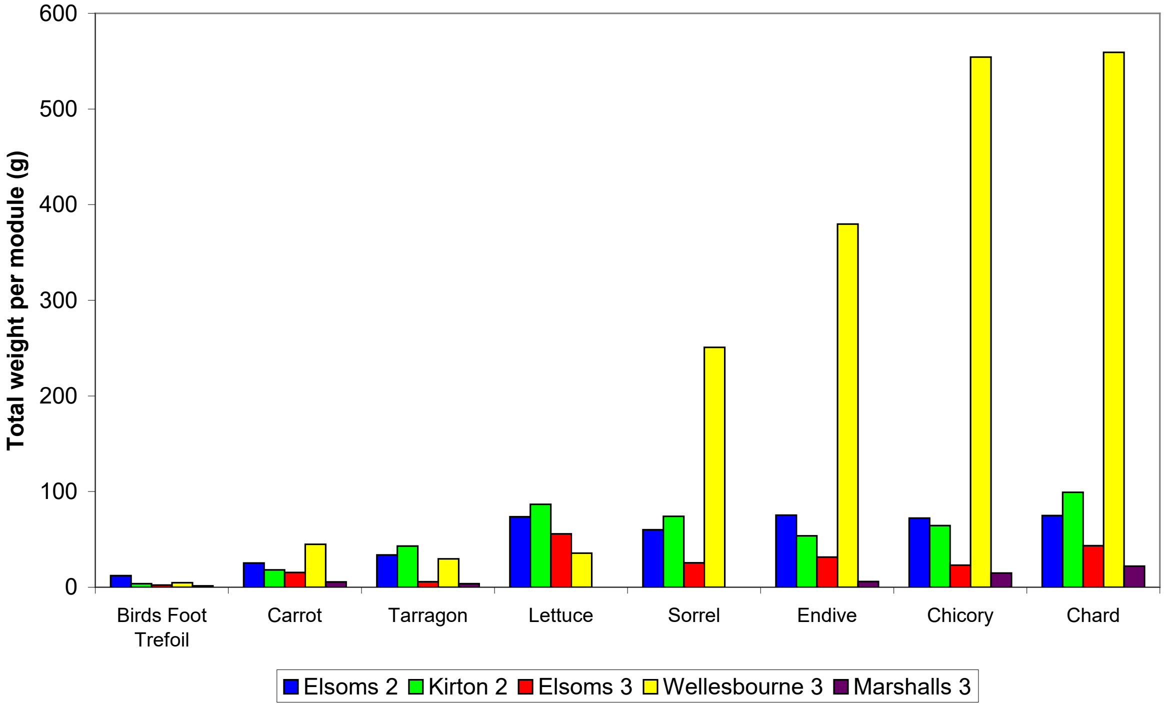

Figure 16. Comparisons between trials – weight of companion plants per module after one generation of cabbage root fly.

Figure 17 shows the mean number of companion plants per module after one generation of cabbage root fly compared with the target number of plants. There was variability between the trials and in the case of the companion plants with a target number of 4 per module, the target number was > or = 4 in only one case.

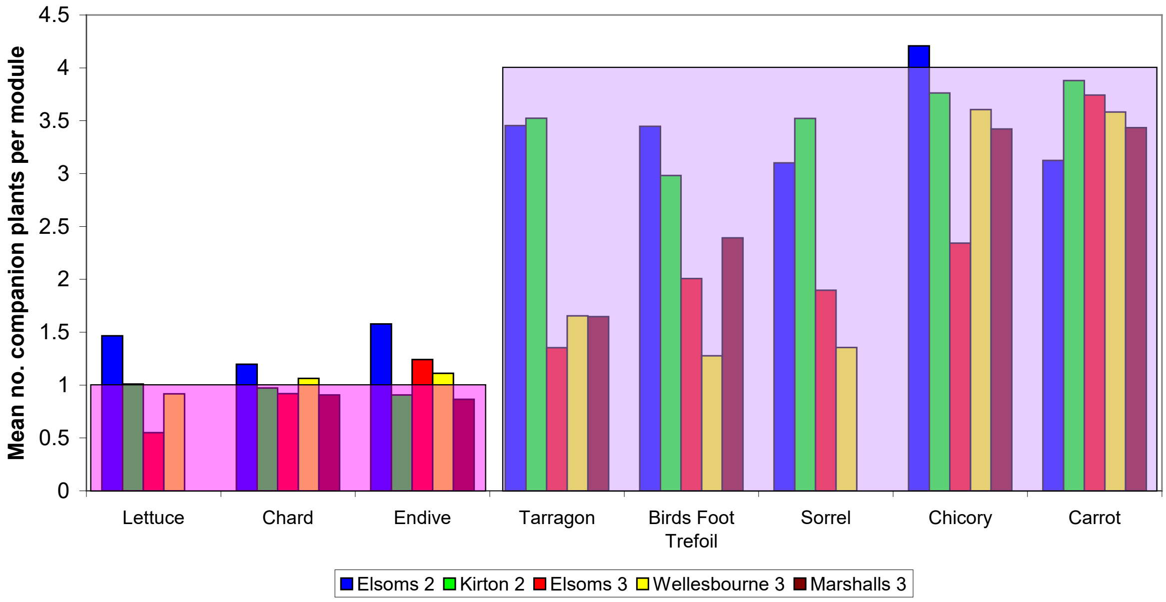

Figure 17. Comparisons between trials – mean number of companion plants per module after one generation of cabbage root fly. The coloured boxes show the target number of plants (1 or 4).

