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SID 5 Research Project Final Report

defra

Project identification

1. Defra Project code   OF0329

2. Project title

    Using weeds to reduce pest insect numbers in organic vegetable crops - a desk study

3. Contractor organisation(s)

    Warwick HRI
    Wellesbourne
    Warwick
    CV35 9EF

4. Total Defra project costs   £

5. Project: start date ....   01 April 2003

    end date ....   31 March 2006

6. It is Defra's intention to publish this form.
   Please confirm your agreement to do so...**YES** ☒ **NO** ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

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■ Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

At present, weeds and pest insects are two of the major constraints to the production of high quality organic vegetable crops, primarily because the range of control measures available to UK growers is extremely limited. Several studies have shown that the numbers of pest insects found on crop plants are reduced considerably when the crops are allowed to become weedy. However, if weeds are not removed by a certain stage of crop growth, they start to compete with the crop plants and yield begins to decline.

Warwick HRI already has models that are used independently to predict both the onset of weed competition and the timing of pest insect attacks. However, in practice, growers have to manage weeds and pest insects at the same time and hence the decisions they make often involve compromises. Therefore, it would seem a natural progression to combine the existing models to show how reductions in crop yield, from altered weeding practices, could be offset by improvement in crop quality from reduced pest numbers.

The aim of this project was to demonstrate how the existing crop protection models could be used to optimise weed and pest control in organically-grown vegetable crops. The strategy could be very useful, as the range of crop protection interventions available to organic growers is strictly limited. Vegetable brassicas were chosen as the experimental crop, because their pest and weed models have been well validated, and because *Brassica* crops account for approximately 20% of the total organic vegetables grown in the UK. However, the research also demonstrates how the system could be adapted for other crop/pest combinations.

The first objective was to quantify the plant 'architecture' needed from weed populations to reduce pest insect infestations in cabbage crops. Three non-host weed plants were used in the study; *Chenopodium album* (fat hen), *Stellaria media* (common chickweed) and *Tripleurospermum inodorum* (scentless mayweed). These species were selected because they are common weeds in field vegetable crops, reduce colonisation by the cabbage root fly (*Delia radicum*) and have contrasting architecture (spread and height). The treatments combined weed species, planting times, plant sizes and plant densities to examine the impact on pest colonisation of cabbage. The different plant sizes and plant densities were achieved using weed plants that were raised in modules and then planted around cabbage plants. The three

test insect species were *Brevicoryne brassicae* (cabbage aphid), *Delia radicum* (cabbage root fly) and *Plutella xylostella.* (diamond-back moth). The trial demonstrated that, for *D. radicum* and *B. brassicae*, the greatest reductions in crop colonisation were produced by a high density of large weeds. The effects on *P. xylostella* were less clear-cut.

The second objective was to combine weed and pest insect models to quantify the interactions between crop growth, weed growth and pest insect colonisation. The initial analysis of the data obtained in Objective 1 used a log-linear model to relate pest counts to various assessments of crop (cabbage) and weed plant size (weed fresh weight, weed dry weight, weed height, weed diameter, crop height and number of crop leaves). Whilst these regressions suggested a number of relationships, they often accounted for only a small percentage of the variance. In this second objective, further statistical analyses were done to consider relationships between the numbers of pests per plant and various crop and weed parameters. The ratio of weed biomass to crop biomass (dry weight) provided the strongest relationship with pest numbers, and is also a measurement that can be obtained easily in the field. Using this relationship, critical values were calculated for each pest : weed combination. Maintaining the weed : crop dry weight ratio above this critical value should provide protection against pest colonisation. For example, a weed : crop dry weight ratio of 32.7 was required for *S. media* to "control" *D. radicum*.

The final objective was to determine the impact of different weeding strategies on 1) yield reduction through weed competition and 2) pest colonisation. A field trial was designed to test these strategies using *S. media* to 'control' *D. radicum* on cabbage in organic growing conditions. Three 'weed' strategies were devised using the crop-weed competition model in combination with the *D. radicum* forecasting model. They were intended to give: 1) a ratio always greater than the 'critical value' (the greatest pest protection, but also the greatest weed competition), 2) a ratio close to the 'critical value' (good pest protection, but less crop yield loss than Treatment 1 due to weed competition), and 3) a ratio always below the 'critical value' (the least pest protection, but also the least yield loss due to weed competition). Different weed : crop ratios were achieved by transplanting module-raised *S. media* of different ages into the cabbage plots. The strategies were timed to coincide with periods of either low or high pest incidence in the field, predicted using the *D. radicum* forecast, and the weeds were removed 4 weeks after transplanting, when the cabbage plants should have been sufficiently well-established to withstand a certain amount of root damage.

Unfortunately, the growth patterns of some of the weed treatments deviated from predictions made by the crop-weed competition model, so that the 'strategies' did not achieve the precise range of weed : crop ratios that had been intended. Despite these deviations, the percentage reduction in cabbage weight at harvest, due to the presence of weeds, was not dissimilar to that predicted by the model.

Damage by *D. radicum* was relatively low. None of the cabbage plants wilted or died, although all suffered larval feeding damage to their roots. However, where the critical ratio was achieved, weed presence had a distinct effect on root damage and the highest density of weeds reduced root damage by the greatest amount when compared with the weed-free control treatment. At harvest, cabbage fresh weight was negatively correlated with the weed : crop ratio, due to competition from the greater biomass of weeds.

Thus despite practical difficulties in achieving the intended weed : crop ratios using transplanted weeds, the trial confirmed the value of a 'green background' in reducing colonisation by *D. radicum.* It also confirmed the negative effect of weed competition on crop yield and demonstrated the 'trade-off' between reductions in pest damage and yield. Although the weeds were removed after the first 4 weeks of cabbage growth, the high density of weeds required over this period caused a significant reduction in crop yield.

Scientific conclusions
1. The current crop-weed competition model is driven purely by radiation interception and this study has highlighted some possible model limitations, in particular, the need to take account of crop and weed growth in nutrient deficient soils and in response to moisture stress. The

model also need to be able to cope with multi-species populations of natural weed flora (i.e. parameters need to be obtained for a wider range of species).

2. The crop-weed competition model provides an adequate prediction of competition based on average plant density. Modification of the model to account for the spatial proximity of the plants and their growth plasticity would enable more realistic and practical strategies to be evaluated (e.g. only having weeds within a small radius of the crop plant)

3. Pest models currently provide a robust prediction of the timing of pest infestations, but predictions of pest abundance and subsequent damage would be needed to fully evaluate the trade-off between yield loss through plant competition and the reduction in pest damage.

Practical conclusions

1. The trade-off between crop yield and pest control is clearly illustrated by the study. Yield loss (up to 30%) due to competition may be tolerable as an alternative to severe pest damage, in situations where infestation levels are high. Variety choice may have compensatory benefits, however, the impact of varietal choice on competition needs to be explored.

2. The study has shown that the strategy of allowing weed presence for a limited period whilst maintaining a weed : crop ratio (total dry weighs per unit area) above a threshold can provide some protection against pest damage. The threshold is dependent on the pest and weed species involved.

3. In practice, planting into a background of natural flora is probably the most practical way of achieving this protection. However, the weeds would need to be well-established before the cabbage was transplanted to achieve the required weed : crop ratio. Further information is needed on the development of natural floras, and on the effect of different weed species compositions.

4. Weeds in close proximity to the crop do reduce pest colonisation, as seen in other studies. Hence a lower total number of weeds could potentially achieve the same protective effect, providing they are close to the crop plant. Further information is needed on the spatial characteristics of plant competition to enable more realistic and practical strategies to be evaluated.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;

- the extent to which the objectives set out in the contract have been met;

- details of methods used and the results obtained, including statistical analysis (if appropriate);

- a discussion of the results and their reliability;

- the main implications of the findings;

- possible future work; and

- any action resulting from the research (e.g. IP, Knowledge Transfer).

Project Background

For the 2004-05 season, (most recent data) the organic fruit and vegetable market was valued at £441M. Of this, 36% of the vegetable volume was imported (Williamson & Cleeton, 2005). There is, therefore, considerable scope for import substitution. At present, weeds and pest insects are two of the major constraints to the production of high quality organic vegetable crops, primarily because the range of control measures available to UK growers is extremely limited.

Several studies have shown that the numbers of pest insects found on crop plants are reduced considerably when the crops are allowed to become weedy (Finch & Collier, 2000). Recent studies at Warwick HRI have shown that it is just the number, size and spatial arrangement of the green objects (e.g. weeds) surrounding a host-plant that reduces pest insect colonisation (Finch & Collier, 2000; Morley, 2001; Finch *et al.*, 2003; Morley *et al.*, 2005.). Hence, keeping crops weed-free ensures that the crop plants are exposed to the maximum pest insect attack possible in that locality. If weeds are not removed by a certain stage of crop growth, however, they start to compete with the crop plants and yield begins to decline. At present, Warwick HRI has robust models that are used independently to predict the onset of weed competition (e.g. DEFRA Project OF 0177) and the timing of pest insect attacks (e.g. Phelps *et al.,* 1993; Hortlink Project 163, HDC projects FV 13 & FV 163a). However, in practice, growers have to manage weeds and pest insects at the same time and hence the decisions they make often involve compromises. Therefore, it would seem a natural progression to combine the existing models to show how reductions in crop yield, from altered weeding practices, could be offset by improvement in crop quality from reduced pest numbers.

