Final Report: 1994-98

Project Number: P 132 & FV 163

Project Title: Adaptive sampling and control of caterpillar pests of horticultural brassica crops

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Location of Project: HRI Kirton, HRI Wellesbourne, HRI Stockbridge House, ADAS Arthur Rickwood

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Date project commenced: 1 August 1994

Date project to be completed: 31 July 1998

Key words: Caterpillar, leafy brassica, small white butterfly, *Pieris rapae*, cabbage moth, *Mamestra brassicae*, large white butterfly, *Pieris brassicae*, garden pebble moth, *Evergestis forficalis*, diamond-back moth, *Plutella xylostella*, silver Y moth, *Autographa gamma*, forecast, development, monitoring, pheromone trap, water trap, sampling, distribution, insecticide, *Bacillus thuringiensis*.

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SCOPE AND OBJECTIVE

Overall objective:

To develop an adaptive sampling and control system for caterpillar pests on horticultural brassicas based on sound scientific principles.

Individual objectives:

1. To determine the distribution of the five key caterpillar pests in commercial fields of horticultural brassicas.

2. To develop an adaptive sampling protocol to provide a cost effective and accurate estimate of pest populations based on the distribution of caterpillars in crops.

3. To develop and validate forecasts that predict the timing of key events in the development of the five pest species, so crop monitoring can be targeted accurately.

4. To quantify the relative susceptibility of the different caterpillar species to different selective products.

5. To assess the effectiveness of current and novel selective agents for the control of caterpillars as compare to broad-spectrum insecticides.

6. To draw together the forecasts and crop sampling methods, derived from knowledge of caterpillar distributions, with selective methods of control in an adaptive sampling and control system.

7. To compare the effectiveness of the adaptive sampling and control programme with current routine treatments of broad-spectrum products to provide a marketable crop.

SUMMARY

The results are summarised briefly by objective:

1. To determine the distribution of the five key caterpillar pests in commercial fields of horticultural brassicas.

- Attacks sporadic.
- All species show 'edge' effects on occasions. Plants on edges often more infested than plants in middle.
- Most species show spatial clustering on some occasions. Some species clumped.
- Strong, consistent relationship between proportion of plants infested and mean infestation level.

- Variation usually greatest between edges of field, but sometimes considerable variation within an edge.

2. To develop an adaptive sampling protocol to provide a cost effective and accurate estimate of pest populations based on the distribution of caterpillars in crops.

- Proportion of plants infested as accurate as numbers of pests/plant.
- Sample from edges of crop to increase chances of detecting worst scenario.
- Sample from all four edges of crop to get best estimate of pest population.
- If wish to treat headlands and main crop independently, take separate samples.
- To ensure good estimate and 'independent' infestation events, sampling plants should be separated by at least 6 or 7 plants.
- Sample over wide area within each edge.
- Large samples give accurate estimates. Reliable decisions possible with smaller samples if proportion of plants infested is either much higher or lower than tolerance level. Good argument for sequential sampling systems.
- Project has identified important characteristics of any sampling situation. Should be possible to use this information plus 'grower constraints' to set up sampling schemes.

3. To develop and validate forecasts that predict the timing of key events in the development of the five pest species, so crop monitoring can be targeted accurately.

- Diamond-back moth and silver Y moth are mainly migrants. Other species overwinter in UK.
- Development rate determined by temperature. Faster when weather warm.
- Generations - cabbage moth (2), garden pebble moth (2), small white butterfly (2+), diamond-back moth (3+).
- Forecasts developed for diamond-back moth, small white butterfly, garden pebble moth, cabbage moth.

4. To quantify the relative susceptibility of the different caterpillar species to different selective products.

- Laboratory bioassays showed wide range in susceptibility of species to *Bt* products (Dipel/Bactospeine and Agree).
- Cabbage moth least susceptible species to Bactospeine/Dipel but more susceptible to Agree.
- Garden pebble moth more susceptible to Agree than other products.
- Agree, Dipel, Bactospeine equally effective against diamond-back moth and small white butterfly.

5. To assess the effectiveness of current and novel selective agents for the control of caterpillars as compared to broad-spectrum insecticides.

Four insecticide efficacy field experiments done at ADAS Arthur Rickwood in 1995. Five treatments: untreated, deltamethrin (Decis), diflubenzuron (Dimilin) and two *Bt* products, Bactospeine and Agree.

- Diflubenzuron least effective of all products tested.
- Deltamethrin gave maximum control within 2-3 days.
- *Bt* products acted more slowly than deltamethrin but similar levels of control against diamond-back moth and small white butterfly within 7-10 days.
- Agree sometimes more active than Bactospeine against cabbage moth and garden pebble moth.

6. To draw together the forecasts and crop sampling methods, derived from knowledge of caterpillar distributions, with selective methods of control in an adaptive sampling and control system.

System of managed control for caterpillar pests of Brussels sprouts was developed and tested in field experiments at ADAS Arthur Rickwood, HRI Kirton and HRI Stockbridge House in 1996 and 1997.