In general, the cauliflower plants treated with Dursban suffered the least larval feeding damage to the roots but none of the treatments were damaged severely by cabbage root fly (maximum score <3; score 3 represents 10-25% of damage to the surface area of the root (Figure 18)). However, the relative performance of the different companion plant treatments varied between trials.

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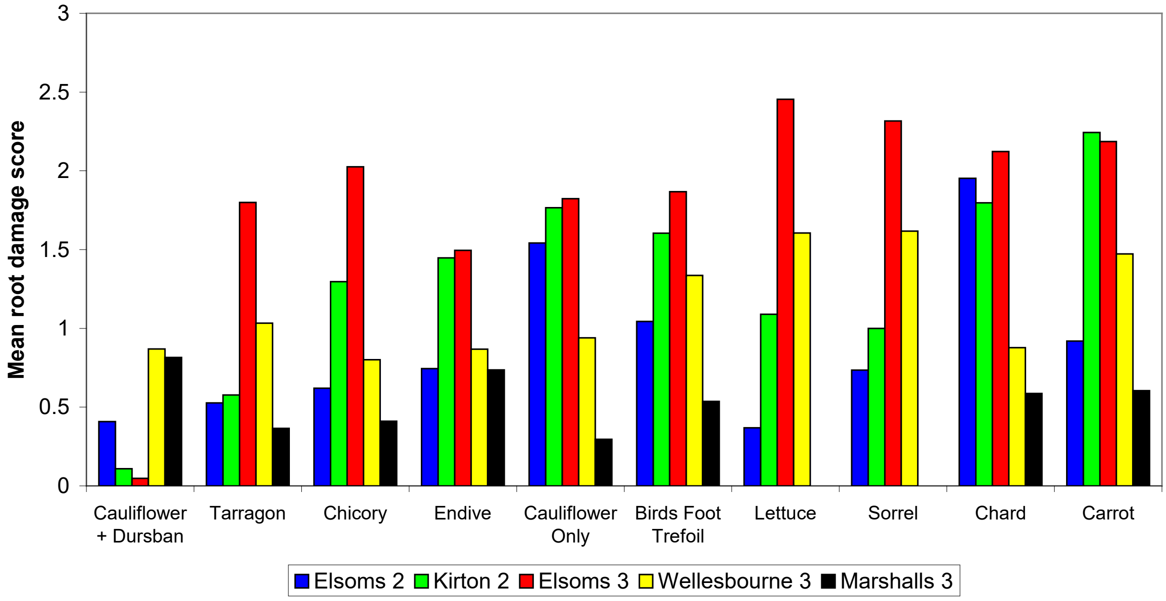

Figure 18. Comparisons between trials – mean root damage score after one generation of cabbage root fly. The damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage

To try and understand why companion plant performance varied between trials, the mean root damage score was plotted against the mean number of companion plants (Figure 19). For the majority of companion plant types, the root damage score was inversely related to the number of companion plants, suggesting that the presence of a higher number of companion plants reduced cabbage root fly damage. Carrot and birds foot trefoil were the main exceptions.

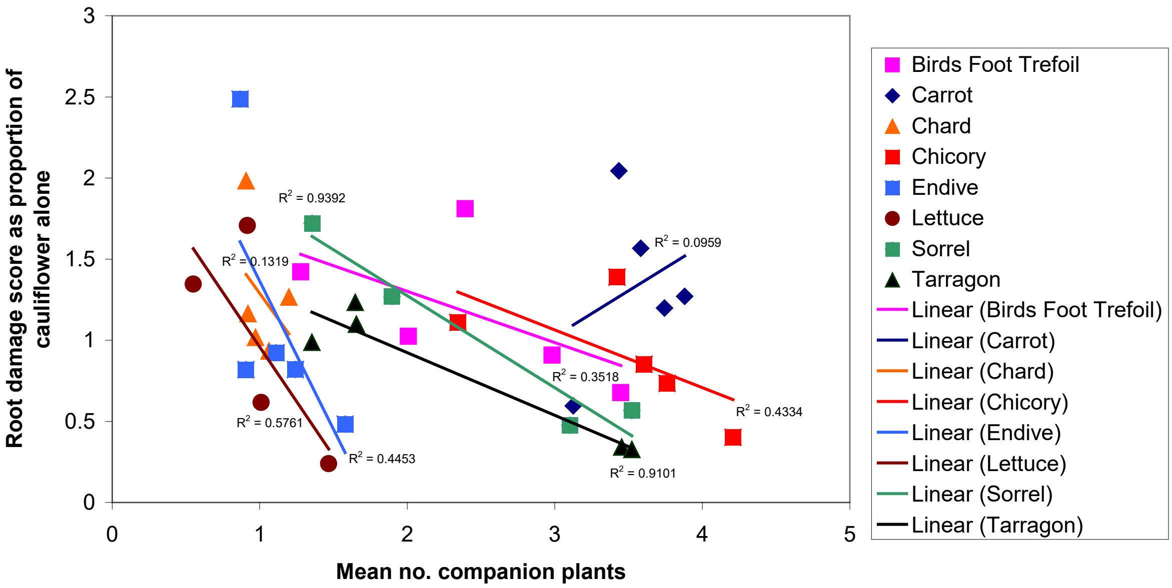

Figure 19. Comparisons between trials – relationship between mean root damage score and mean number of companion plants after one generation of cabbage root fly.