Project aim

The aim of this project is to demonstrate how the existing crop protection models could be used to optimise weed and pest control in organically-grown vegetable crops.

Such a strategy could be extremely useful, as the range of crop protection interventions available to organic growers is strictly limited. Vegetable brassicas have been chosen as the experimental crop, because their pest and weed models have been well validated and because *Brassica* crops account for approximately 20% of the total organic vegetables grown in the UK. However, the research should also show how the system could be adapted for other crop/pest combinations.

Much of the published work which forms the science base that underpins this project was funded by MAFF. The work relates to DEFRA's policy objectives of ensuring farming is carried out in a sustainable, diverse and adaptable manner. Such an approach should promote a competitive and integrated supply of food that is responsive to the needs of consumers. This project relates to the following UKROFS R & D priorities for horticultural crops: 1) pest control (cabbage root fly, aphids), 2) development of control strategies for broad-leaved weeds (weed/crop interactions) 3) development of alternative cropping practices and 4) technology transfer. In addition, the project is complementary to Warwick HRI's existing programme of work on the insect and weed pests of horticultural crops. Apart from showing how techniques developed for conventional horticulture could be used by organic growers, the project also identifies subject areas that require further work.

The three objectives of the project are as follows:

Objective 1
To quantify the plant architecture needed in naturally-occurring populations of weeds to reduce pest insect infestations in cabbage crops.

Objective 2
To combine weed and pest insect models to quantify the interactions between crop growth, weed growth and pest insect numbers.

Objective 3
To determine the best time to weed cabbage crops to offset the negative effect of weed competition with the positive effect of reduced pest insect numbers.

Objective 1
To quantify the plant architecture needed in naturally-occurring populations of weeds to reduce pest insect infestations in cabbage crops.

Materials & Methods

The three non-host weed plants used in the study were;
- *Chenopodium album* – fat hen,
- *Stellaria media* – common chickweed
- *Tripleurospermum inodorum* - scentless mayweed

These species were selected because they are common weeds in field vegetable crops, reduce colonisation by the cabbage root fly (*Delia radicum*) (Finch *et al.*, 2003) and have contrasting architecture (spread and height). The weed plants were raised in modules and then planted in different spatial arrangements around a central 'hole', so that potted cabbage plants placed in the hole would be surrounded by either 0, 2, 4 or 8 weed plants (Figure 1). The treatments were arranged in a randomised block design and were enclosed by a fine mesh field cage into which three test insect species were released (Figure 2). The three test insect species were:

- *Brevicoryne brassicae* L*. –* cabbage aphid
- *Delia radicum* L*. –* cabbage root fly
- *Plutella xylostella* L*. -* diamond-back moth

The effects of the weeds on insect colonisation were determined at three stages of weed growth and at three stages of cabbage growth and the tests were repeated on three separate planting occasions during the summer. Records were taken of the numbers of eggs laid on each cabbage plant by *D. radicum* and *P. xylostella* and the numbers of *B. brassicae* that had colonised each plant. The information was used to define the physical characteristics of the weed species (e.g. diameter and height), at different stages of cabbage growth, needed to reduce colonisation by pest insects.
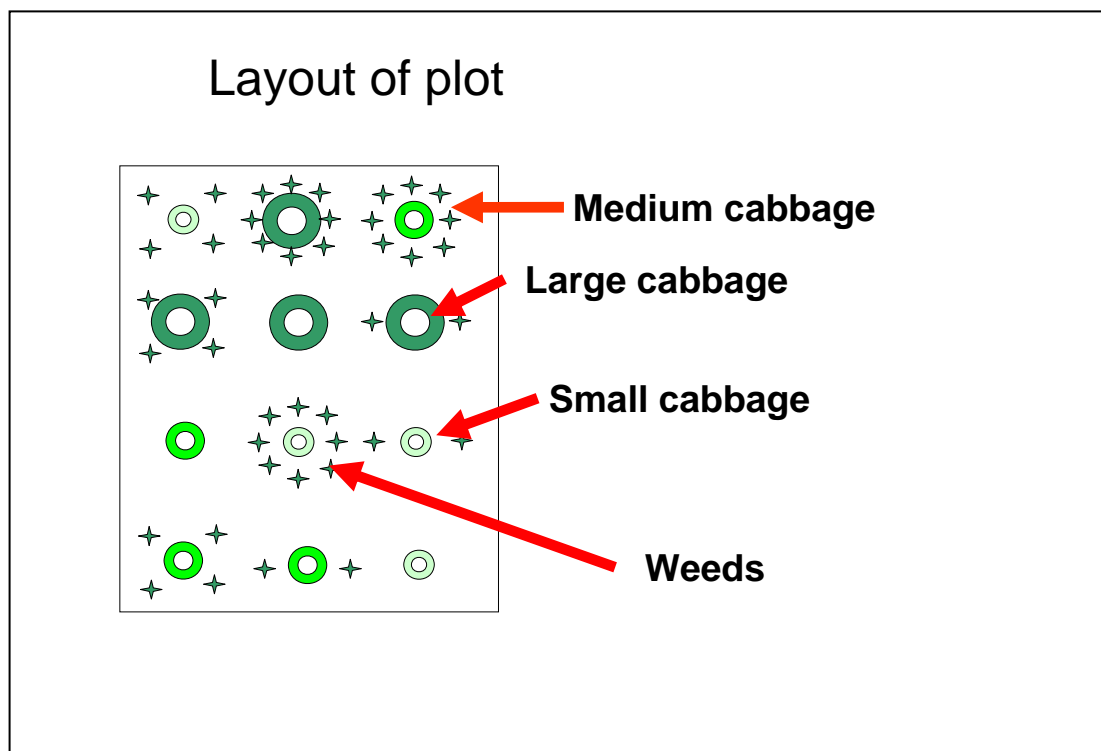

Figure 1   Different spatial arrangements of weeds around cabbages in a typical caged plot

Results

The mean heights and leaf numbers of small, medium and large test cabbage plants were 15, 23, 30 cm and 5, 8 and 11 leaves respectively. As expected, the heights of the three weed species varied; *C. album* was the tallest weed at each growth stage and *S. media* was the shortest. Large *C. album* and *T. inodorum* plants were both taller than large cabbage plants. Weed plant diameters also varied, but the relative sizes of the three weed species depended on growth stage. Despite these differences in size and spread, the fresh weights of small, medium and large weeds of the three species were similar (means of 1.9, 27.2 and 208.6 g respectively), as were the dry weights. Analysis of Variance of the insect colonisation data showed that there were a number of main effects related to variation in cabbage size and weed size, density and species. There were also a number of interactions.

Figure 2   *Fine mesh field cage into which the test insects (Brevicoryne brassicae, Delia radicum, Plutella xylostella) were released*

Effects on insect colonisation

- **The size of the cabbage plants** affected colonisation by all three insect species. In all cases, host-plant size had a positive effect on insect colonisation and 2-3 as many insects colonised the large and medium-sized cabbage plants compared with the small cabbage plants (Figure 3). However, the difference between the medium-sized and large cabbage plants was relatively small.
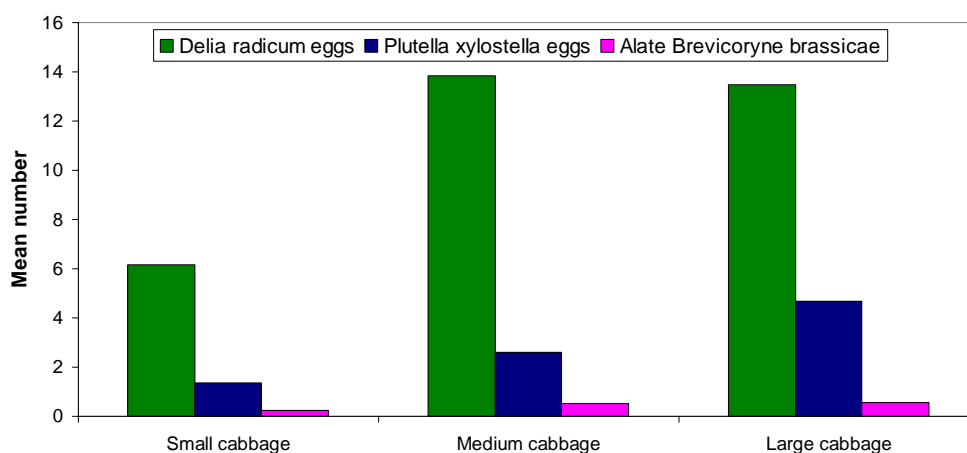

Figure 3.   *The mean numbers of Delia radicum eggs, Plutella xylostella eggs and Brevicoryne brassicae alates found on small, medium or large cabbage plants.*