It used:

- Information on pest activity (forecasts/monitoring) to target start of crop walking.
- Crop walking to estimate proportion of plants infested.
- Previously determined pest tolerance levels to decide whether to **spray** immediately, **not to spray**, or to return to re-assess the crop at a later date (**no decision**).

Management system was executed using either deltamethrin (Decis) or *Bt* (Agree) to control the caterpillars. Managed plots were compared with plots, which had been sprayed routinely with deltamethrin and with untreated plots.

7. To compare the effectiveness of the adaptive sampling and control programme with current routine treatments of broad-spectrum products to provide a marketable crop.

- In 1996, management system equally effective whether deltamethrin or Agree used.
- Both treatments as effective as routine two-weekly sprays of deltamethrin.
- Caterpillar infestations considerably lower in 1997 and damage low in all plots, including untreated controls.
- In 1996, average of 8.3 sprays applied to managed plots. In 1997 reduced to 1.7 sprays.
- Routine programmes of 10-12 sprays/crop did not produce 100% undamaged buttons.
- Buttons on lower parts of stem most damaged.

ACTION POINTS FOR GROWERS

1. Attacks by caterpillars are sporadic and do not occur in every crop each year. Of the five species of caterpillar included in this study, the diamond-back moth (*Plutella xylostella*) appears to have been the most damaging commercially. This was followed by, in decreasing order of importance, the small white butterfly (*Pieris rapae*), cabbage moth (*Mamestra brassicae*), garden pebble moth (*Evergestis forficalis*), large white butterfly (*Pieris brassicae*) and silver Y moth (*Autographa gamma*).

2. Sampling has shown that, on average, plants on the edges of a brassica crop are more heavily infested with caterpillars than those in the middle. Variation is usually greatest between the edges of field, but there is sometimes considerable variation within an edge

3. The pheromone traps used in this project for diamond-back and garden pebble moths were effective and caught few individuals of non-target species. The lures used for cabbage moth were relatively non-specific and ineffective. Very few adult cabbage moths were captured, although caterpillars were observed in untreated plots at several sites. Water traps captured adult small white butterflies at all sites, but few large white butterflies were captured. Vertical yellow/orange sticky traps did not capture as many butterflies as water traps.

4. Diamond-back moth and silver Y moth are mainly migrants. Other species overwinter in UK. Diamond-back moths complete up to 4 generations each year, small white butterflies 2-3 generations, garden pebble and cabbage moths, 2 generations.

5. Preliminary forecasts of the timing of activity have been developed for diamond-back moth, small white butterfly, cabbage moth and garden pebble moth. These were validated using monitoring data collected at four sites during 1994-1997. The forecasts now require further validation and refinement before they can be used on a commercial scale.

6. Laboratory bioassays showed a wide range in the susceptibility of pest species to the *Bt* (*Bacillus thuringiensis*) products tested (Dipel/Bactospeine and Agree (not registered in the UK)). The cabbage moth was the species least susceptible to Bactospeine/Dipel, but was more susceptible to Agree. The garden pebble moth was also more susceptible to Agree than to the other two products. However, Agree, Dipel and Bactospeine were equally effective against the diamond-back moth and small white butterfly.

7. Four insecticide efficacy field experiments were done at ADAS Arthur Rickwood in 1995. There were five treatments: untreated, deltamethrin (Decis), diflubenzuron (Dimilin) and the two *Bt* products, Bactospeine and Agree. Diflubenzuron was the least effective of all the products tested. Deltamethrin gave maximum control within 2-3 days of treatment. Both *Bt* products acted more slowly that deltamethrin but usually gave similar levels of control against the diamond-back moth and small white butterfly within 7-10 days. Agree was sometimes more active than Bactospeine against the cabbage moth and garden pebble moth.

8. In 1996, a preliminary management system for the control of caterpillars on Brussels

sprouts was equally effective whether deltamethrin or the *Bt* product Agree was used. Both treatments were as effective as routine two-weekly sprays of deltamethrin. A revised management system was evaluated in 1997. Caterpillar infestations were considerably lower in 1997 and damage was low in all plots, including the insecticide-free controls. In 1996, an average of 8.3 sprays was applied to the managed plots whereas in 1997 this was reduced to 1.7 sprays in response to the low numbers of caterpillars.

BENEFITS

- Customised sampling protocols can be produced which are tailored to the requirements of the grower in terms of tolerance levels used, accuracy required and time spent in sampling.

- Forecasts have been developed for diamond-back moth, small white butterfly, garden pebble moth and cabbage moth.

- The effective use of *Bt* products to control caterpillar pests of brassica crops has been demonstrated. In the future, Agree, or a similar *Bt* product, may be made available to UK growers as an insecticide for brassica crops.

- The principles underlying the caterpillar management system can be made available to growers, advisors and retailers.

SCIENCE SECTION

INTRODUCTION

Edible brassica crops are sprayed extensively to control foliar pests, particularly caterpillars and aphids (Garthwaite *et al.*, 1995). Crops are often treated routinely with little reference to pest numbers or crop growth stage. The caterpillars of several species of butterfly and moth can damage brassica crops, but with varying severities in different seasons.