Damage to the lower stem varied between trials but was less variable between treatments than root damage (Figure 20).

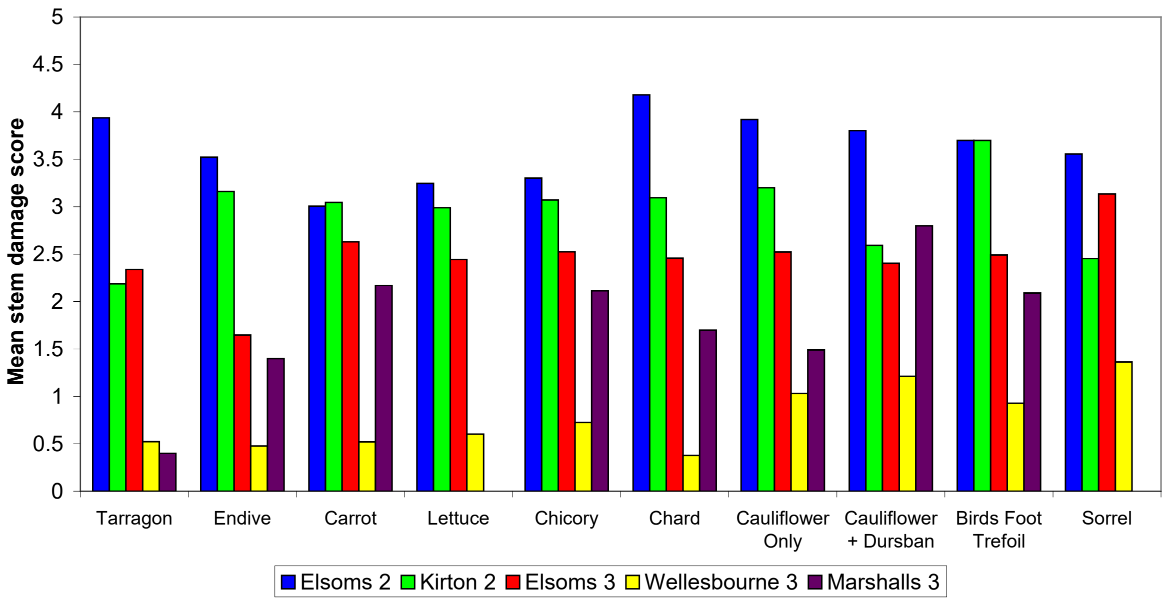

Figure 20. Comparisons between trials – mean stem damage score after one generation of cabbage root fly. The damage categories were: 0 = no damage, 1 = <5%, 2 = 5-10%, 3 = 10-25%, 4 = 25-50% and 5 = >50% damage.

There were also differences between treatments in the yield and quality of cauliflower curds at harvest but the differences between trials were often greater than the differences between treatments, possibly due to the extreme weather conditions that occurred during part of the summer (Figures 21-23).