- **Weed species** had no effect on colonisation by *B. brassicae* and *D. radicum* (Figure 4). However, *P. xylostella* preferred to lay eggs on plants surrounded by *S. media,* whereas plants surrounded by *C. album* were least preferred.
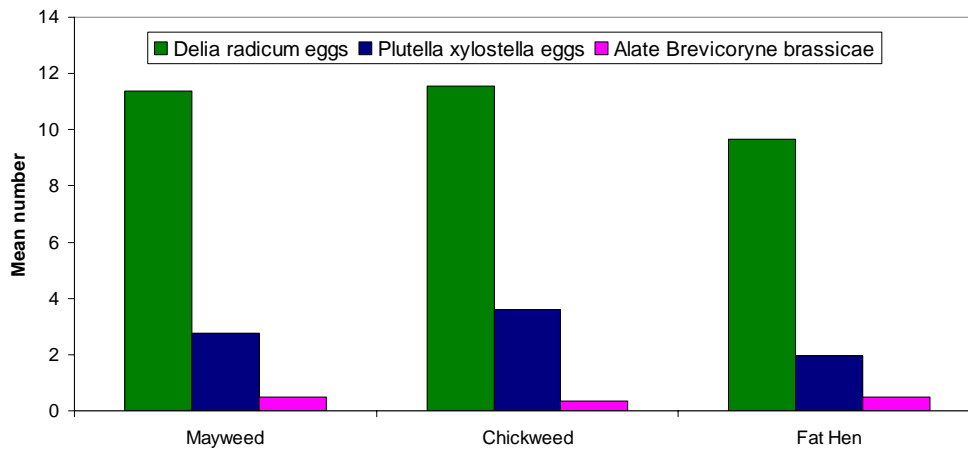

Figure 4.   *The mean numbers of Delia radicum eggs, Plutella xylostella eggs and Brevicoryne brassicae alates found on cabbage plants surrounded by one of the three test weed species.*

- **Weed size** had a negative effect on ; by *B. brassicae* and *D. radicum* (Figure 5). Female *D. radicum* laid 3 times as many eggs on cabbage plants surrounded by small weeds compared with large weeds. Similarly, twice as many alate *B. brassicae* settled on cabbage plants surrounded by small weeds compared with large weeds. In contrast, adult *P. xylostella* laid 3 times as many eggs on cabbage plants surrounded by large weeds as those surrounded by small weeds.

Figure 5.   *The mean numbers of Delia radicum eggs, Plutella xylostella eggs and Brevicoryne brassicae alates found on cabbage plants surrounded by small, medium or large weeds.*

- **Weed density**, but not weed species, influenced oviposition by *D. radicum* and colonisation by alate *B. brassicae*; the presence of 2, 4 or 8 weed plants reduced *D. radicum* oviposition by 36%, 40% and 48% and *B. brassicae* colonisation by 38%, 35% and 54% respectively (Figure 6). In all cases, the cabbage plants surrounded by bare soil were the most heavily colonised. Oviposition by *P. xylostella* had a less pronounced response to weed density and the presence of 2, 4 or 8 weed plants reduced oviposition by only 15, 21 and 17% respectively.
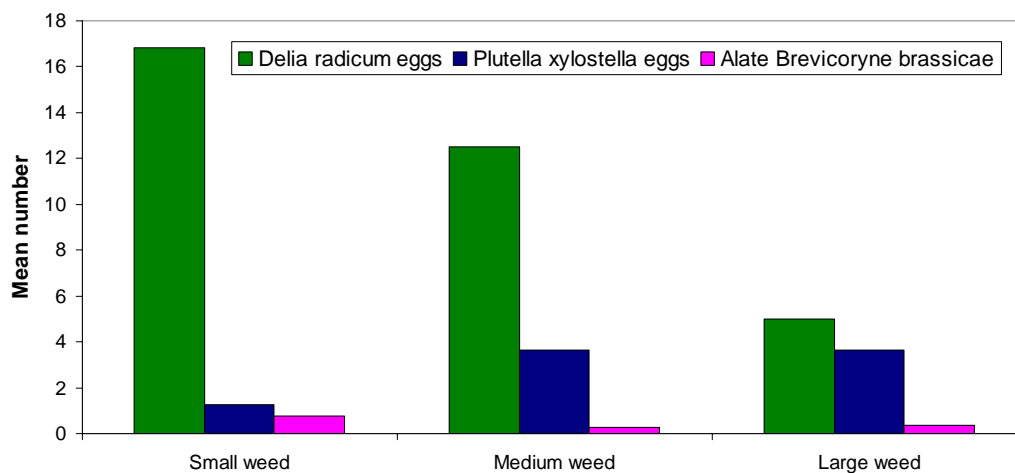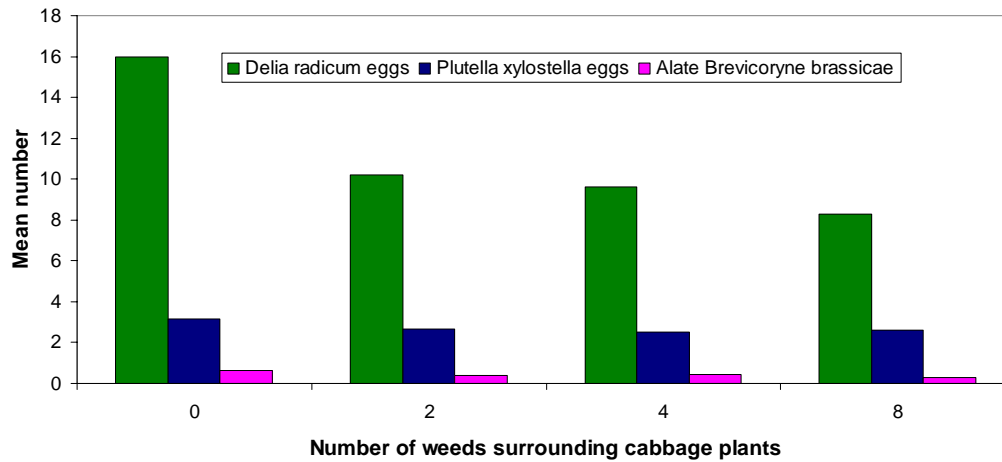
Figure 6.   The mean numbers of Delia radicum eggs, Plutella xylostella eggs and Brevicoryne brassicae alates found on cabbage plants surrounded by 0, 2, 4 or 8 weed plants.

- **Interactions** between cabbage size and weed size or cabbage size and weed density were not observed with *D. radicum* and *B. brassicae*, indicating that a particular arrangement of weeds produced a consistent percentage reduction in colonisation, regardless of the size of the cabbage plant. This was not the case with *P. xylostella* where there was an interaction between crop size and weed size, although not between crop size and weed density.

Main conclusions of objective 1:

With *D. radicum* and *B. brassicae*, the greatest reductions in crop colonisation were produced by a high density of large weeds. The effects on *P. xylostella* were less clear-cut.

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Objective 2
To combine weed and pest insect models to quantify the interactions between crop growth, weed growth and pest insect numbers

The next stage of the project was primarily desk-based modelling, including regression analysis of the plant/weed parameters to identify key relationships. In addition, plant growth data, and data collected previously, were used to model inter-specific competition between the crop and the three weed species.

Identifying the critical crop:weed parameter ratios for reducing pest colonisation
The outdoor experiments in year 1 (Objective 1) combined weed species (*S. media, T. inodorum* and *C. album*), planting times, plant sizes and plant densities to examine the impact on pest colonisation (*B. brassicae, D. radicum, P. xylostella*) of cabbage.   The initial analysis of the pest colonisation data used a log-linear model to relate the individual pest counts to various individual assessments of crop (cabbage) and weed plant size (weed fresh weight, weed dry weight, weed height, weed diameter, crop height and number of crop leaves). Whilst these regressions suggested some relationships, they often accounted for only a small percentage of the variance.

In Objective 2, a different approach was used to consider relationships between mean pest numbers per plant and mean crop and weed parameter values averaged over all the replicates and planting occasions (i.e. vales for each of the 27 different combinations of crop size [small, medium, large], weed size [small, medium, large] and weed density [2, 4, 8 plants]). A number of ratios were calculated:

- Weed height : crop height

- Mean weed fresh weight : crop fresh weight

- Mean weed dry weight : crop dry weight

- Total weed fresh weight (i.e. total biomass from 2, 4 or 8 weed plants) : crop fresh weight

- Total weed dry weight (i.e. total biomass from 2, 4 or 8 weed plants) : crop dry weight

Plots of the pest count data against these ratios suggested that an exponential decay curve would be the most appropriate form of response function.

Separate regression analyses were made for each combination of each of the three weed species with each of the three pest species. Importantly, these analyses allowed the calculation of critical ratios, for each of the weed/pest combinations tested, above which pest colonisation should be kept close to the modelled minimum value.

As the crop-weed competition model (Benjamin & Aikman, 1995) simulates changes in dry weight over time as its output (rather than changes in, for example, fresh weight or height), the ratio of <u>total weed dry weight : total crop dry weight (per unit area) was identified as the most appropriate explanatory variable to use for the next stage of simulation modelling</u>.

For each weed : pest relationship, the critical ratio was determined to be that at which the 'fitted' number of pests was equal to the lower asymptote plus the standard error of the lower asymptote. For example, the critical weed to crop biomass ratio (whole plant dry weight in a given area) for *T. inodorum* : *D. radicum* was 86.9, whilst the critical ratio for *S. media* : *B. brassicae* was 38.9. Suitable critical ratios could be identified for all three weed species with *D. radicum* only (Table1).

Weed species	Pest insect	Critical ratio
C. album	*D. radicum*	32.6
S. media	*D. radicum*	**32.7**
S. media	*P. xylostella*	46.6
S. media	*B. brassicae*	38.9
T. inodorum	*D. radicum*	86.9

Table 1.   Critical ratios of weed to crop dry weight (whole plant) for a range of weed pest combinations

Simulations to identify the weed sizes and densities required to achieve these critical ratios.

Having identified critical ratios, simulations were run to identify the initial size and density of weeds required to achieve these ratios, to minimise pest attack over an appropriate period. The crop-weed competition model (Benjamin & Aikman, 1995) was used to simulate the effects of both *S. media* and T*. inodorum* (both parameterised previously in the competition model) for a range of combinations of crop planting date, weed density and weight at the time of crop transplanting. In these simulations, the cabbage was planted on 6 separate, typical, occasions through the season (15 April, 15 May, 15 June, 15 July, 15 August and 15 September) using typical cabbage transplant dry weights and a standard cabbage plant spacing as starting values.

Combining crop-weed competition and pest forecasting models to quantify the interactions between crop growth, weed growth and pest insect numbers

The *D. radicum* forecasting model (part of the MORPH decision support system - http://www2.warwick.ac.uk/fac/sci/hri2/research/morph/) uses air and soil temperature records to predict the timing and duration of oviposition by each of the three generations of *D. radicum* (Phelps *et al.*, 1993). In contrast, crop and weed growth are modelled using radiation.

Temperature and radiation data from 1998 to 2004 were retrieved from the Wellesbourne meteorological data archive and used with the *D. radicum* forecasting model to determine the variability between years in periods of peak pest colonisation (oviposition) in years of high, average and low radiation.

The times of 50% and 80% oviposition were interpolated from the model output because:

- the 50% value gave an indication of whether it was an 'early' or 'late' year,

- the 80% value was used to indicate the date when the danger of oviposition had passed.

Examples of 'early' and 'late' oviposition occurring under conditions of high, average and low radiation were identified (Table 2). For example 1999 was a low radiation year with an early third generation of *D. radicum*, whilst 2001 was a high radiation year with a late first generation. On average, the period between 50% and 80% oviposition was 2 weeks.

	Time of 50% oviposition (days from 1 January)				
	1998	**1999**	**2000** Average radiation	**2001**	**2003**
	Low radiation			High radiation	
Gen 1	125	122	127	136	122
Gen 2	192	188	198	198	187
Gen 3	250	242	253	253	238

	Time of 80% oviposition (days from 1 January)				
	1998	**1999**	**2000**	**2001**	**2003**
Gen 1	139	138	138	148	142
Gen 2	208	202	215	211	201
Gen 3	265	254	266	272	255

Table 2   Examples of 'early' and 'late' oviposition by D. radicum occurring under conditions of high, average and low radiation.

Main conclusions of Objective 2:

We have demonstrated that using predictions from the crop-weed competition model, it is possible to identify the necessary weed densities and weed weights required at the time the crop is transplanted to achieve weed : crop dry weight ratios above a critical value throughout the appropriate risk period for pest colonisation. The risk periods for pest colonisation can be identified using an appropriate pest forecasting model. Predictions from the crop-weed competition model can then be used to indicate the trade-off between any adverse effect of the weed on crop yield and the reduced risk of *D. radicum* damage.

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Objective 3
To determine the best time to weed cabbage crops to offset the negative effect of weed competition with the positive effect of reduced pest insect numbers

A strategy for 'pest control using weeds', based on use of the crop-weed competition model in combination with a pest forecasting model, was evaluated in the field in Year 3. The aim was to test a range of 'weed' treatments using *S. media* to control *D. radicum* on cabbage.

Using *Stellaria media* (chickweed) to control *Delia radicum* (cabbage root fly) on cabbage

Materials & Methods

The evaluation was done at Warwick HRI, Wellesbourne in an area of organic land certified by the Soil Association. Weed (*S. media*) transplants of three different ages (and hence weights) were used to provide a range of weed : crop ratios during a critical period, which was assumed to be four weeks from

transplanting. A 4-week period was chosen because, by this time, the cabbage plants should have established a reasonably extensive root system outside the module and thus be able to tolerate higher levels of feeding damage by *D. radicum* larvae. After the 4-week critical period, the weeds were removed. Additional 'weed' treatments included a 'natural weed' treatment where the natural weed flora was allowed to develop and a 'bare soil' treatment (control) where the plots were kept weed-free.

The cabbage plants were raised in modules in a greenhouse. The weed seeds were germinated in incubators in the laboratory and the seedlings were raised in modules under glass to produce plants of comparable size and weight within a given cohort (Figure 7). The three weed cohorts were sown 7, 6 and 5 weeks respectively before the target transplanting date.

Figure 7.   *Cohorts 1, 2 and 3 of S. media (Chickweed) being raised in the glasshouse at Wellesbourne.*

The evaluation was repeated on two occasions: 1) weeds and cabbages planted in early June between the first and second generations of *D. radicum*, when the risk of oviposition was low (target date 8 June) and 2) weeds and cabbages planted in early July at the start of the second generation, when the risk of oviposition was high (target date 7 July).

Identifying the optimal weed : crop weight ratios to achieve maximum pest control and minimum weed competition

Before the first trial was planted, the crop-weed competition model was used to determine how to achieve suitable ratios of weed : crop dry weights to give protection during the 4-week critical period. Using modelling output from the 2003 experiment (Objective 1), the threshold for providing *D. radicum* 'control' with *S. media* was a weed : crop ratio of **32.7** (total dry weights per unit area). If the ratio is maintained above this, then *D. radicum* oviposition should be reduced.

The three *S. media* treatments were:

1. with a ratio always greater than the threshold (oldest weeds). This treatment should offer the greatest pest protection, but also the greatest weed competition (Cohort 1).
2. with a ratio close to the threshold (initially above it, but below it at the end of 28 days) (middle-aged weeds). This treatment should offer good pest protection, but less crop yield than Treatment 1 due to weed competition (Cohort 2).
3. with a ratio always below the threshold (youngest weeds). This treatment should offer the least pest protection, but also the least yield loss caused by weed competition (Cohort 3).

The crop-weed competition model simulations run in Objective 2 were used to identify the initial weed size and density required to achieve these three treatments. Growth simulations were run using

Wellesbourne meteorological data from 1998, 1999, 2000, 2001 and 2003. This was to give a range of seasons (shown in Objective 2, Table 2). These simulations allowed us to identify;

1) the appropriate planting density of approximately 150 weeds m^{-2}
2) the initial transplant size of weeds required to achieve the three treatments at this density (obtained 7, 6 and 5 weeks after sowing *S. media*).

Planting plan
The cabbage plants were spaced at the commercial spacing of 0.5 m between plants in both directions. To achieve approximately 150 weed plants per m^2 at an equal spacing in both directions required a 12-by-12 grid within each square metre (Figure 8). On the basis of the planting grid, the actual densities were **3.28** plants per m^2 for cabbage and **144.26** plants per m^2 for weeds. These densities gave a slightly greater ratio of weed : crop densities than for the simulations, and hence the total dry weight ratios were also slightly greater than from the simulations.

Figure 8   *Trial plots in 2005 showing cabbages (at commercial spacing of 0.5 circled in orange) and S. media (chickweed) at a density of approximately 150 plants m^2, to achieve the target ratio.*

Cultural details
The five treatments were:

1. Background planting of *S. media* Cohort 3 – youngest weeds
2. Background planting of *S. media* Cohort 2 – middle-aged weeds
3. Background planting of *S. media* Cohort 1 – oldest weeds
4. Weed-free control
5. Natural weed flora as background

The first trial (Planting 1) was transplanted with cabbage cultivar Stonehead on the target date of 8 June. However, the cabbage plants were severely damaged by pigeons, and were replaced on 15 June. The replacement plants were cultivar Sirador. The second trial, Planting 2 was transplanted on the target date of 7 July (with the original Stonehead cultivar). Treatments 1, 2 and 3 were hand-weeded during the 4-week period following transplanting, leaving only the transplanted *S. media*. Treatment 4 (the weed-free control) was hand-weeded throughout. All weeds were removed from treatments 1, 2, 3 and 5 after 4 weeks. Figure 9 shows the trial layout for Planting 1 (on 15 June).

Figure 9   First planting in organic area, Warwick HRI, Wellesbourne, June 2005.