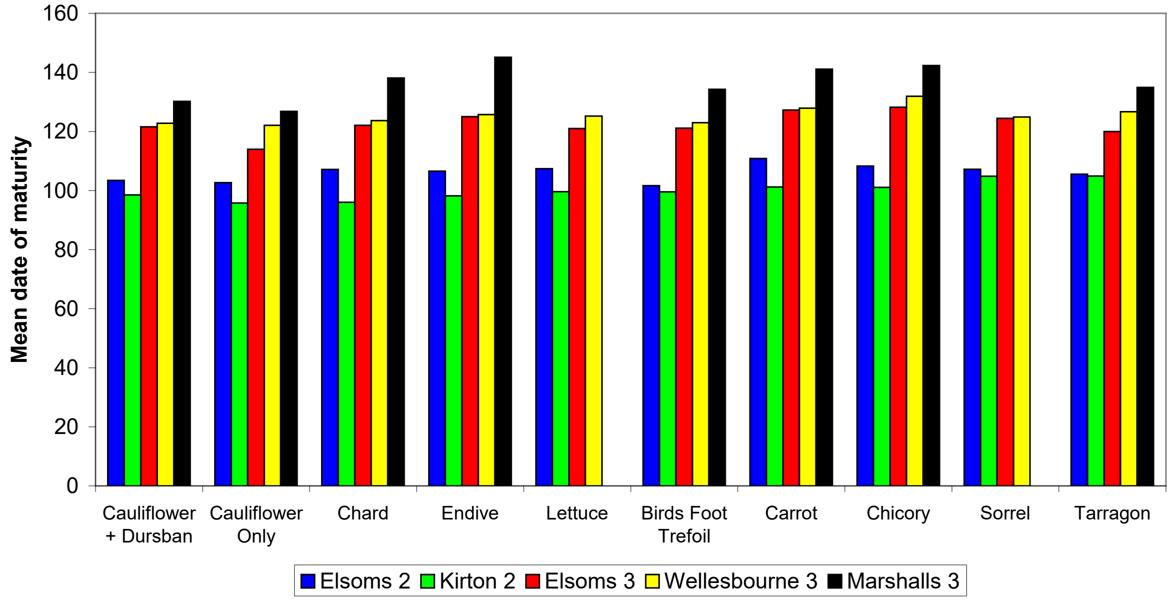

Figure 21. Comparisons between trials – mean date of curd maturity in days from planting.

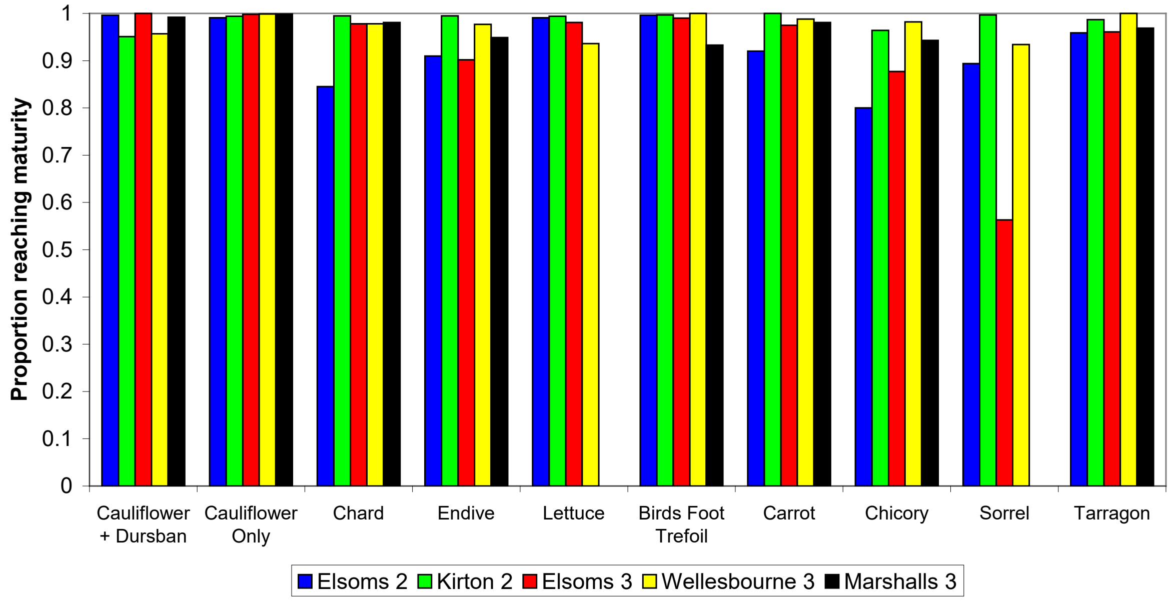

Figure 22. Comparisons between trials – mean proportion of curds reaching maturity.

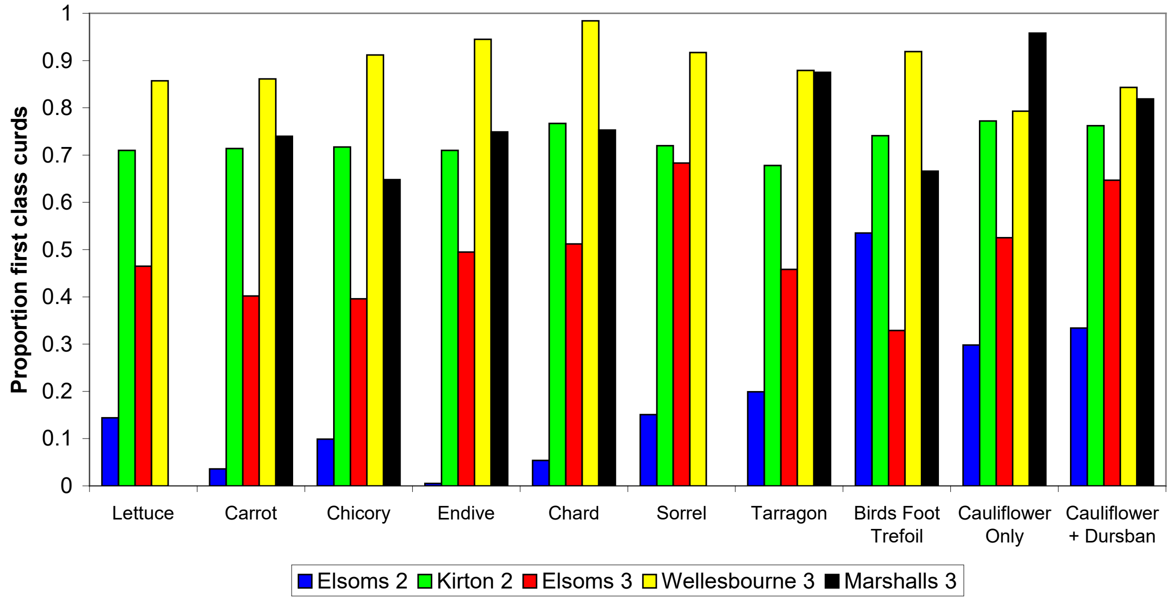

Figure 23. Comparisons between trials – mean proportion of first class curds.