Assessments
Plant samples were taken at the time of transplanting the cabbages and weeds (including the re-transplanting of Planting 1). The cabbage plants were inspected at intervals for the presence of foliar pests (e.g. aphids, caterpillars, flea beetles) and pest damage. Samples of cabbage and weed plants were removed 4 weeks after the cabbage had been transplanted, to record fresh and dry weights (foliage and roots) and feeding damage by *D. radicum* larvae. A 50 cm x 100 cm quadrat of weed material (foliage and roots) was removed from Treatment 5.

The remaining cabbage plants were harvested on 8 September (Planting 1) and 24 October (Planting 2). These plants were assessed for pest damage and their fresh weight, dry weight, head diameter and quality score were recorded.

To provide background information, *D. radicum* activity was monitored in a small plot of cauliflower at Wellesbourne. Soil samples were taken from 20 plants twice a week. *Delia radicum* eggs were extracted from the soil by flotation and then counted.

Results and Discussion:

Simulations to check initial weed : crop ratios
The crop-weed competition model was re-run with the cabbage and weed transplant weights to check whether the required weed : crop dry weight ratios would be achieved.   The initial (8 June) transplanting weights for Planting 1 were lower than had been expected, so that the weed : crop ratios were lower than required. For the subsequent re-planting of the cabbage (15 June – following pigeon damage) revised weed weights were estimated based on those measured on 8 June, and the crop-weed competition model simulations then suggested that the required weed : crop dry weight ratios would be achieved. In fact, the true weights on 15 June (Table 3) had exceeded the model predictions, with little discrimination between the three cohorts (i.e. the young weeds had grown better than expected). For Planting 2, although the weed transplant weights were larger than had been expected, the cabbage transplant weights were similarly increased, resulting in lower weed : crop dry weight ratios than required (Table 3).

Weed weights
At the time of transplanting, the youngest weeds were the lightest and the oldest weeds were the heaviest (Figure 10). However, this situation changed rapidly once the weeds were growing in the field. In Planting 1, the weights of all three weed cohorts were very similar within one week of transplanting (Figure 10), showing that the youngest weeds had been able to gain weight more rapidly than the older cohorts. By the time of the 4-week assessment, the oldest weeds were the lightest in both plantings. The total weed weight per unit area in Treatment 5 (natural weed flora) was, on average, <10% of that achieved using the transplanted weeds.
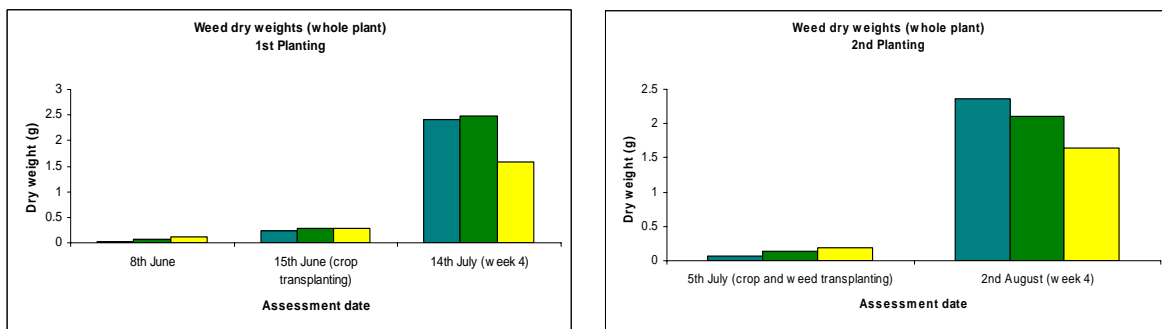

Figure 10   Weed dry weights (whole plant) for Planting 1 (left) and Planting 2 (right). Treatment 1 ■ (youngest weeds), Treatment 2 ■ (middle-aged weeds), Treatment 3 ■ (oldest weeds), Assessments made on 3 occasions for Planting 1 and two occasions for Planting 2.

It is likely that the oldest weeds were beginning to suffer from space and nutrient stress after 7 weeks in the modules and this resulted in the plants performing poorly when transplanted. In the field, these older plants also appeared to show signs of premature senescence. Thus raising the weeds in modules and holding them for this extended period of time had a negative impact on their subsequent growth and did not produce the anticipated treatment effect.   Therefore, although the three weed cohorts produced different weed : crop biomass ratios (Table 4), they differed from those anticipated from the assumption that the weeds were able to grow freely.

Cabbage weight and quality
The youngest weeds (Treatment 1) grew well and went on to exert the greatest amount of competition on the cabbage plants, because they attained the largest size. This is demonstrated by the lower cabbage weights at 4 weeks and at harvest for both plantings (Figure 11). The heaviest cabbage plants were produced by the weed-free treatment (Treatment 4) in Planting 1 and by the oldest weeds (Treatment 3) in Planting 2.

The natural weed flora consisted mainly of *Spergula arvensis* (corn spurry), *Veronica persica* (field speedwell) and *Capsella-bursa pastoris* (shepherd's purse). At the time of the 4-week assessment, the 'natural weed flora' treatment (Treatment 5) did not reduce cabbage size compared with the weed-free control treatment. However, by the time Planting 1 was harvested, there were large differences between treatments and the cabbage plants from Treatment 5 were smaller than those from any of the other treatments. This suggests that the natural weed flora had a more competitive effect on the crop than the *S. media* alone, despite all weeds having been removed from the plots at week 4. It is possible that root competition by the naturally-established weeds was more aggressive and had a more prolonged effect, than that caused by the transplanted weeds. This effect was not observed in Planting 2, possibly because soil disturbance during seedbed preparation (5 July) was at a time when the natural flush of weed emergence had declined, resulting in a lower weed pressure.

Overall, weed growth did not follow the predictions (based on known starting weights) given by the crop-weed competition model. This was most likely due to the stress of transplanting and the early senescence of the older weed cohort.
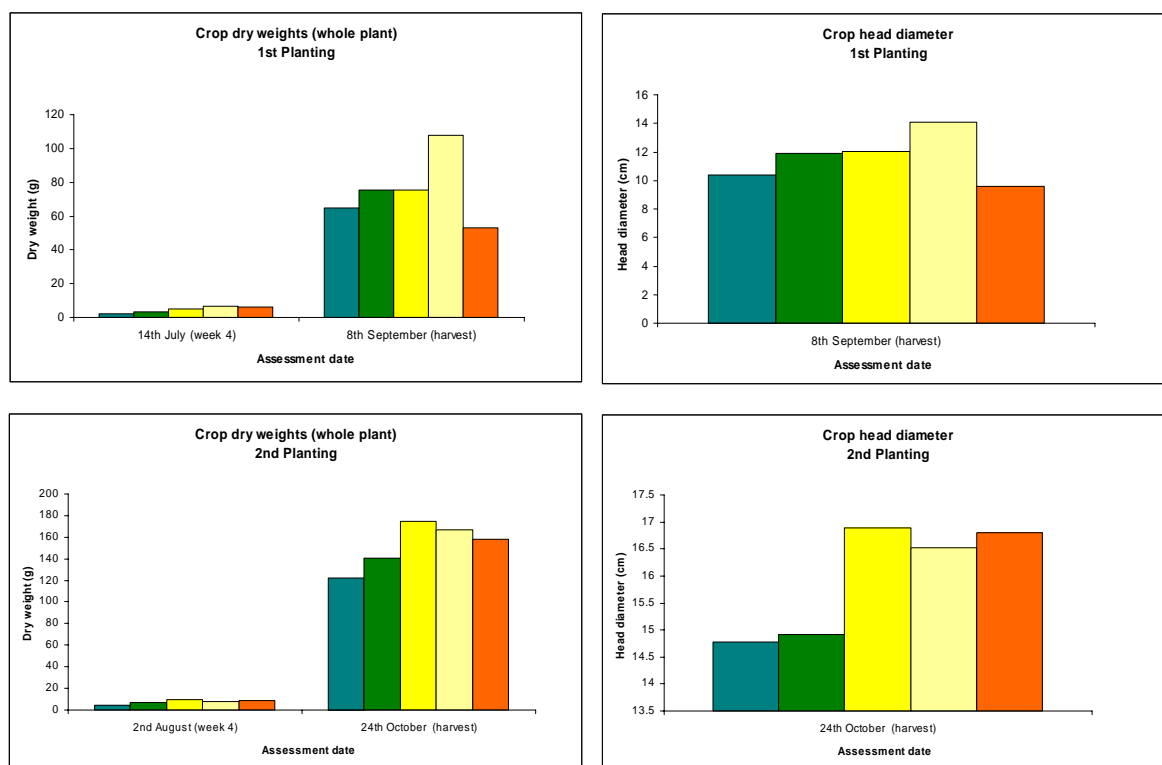

Figure 11   Cabbage dry weights and head diameters at harvest for Planting 1 (top) and Planting 2 (bottom). Treatment 1 ■ (youngest weeds), Treatment 2 ■ (middle-aged weeds), Treatment 3 ■ (oldest weeds), Treatment 4 ■ (weed-free) and Treatment 5 ■ (natural weed flora)

Weed : crop ratios

Because of the unexpected differences in the growth of the three weed cohorts, the planned weed : crop ratios were not achieved for the entire 4-week critical period in either of the two plantings (Table 4). At transplanting time, all treatments in Planting 1 started below the critical ratio of 32.7. By Week 4, the youngest weed cohort had exceeded the critical ratio, whilst the middle-aged and old weeds remained below the critical ratio. Indeed, the ratio resulting from the older weed cohort actually declined compared with the ratio at transplanting, probably due to senescence. For Planting 2, none of the *S. media* achieved the critical ratio at any point during the 4-week critical period.

Planting 1

Weed Plant Age	At transplanting			At 4 weeks after transplanting		
	Weed (g dry weight per plant)	Crop (g dry weight per plant)	Weed : crop Ratio (total dry wt. per m^2)	Weed (g dry weight per plant)	Crop (g dry weight per plant)	Weed : crop Ratio (total dry wt. per m^2)
Young	0.230	0.735	13.76	2.421	1.96	54.32
Mid	0.288	0.735	17.23	2.486	3.39	32.25
Old	0.278	0.735	16.64	1.593	4.94	14.18

Planting 2

Weed Plant Age	At transplanting			At 4 weeks after transplanting		
	Weed (g dry weight per plant)	Crop (g dry weight per plant)	Weed : crop Ratio (total dry wt. per m^2)	Weed (g dry weight per plant)	Crop (g dry weight per plant)	Weed : crop Ratio (total dry wt. per m^2)
Young	0.060	0.315	8.38	2.37	4.32	24.13
Mid	0.142	0.315	19.83	2.11	7.31	12.70
Old	0.195	0.315	27.23	1.65	9.21	7.88

Table 4   Estimated weed : crop ratios for Planting 1 and Planting 2 based on a cabbage density of 3.28 per m^2 and a weed density of 144.26 per m^2

Pest incidence on cabbages

As planned, Planting 1 was transplanted during a period of low pest incidence between the first and second generations of *D. radicum* (Figure 12). Oviposition by the second generation started in early July, so the plots were exposed to higher pest pressure during the latter half of the weed-treatment period. None of the plants showed extreme reactions to *D. radicum* larval feeding damage (wilting or death), indicating that the infestation was relatively slight.

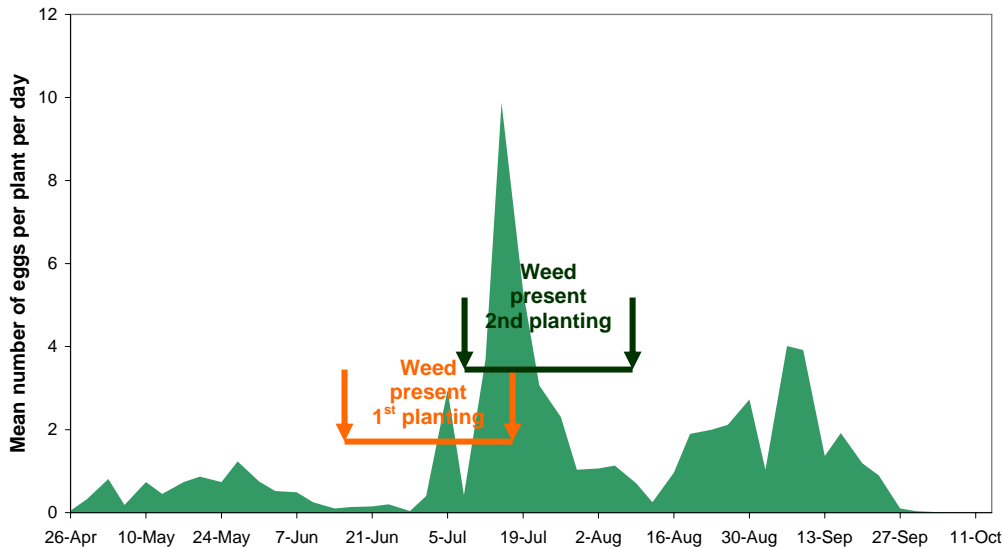**Cabbage root fly egg-laying - Wellesbourne 2005**

Figure 12   Numbers of D. radicum eggs laid in a plot of cauliflower at Wellesbourne in 2005. The 4-week periods when weed was present coincide with a period of low pest incidence for Planting 1 (━) and a period of high pest incidence for planting 2 (━).

However, although this was a period of low pest incidence, the different weed treatments had a distinct effect on root damage when the cabbage plants were assessed on 14 July (Week 4) and the highest density of weeds (Treatment 1) reduced root damage by the greatest amount when compared with the

weed-free control (Figure 13). The natural weed flora (Treatment 5), which had the lowest weed density, had the least effect on root damage compared with the control treatment. At the time of the final harvest on 8 September, there was no difference in the amount of root damage between treatments, which is not unexpected, since the weed treatments had been removed some 8 weeks earlier

Again as planned, Planting 2 was transplanted during a period of high pest incidence, at the start of oviposition by the second generation of *D. radicum*. When the plants were assessed on 2 August, 4 weeks after transplanting, the root damage score from plants in the untreated plots was similar to that in Planting 1 (Figure 13). However, on this occasion there was no difference between treatments and, not surprisingly, there was also no difference between treatments at the time of the final harvest on 24 October.
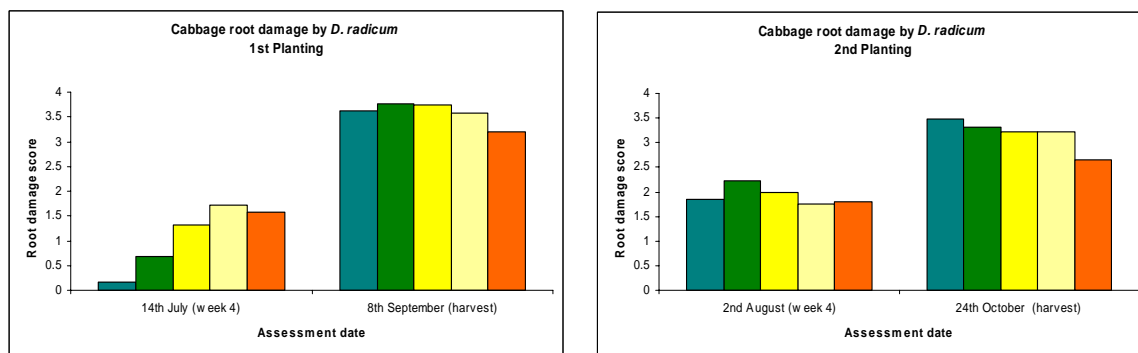

Figure 13   Cabbage root damage (shown as a score) caused by D. radicum for Planting 1 (left) and Planting 2 (right). Treatment 1 ■ (youngest weeds), Treatment 2■ (middle-aged weeds), Treatment 3 ■ (oldest weeds), Treatment 4 ■ (weed free) and Treatment 5 ■ (natural weed flora). Damage assessments made at week 4 and at harvest

There was evidence that the weed treatments in Planting 1 also reduced flea beetle damage and colonisation by alate *Brevicoryne brassicae* when the cabbage crop was young (assessment made on 1 July) (Figure 14).
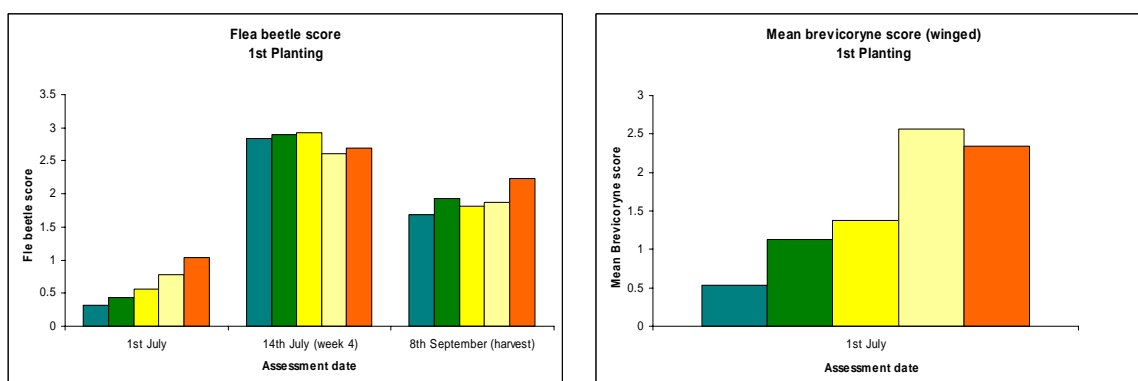

Figure 14 Flea beetle damage scores (0= none; 5= severe) (left) and alate Brevicoryne brassicae scores (0= none; 1 = 1-3; 2=4-10; 3=11-30) (right) for Planting 1. Treatment 1 ■ (youngest weeds), Treatment 2 ■ (middle-aged weeds), Treatment 3 ■ (oldest weeds), Treatment 4 ■ (weed free) and Treatment 5 ■ (natural weed flora).