6. Determine how the companion plant system developed for cabbage root fly control affects 1) other pest insects.

<u>Materials and methods</u>

The aim of the work done in 2007 was to determine how the companion plant system developed for cabbage root fly control might affect other pests. The experiments with *Plutella xylostella* and *Pieris brassicae* were done in a 'rotating' cage at Warwick HRI, Wellesbourne (Figure 24), using insects from the Warwick HRI cultures and cauliflower plants and companion plants (carrot, chard, birds foot trefoil, lettuce) that had been grown in a greenhouse. The experiments with *Brevicoryne brassicae* were done in large Perspex cages.

The rotating cage was a wooden-framed test chamber with two equal sized compartments (160 x 160 x 63 cm high) arranged one above the other. Each compartment contained a 145 cm diameter turntable, which rotated once every 4 minutes. As insects are often positively phototactic, the rotation ensured that everything placed on the turntables was exposed equally to the insects, which tended to aggregate near the fluorescent lights used to illuminate the test chamber.

Figure 24.   Rotating cage showing the two compartments into which test insects are released.

Each turntable had space for four custom-made trays. Each of these was segment –shaped and covered one quarter of the turntable. For these experiments the trays were filled to the top with sieved soil and a single empty plant pot (9 x 9 cm) was inserted into the centre of each tray to hold a pot containing a cauliflower plant and its associated companion plants. The soil was then spread over the surface of the pots so that the plants were presented in a bare soil background, as they would be in the field.

Each experiment was done over of a number of runs, using both compartments of the rotating cage. For each experimental run, eight fresh cauliflower plants of the same age were selected from the greenhouse. The total number of leaves and the height of each plant were recorded. The pots were topped up with a layer of silver sand followed by sieved soil. Once the plants were in place, fixed numbers of insects were released into each compartment of the cage, where they remained for 24 hours. The cage was maintained in a constant temperature room at 19 $\pm$ 2^{o}C with a 16 h photoperiod.

The experiments with *Brevicoryne brassicae* were done in Perspex cages (1 x 0.45 x 0.38 m high). The potted cauliflower and companion plants were sunk into trays (39 x 30 x 11 cm high and covered in black polythene) of soil and the treatments were placed in a line (two treatments per tray and two trays per cage) using random numbers to determine the position of each plant.

After 24 hours, the plants were removed from the cages, labelled by treatment and then taken to a laboratory. The cauliflower and companion plants were inspected carefully to record the number of eggs laid on each treatment (*Plutella xylostella*, *Pieris brassicae*) or the numbers of winged and wingless *Brevicoryne brassica* on each treatment. The results are summarised in Figures 25-28. Further replications are required.

<u>Results</u>

Pieris brassicae females laid most of their eggs on the cauliflower plants, although, unusually, a few eggs were laid on the carrot companion plants in one of the experiments. On average, they laid more eggs on the cauliflower plants surrounded by bare soil than on those presented with companion plants (Figure 25).

Plutella xylostella females did not discriminate between cauliflower plants and companion plants as oviposition sites and in general, the cauliflower/companion plant combinations were preferred to the cauliflower plants surrounded by bare soil (Figures 26-27).

Brevicoryne brassicae females appeared to have an equal preference for the cauliflower plants whether or not they were presented with companion plants. They did not settle and reproduce on any of the companion plants themselves (Figure 28).