The relationship between the weed : crop ratio and root damage due to *D.radicum.*
In Planting 1, a range of weed : crop ratios were achieved around the target ratio of 32.7 (Figure 15) and higher weed : crop ratios were associated with lower levels of root damage. However the target weed : crop ratio was never achieved in Planting 2 and the different weed treatments had no effect on root damage compared with the weed-free control treatment.
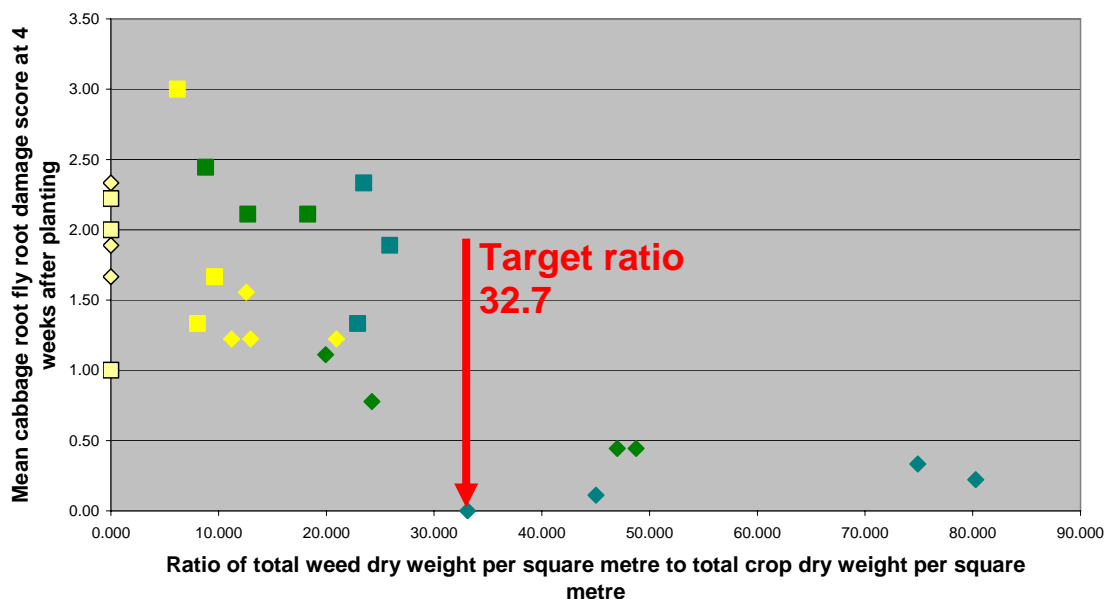
Root damage at 4 weeks v Weed-Crop Ratio

Figure 15   Root damage at 4 weeks v weed : crop ratio. Treatment 1 ■ (youngest weeds), Treatment 2 ■ (middle-aged weeds), Treatment 3 ■ (oldest weeds), Treatment 4 ■ (weed free). Planting 1 shown by diamonds and planting 2 by squares.

The relationship between the *weed : crop ratio and cab*bage growth

At harvest, cabbage fresh weight was negatively correlated with the weed : crop ratio, due to competition from the greater biomass of weeds. This was particularly pronounced in the presence of the younger *S. media,* which grew the most vigorously in the field (Figure 16). The contrast in cabbage fresh weight at harvest between Plantings 1 and 2 was probably because the cabbages grown in the two plantings were different cultivars.

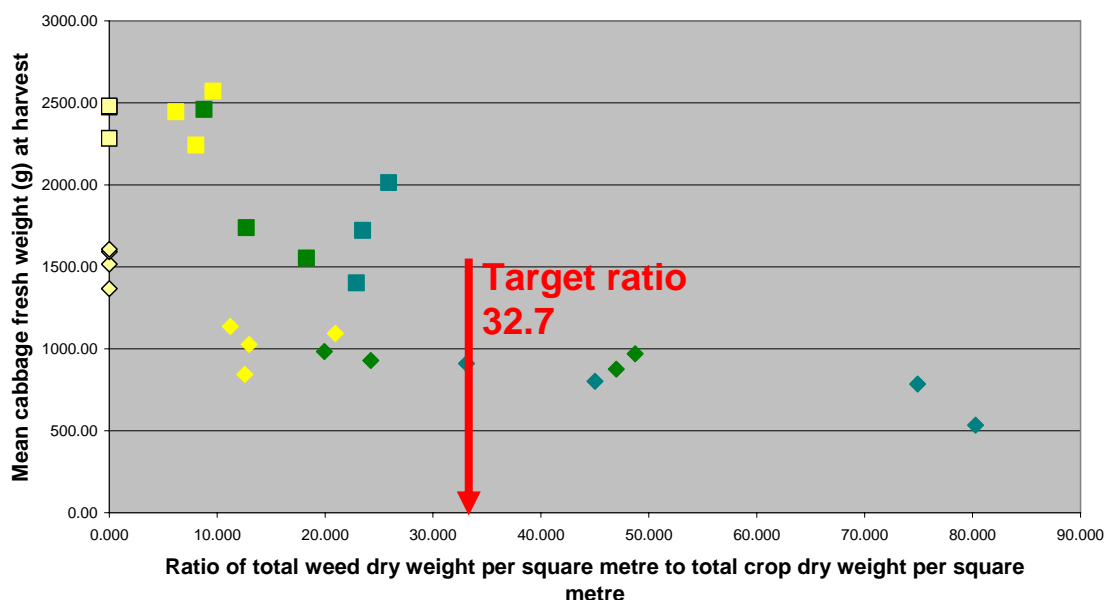Crop fresh weight at harvest v Weed-Crop Ratio

Figure 16   Crop fresh weight at harvest v weed : crop ratio. Treatment 1 ■ (youngest weeds), Treatment 2 ■ (middle-aged weeds), Treatment 3 ■ (oldest weeds), Treatment 4 ■ (weed free). Planting 1 shown by diamonds and planting 2 by squares.

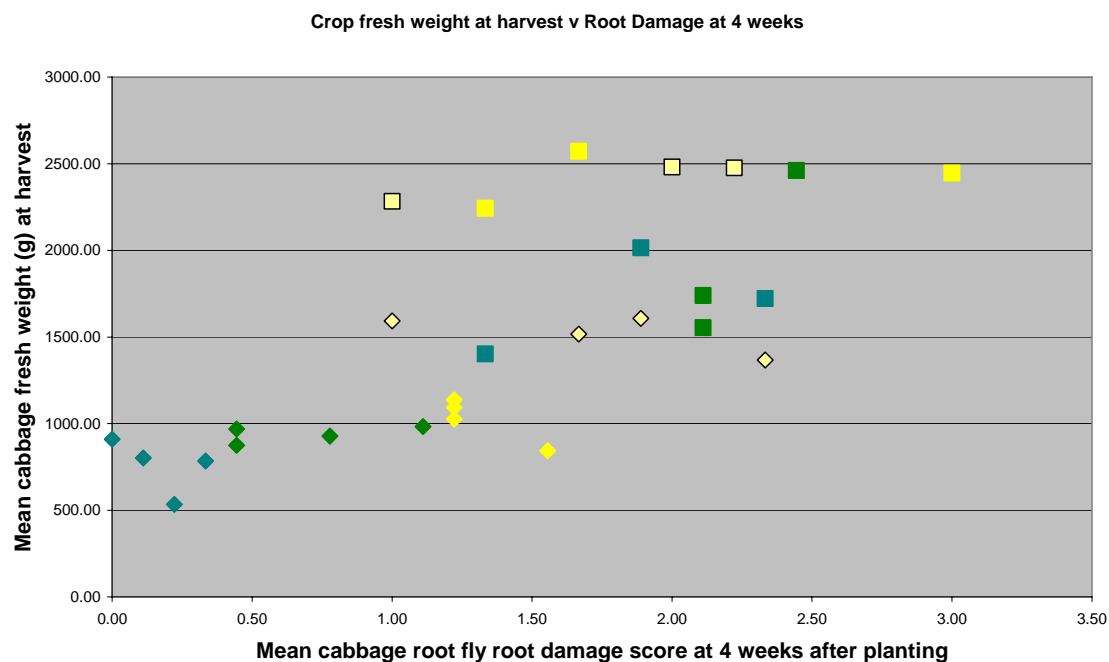**Crop fresh weight at harvest v Root Damage at 4 weeks**

Figure 17   Crop fresh weight at harvest v root damage at 4 weeks. Treatment 1 ▪ (youngest weeds), Treatment 2 ▪ (middle-aged weeds), Treatment 3 ▪ (oldest weeds), Treatment 4 ▪ (weed free). Planting 1 shown by diamonds and planting 2 by squares.

The relationship between cabbage fresh weight at harvest and *D. radicum* root damage at 4 weeks (Figure 17) illustrates the trade-off between root damage and yield loss resulting from this pest control strategy. Generally, lower root damage at 4 weeks was associated with a lower final yield. This is because the amount of weed necessary to reduce colonisation by *D. radicum* also reduced yield. Similarly, where the weeds had not grown sufficiently to offer any protective effect (e.g. the older weeds which showed signs of senescence) there was little reduction in crop yield due to weed competition.