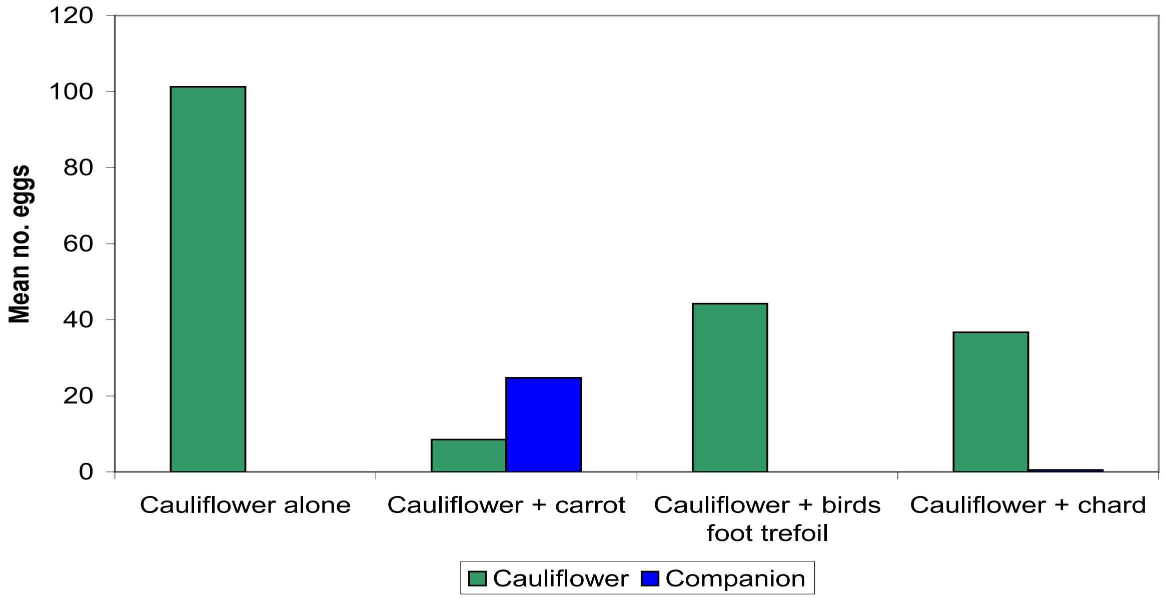

Figure 25. The mean number of eggs laid by female *Pieris brassicae* (large white butterfly) on cauliflower and companion plants in the rotating cage.

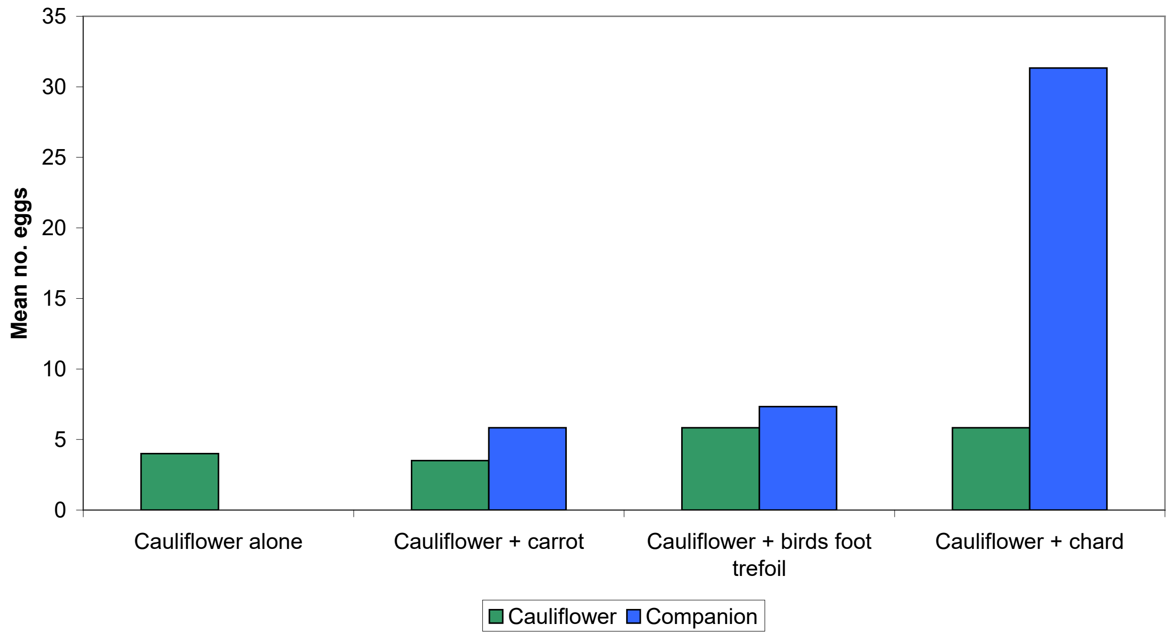

Figure 26. The mean number of eggs laid by female *Plutella xylostella* (diamond-back moth) on cauliflower and companion plants in the rotating cage.