Main conclusions of Objective 3:

Critique of the field trial approach
The strategy used to create a range of weed : crop ratios was only partially successful due to the poor growth of the transplanted weeds and to senescence of the oldest cohort in particular. An alternative approach would have been to use only young weeds, but to transplant some of them at a much higher density.

Model adequacy
The crop-weed competition model used to identify the initial plant weights and planting densities for both crop and weed was re-run with the actual initial plant weights and planting densities, using the 2005 meteorological data starting from the actual transplanting dates. Using the previously derived parameters for organic growing conditions (Defra project OF0177), the model predicted some deviations from the observed data.

•   Crop growth - the over-prediction of the crop plant dry weight at harvest in the absence of weeds could be caused by the use of a different cabbage cultivar from that used to parameterise the model. Similarly the crop plant dry weight at harvest was over-predicted for the treatments with different ages/sizes of weeds present for the first four weeks. However, the predicted percentage reduction in crop plant dry weight at harvest due to the presence of the different ages of weeds was not dissimilar from that observed, particularly for Planting 1.

•   Weed growth - weed plant dry weights at 4 weeks after transplanting were also poorly predicted by the model, with weights for the young weeds under-predicted and those for the old weeds over-predicted. The likely explanation for these poor predictions is that the model does not take account of

the additional stress imposed on the older transplants through transplant shock of root-bound modules at transplanting. These effects are likely to reduce the growth rate of the transplanted seedlings relative to the less-stressed young seedlings. A modification of the crop-weed competition model to take account of these stress-induced effects on growth rate might lead to more realistic predictions of weed growth and hence competition.

- Weed : crop ratios - the poor predictions of weed growth also led to poor prediction of the weed : crop ratio. Whilst the model predicted a reduction in this ratio from the start to the end of the 4-week period, some treatments showed an increase. Modifying the competition model to increase the relative growth rate of the weed, compared to that for the crop, leads to a predicted pattern for the weed : crop ratio more similar to that observed. One possible explanation for this higher relative weed growth rate is an effect of nutrient deficiency on the growth of weed and crop, with the weed growth rate being less sensitive to reductions in nutrient availability than that for the crop.

- Spatial aspects - a final limitation of the competition model is the dependence of the predictions on average plant density for each cohort (crop and weed in this case) rather than being able to simulate the effect of exact spatial position. It is likely (see below for comments on practical strategy) that it is only necessary to include weed plants relatively close to the crop plant to achieve the required reduction in pest numbers. This would result in a lower average plant density overall, though possibly with the achieved weed density within a small region immediately around the crop plant. An explicit spatial model would be required to simulate the impact of such an approach.

- Competition and pest control - using the achieved plant densities, the competition model predicts a reduction in crop plant weight at harvest, even if weeds are present for only a short time after crop transplanting (for example, a reduction of around 10% when weeds are present for just 15 days). To evaluate properly the potential of using the presence of weeds to reduce pest numbers, not only are the suggested improvements in the competition model needed, but further developments in the pest models are also required. Currently the pest model provides a prediction of the timing of pest activity, but to balance the loss in crop yield against the reduction in pest damage, a model linking the accumulated level of pest activity with pest damage at harvest would be required.

Assessment of strategy

- Trade-off between competition and pest control - despite difficulties in achieving the desired weed : crop ratios, this trial confirmed the value of a 'green background' in reducing oviposition by *D. radicum.* It also confirmed the negative effect of weed competition on crop yield and demonstrated the 'trade-off' between reductions in pest damage and yield. Although the weeds were removed after the first 4 weeks of cabbage growth, they still had a distinct effect on crop yield, related to their density.

- Practicalities of using the natural weed flora - in practice, organic growers would not 'transplant' weeds but would be using the natural weed flora to provide a green background. The trial has demonstrated that to achieve the required weed : crop ratio using the natural weed flora would require the weeds to be well-established prior to cabbage transplanting. However, both the competitive effect and pest control impact of a natural weed flora will depend on the composition and density of that flora.

- Proximity of weeds to crop - there is increasing evidence from studies on companion planting that, to be effective in reducing pest colonisation, the non-host plants should be in close proximity to the crop plant (Morley, 2001; Collier, unpublished data). Therefore, it is likely that only the weeds that were close to the cabbage plants contributed to 'pest control' and that the same effect could be produced if a lower total number of weeds were allowed to surround the host plant. This lower number of weeds might have less effect on crop yield, depending on the spatial characteristics of plant competition.

- Pest pressure - in these trials, *D. radicum* damage in the weed-free control plots was relatively low. None of the cabbage plants wilted or died, although all suffered some larval feeding damage to their roots. Thus, in this case, the 'protection' provided by the more effective weed treatments was 'unnecessary' and the resulting yield loss was not 'justified'. However, if pest damage had been more severe, then the weed-free control plots would have suffered some yield loss due to wilting and plant death, which would have made the weed treatment strategy look a more attractive option.

Conclusions of the study and guidelines on how best to manage weed populations to reduce crop-colonisation by pest insects:

Scientific conclusions

1) The current crop-weed competition model is driven purely by radiation interception. There are clear limitations to the model in terms of its ability to cope with multi-species populations of natural weed flora (i.e. parameters need to be obtained for a wider range of species), the relative growth of crop and weeds in nutrient deficient soils, and crop and weed response to moisture stress.
2) The crop-weed competition model provides an adequate prediction of competition based on average plant density. Modification of the model to account for the spatial proximity of the plants and their growth plasticity would enable more realistic and practical strategies to be evaluated (e.g. only having weeds within a small radius of the crop plant)
3) Pest models currently provide a robust prediction of the timing of pest infestations, but predictions of pest abundance and subsequent damage would be needed to fully evaluate the trade-off between yield loss through plant competition and the reduction in pest damage.

Practical conclusions

1) The trade-off between crop yield and pest control is clearly illustrated by the study. Yield loss (up to 30%) due to competition may be tolerable and variety choice may have compensatory benefits. However, the impact of varietal choice on competition needs to be explored.
2) The study has shown that the strategy of allowing weed presence for a limited period can provide some protection against pest damage.
3) Planting into a background of natural flora is probably the most practical way of achieving this protection, but further information is needed on the development of natural floras, and on the effect of different weed species compositions.
4) Weeds in close proximity to the crop do reduce pest colonisation, as seen in other studies, but further information is needed on the competitive impact of these weeds on the crop.

Knowledge Transfer

Talks

- Pest control without insecticides – Midlands Grower Show June 2003
- Pest control in organic field vegetable and salad crops – Organic Growers Day – Duchy College, Cornwall July 2003.
- Alternative approaches to foliar pest problems. Brassica Growers Association Conference January 2004 (described in HDC News March 2004).
- Organic Open Day at Kirton Research Centre, Warwick HRI, July 2004
- HDRA Open Day Pollybell Farms, September 2004
- Organic Workshop HDRA/Warwick HRI at Warwick HRI, Wellesbourne, October 2004
- Seminar on weed management in horticulture at the University of Reading, March 2005
- Seminar Integrated Pest Management in horticultural crops at Harper Adams April 2005
- Insecticide-free management of vegetable pests AAB meeting, Peterborough September 2005
- Using weeds to control pest insects Vegetable Consultants Association AGM, Moreton in Marsh, December 2005
- Can we exploit nature to control brassica pests? Brassica Conference, Wellesbourne, January 2006
- Seminar on Integrated Pest Management in horticultural crops Seminar at Newcastle University, March 2006

Posters

- The effect of increased crop diversity on colonisation by pest insects of *Brassica* crops. *BCPC International Congress, Crop Science and Technology November 2003*.
- Effect of within crop diversity on colonization by pest insects. Organic Farming: Science and Practice for Profitable Livestock and Cropping. *BGS/AAB/COR Conference held at the Harper Adams University College, Newport, Shropshire, 20-22 April 2004*

Related papers

- Collier, R.H. & Finch, S. (2003). The effect of increased crop diversity on colonisation by pest insects of *Brassica* crops. *BCPC International Congress, Crop Science and Technology 2003*, 439-444.
- Finch, S. & Collier, R.H. (2004). Effect of within crop diversity on colonization by pest insects. Organic Farming: Science and Practice for Profitable Livestock and Cropping. *Proceedings of the BGS/AAB/COR Conference held at the Harper Adams University College, Newport, Shropshire, 20-22 April 2004*. 204-207.
- Billiald, H., Finch, S., Collier, R. & Elliott, M. (2005). Disrupting host-plant finding by pest insects of cruciferous plants using aromatic and non-aromatic plants. *Integrated Protection in Field Vegetable Crops. IOBC/WPRS Bulletin,* 28 (4), 53-59.
- Finch, S. & Collier, R.H. (2005). Answers to questions concerning the "Appropriate/inappropriate landing" theory of host-plant finding. *Integrated Protection in Field Vegetable Crops. IOBC/WPRS Bulletin,* 28 (4), 103-121.
- Morley, K., Finch, S. & Collier, R.H. (2005). Post-alightment behaviour of the female cabbage root fly during the search for a host plant. *Integrated Protection in Field Vegetable Crops. IOBC/WPRS Bulletin,* 28 (4), 123-128.
- 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.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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