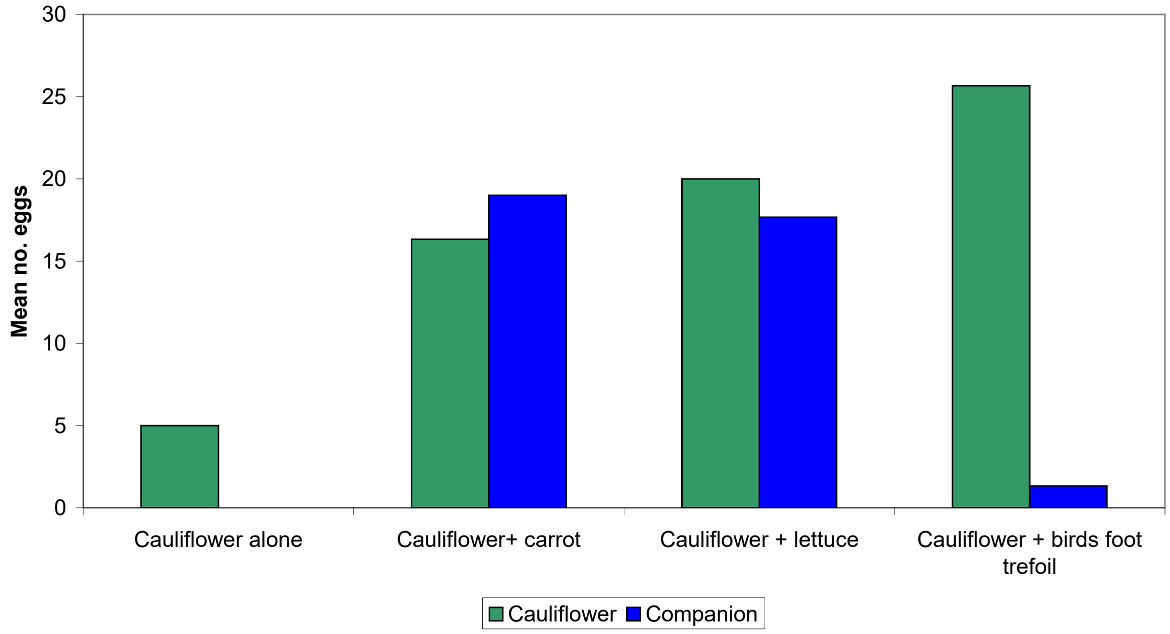

Figure 27. The mean number of eggs laid by female *Plutella xylostella* (diamond-back moth) on cauliflower and companion plants in the rotating cage.

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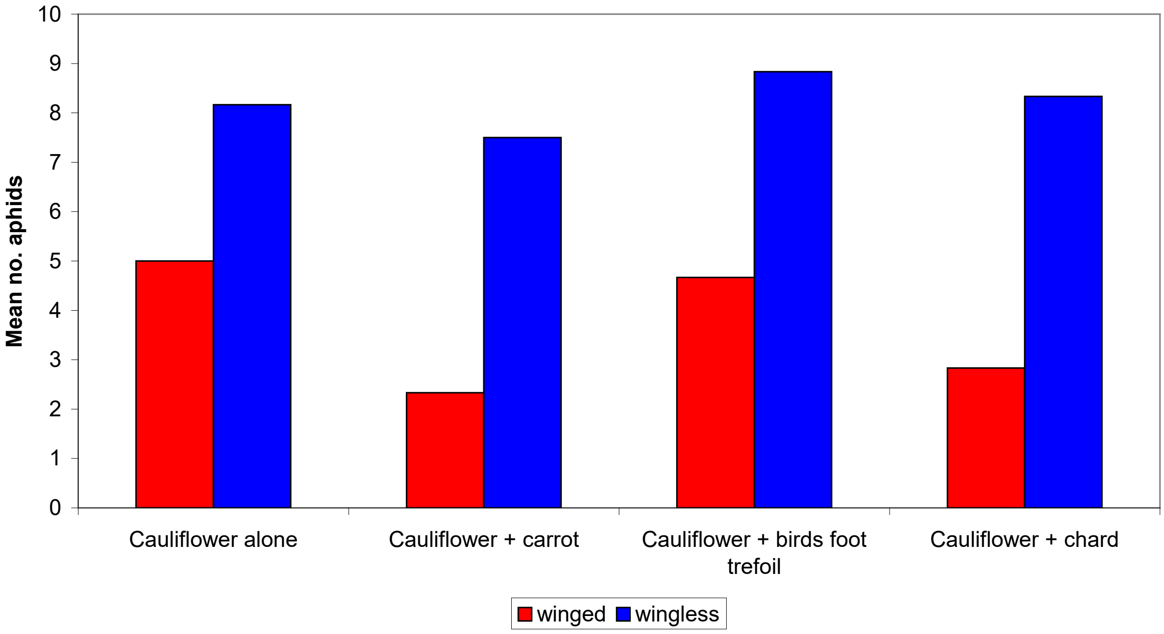

Figure 28. The mean numbers of winged and wingless *Brevicoryne brassicae* (cabbage aphid) on cauliflower plants in a long Perspex cage

DISCUSSION

Objective 5 Develop and refine robust systems for growing brassicas and companion plants together, so that the negative effects of competition are offset by the positive effects of reduced pest numbers.

The eight field trials have provided a large amount of data and have indicated the range of interactions that need to be considered, both in interpreting the data from the trials and in developing a system for using companion plants to control cabbage root fly and other pests. The data require further analysis before final conclusions can be drawn from the 2007 trials.

The preliminary conclusions from this trial are:

- It is sometimes difficult to achieve the correct density of companion plants in every module in an experimental trial on this scale. To a certain extent this depends on the companion plant seed – both its size and viability. This is obviously also a consideration for the development of a commercially-viable system of growing brassicas with companion plants.

- Even if the modules contain the correct number of companion plants prior to transplanting then some of them may 'disappear' either as a result of planting or for other reasons during the first few weeks of growth.
- If cauliflowers are not 'presented' with a sufficient amount of alternative green surfaces (companion plants) then they are likely to be more susceptible to egg-laying by female cabbage root flies. Thus when considering the effects of the 'treatments' it is also important to take into account how close companion plant numbers were to those intended.
- Generally the cauliflower plants treated with Dursban suffered lower levels of cabbage root fly feeding damage to the roots, but this was not true for damage to the lower stem area.
- Despite the different pressures that the different types of companion plant placed on the growing cauliflowers, many of the companion plant treatments in the trials yielded good quality curds. There were considerable differences between trials in the proportion of good quality curds produced and some of these are likely to be attributable to the very variable conditions under which the trials were grown in 2007.
- Future work should concentrate on producing cauliflower plants surrounded by a relatively large and consistent area of alternative green surfaces (companion plants) to disrupt egg-laying by the cabbage root fly.
- In these trials, the plots within a block were adjacent to one another (although their order was randomised) and they were relatively narrow, being 3 plants wide. In some cases, when the plants were well-established, the companion plants from one plot 'flowed' onto the adjacent plots. It is therefore important to make plots larger and more separate as the system is scaled-up, in order to avoid 'interference' between treatments.

Objective 6 Determine how the companion plant system developed for cabbage root fly control affects 1) other pest insects.

The behaviour of the three test insects was variable between replicates and further testing is required. The results for *Pieris brassicae* are consistent with a previous study (Finch & Kienegger, 1997), indicating that the egg-laying by this butterfly can be disrupted by the presence of companion plants. The results for *Plutella xylostella* are also consistent with previous observations, that it is one of the brassica pest species whose colonisation behaviour is least affected by the presence of companion plants (Finch & Kienegger, 1997; D. George and R. Collier, unpublished data) and which will lay its eggs on other surfaces apart from those of its brassica host plants (R. Collier, unpublished data). The results for *Brevicoryne brassicae* are more unexpected, since the study by Finch & Kienegger and a subsequent study at Warwick HRI presenting *B. brassicae* with cabbage plants in a background of weeds (R. Collier, unpublished data) showed that colonisation was disrupted considerably by the presence of alternative green surfaces.

TECHNOLOGY TRANSFER

The project was summarised in a presentation at a Horticulture LINK event on 28 November 2007.

ACKNOWLEDGEMENTS

We thank Defra and the HDC for supporting this work.

REFERENCES

Basic Horticultural Statistics for the United Kingdom 2004. Crop Years 1993 - 2003. Department for Environment, Food and Rural Affairs, National Statistics. http://statistics.defra.gov.uk/esg/publications/bhs/2004/default.asp

Andow, D.A., 1991. Vegetational diversity and arthropod population response. *Annual Review of Entomology* **36**: 561-586.

Finch, S. & R.H. Collier (2000). Host-plant selection by insects – a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. *Entomologia experimentalis et applicata* **96**: 91-102.

Finch, S. & Kienegger, M. (1997). A behavioural study to help clarify how undersowing with clover affects host-plant selection by pest insects of brassica crops. *Entomologia experimentalis et applicata* **84:** 165-172.

Morley, K., Finch, S. & Collier, R.H. (2005). Companion planting – behaviour of the cabbage root fly on host plants and non-host plants. *Entomologia experimentalis et applicata,* **117**, 15-25.

Richards, O.W., 1940. The biology of the small white butterfly (*Pieris rapae*) with special reference to the factors controlling its abundance. *Journal of Animal Ecology* **9**: 243-288.

Project objectives

1. Determine how the height, leaf area, proximity and spatial arrangement of the companion plants affects host plant selection and egg laying by female cabbage root flies on brassicas.

2. Determine how the leaf shape of the companion plants affects host plant selection and egg laying by female cabbage root flies on brassicas.

3. Identify companion plant species that would reduce cabbage root fly egg laying to the desired level.

4. Determine the parameter values of these species and the associated brassica plants for a growth and competition model to allow the companion species to be identified that would compete least with the brassicas.

5. Develop and refine robust systems for growing brassicas and companion plants together, so that the negative effects of competition are offset by the positive effects of reduced pest numbers.

6. Determine how the companion plant system developed for cabbage root fly control affects 1) other pest insects and 2) levels of pest predation and parasitism compared with 'bare soil' crops.

Project milestones

Milestone	Date	Description
Year 1		
1.1	17 Feb 06	Effects of companion plant size and position on CRF determined
2.1	1 Mar 06	Effects of leaf structure on CRF determined
3.1	31 May 06	Up to 10 possible companion species identified for growth trials
Year 2		
4.1	25 Oct 06	Plant growth characteristics determined in trials
4.2	6 Dec 06	Competition model re-parameterised
4.3	14 Feb 07	Scenarios tested using competition model
5.1	28 Feb 07	Up to 15 companion plant treatments identified for trials in 2007
Year 3		
6.1	18 Dec 07	Effects of 'optimum' companion plants on other pests determined
5.2	31 Jan 08	Up to 5 companion plant treatments identified for trials in 2008
Year 4		
6.2	18 Dec 08	Effects of companion plants on predation/parasitism determined
5.3	31 Jan 09	Up to 2 companion plant treatments identified for trials in 2009
Year 5		
5.4	18 Dec 09	Performance of final companion plant system(s) vs CRF evaluated
6.3	18 Dec 09	Effects of final system(s) on other insects determined
5.5	31 Dec 09	Final report submitted