Previous MAFF-funded research and a parallel HDC-funded project have shown that considerable savings can be made in applications of insecticides for caterpillar control by using systems of managed control to apply sprays only when necessary (Blood Smyth *et al.*, 1992; 1994; Emmett, 1992; Paterson *et al.*, 1994). Pest numbers were assessed by careful field sampling and treatment decisions were made using previously determined pest tolerance levels. However, to date, even within commercial crops, all the results had been obtained from plot experiments. Sampling techniques needed to be developed to make them more appropriate to commercial practice and to reduce the cost of monitoring, by targeting crop visits to coincide with critical life stages of the pests.

At present most growers control caterpillars using broad-spectrum pyrethroid insecticides. However, there may be scope for the use of more selective pesticides, such as diflubenzuron (Dimilin) or the insect pathogenic bacterium *Bacillus thuringiensis* (*Bt*). New developments in selective products have resulted from recent MAFF-funded work and strains of *Bt* with improved activity against a range of caterpillar pests have been developed by combining strain selection with genetic studies. A number of trans-conjugant strains of *Bt* have been produced and the best (coded GC91) has been patented by the Agricultural Genetics Company and is being produced commercially in the USA.

The aim of this project was to develop a strategy for the control of caterpillar pests in commercial Brussels sprout crops employing appropriate field sampling techniques, targeted in time through forecasts of pest development. Using appropriate pest tolerance levels, applications of selective pesticides would be made only when necessary, thereby achieving a more sustainable system of caterpillar control.

The within-crop distribution of the key caterpillar pests (small white butterfly, *Pieris rapae*; large white butterfly, *Pieris brassicae*; cabbage moth, *Mamestra brassicae*; diamond-back moth, *Plutella xylostella*; garden pebble moth, *Evergestis forficalis*; silver Y moth, *Autographa gamma*) was determined to enable development of a sampling protocol to assess caterpillar populations accurately in commercial fields. To target crop visits, forecasts to predict the timing of key events in the life cycle of the four main pest species were developed, and validated using field-monitoring data. Laboratory assays were used to assess the relative susceptibility of the different caterpillar species to different selective products (Dimilin, Bactospeine, Agree) and field experiments were used to compare the effectiveness of these selective products with broad-spectrum insecticides.

Finally, the system of caterpillar control developed was compared with conventional routine use of broad-spectrum insecticides. Comparisons were made between the respective sampling and control inputs, and at harvest, crop marketability was assessed.

Scientific objectives

Overall objective:

To develop an adaptive sampling and control system for caterpillar pests on horticultural brassicas based on sound scientific principles.

Individual objectives:

1. To determine the distribution of the five key caterpillar pests in commercial fields of horticultural brassicas.

2. To develop an adaptive sampling protocol to provide a cost effective and accurate estimate of pest populations based on the distribution of caterpillars in crops.

3. To develop and validate forecasts that predict the timing of key events in the development of the five pest species, so crop monitoring can be targeted accurately.

4. To quantify the relative susceptibility of the different caterpillar species to different selective products.

5. To assess the effectiveness of current and novel selective agents for the control of caterpillars as compare to broad-spectrum insecticides.

6. To draw together the forecasts and crop sampling methods, derived from knowledge of caterpillar distributions, with selective methods of control in an adaptive sampling and control system.

7. To compare the effectiveness of the adaptive sampling and control programme with current routine treatments of broad-spectrum products to provide a marketable crop.

EXPERIMENTAL

The experimental work described in this section is presented by objective.

1. To determine the distribution of the five key caterpillar pests in commercial fields of horticultural brassicas.

Determination of within-crop distribution of caterpillars

Sampling was done in all four years of the project (Table 1a). In the first two years, samples were taken from untreated plots located at the experimental sites (HRI Kirton, HRI Stockbridge House, HRI Wellesbourne, ADAS Arthur Rickwood). This was to provide relatively large infestations, which had not been treated with insecticide, from which to determine the underlying distribution of caterpillars.

Caterpillar populations were also sampled in commercial brassica crops during all four years of the project to determine the within-crop distribution of each pest species. As these were commercial crops, pesticide treatments were applied from time to time and crops were sampled usually before a fresh treatment was applied. However, in many cases, infestation levels and the variety of species present were lower in the commercial crops than in the untreated plots.

Sampling was done by teams based at HRI Kirton, HRI Stockbridge House and ADAS Arthur Rickwood. Crops were located by direct contact with growers (OLGA, UNIVEG, Bedfordshire Growers), by ADAS and by other consultants. In addition, in 1994, a short article was placed in the 'Grower', requesting suitable sites.

Plants were sampled for six species (*P. xylostella*, *M. brassicae*, *E. forficalis*, *A. gamma*, *P. rapae*, *P. brassicae*). Where feasible, the numbers of eggs, caterpillars and pupae of each species were recorded on each plant. The length of each caterpillar was estimated in mm, as an indication of development stage. The data for each field were entered onto spreadsheets prior to analysis.

A plan was drawn of each commercial field to record its approximate dimensions and orientation (N, S, E, W), the crop and the height of the field boundaries. Photographs were taken of the field boundaries.

Sampling in untreated field plots

1994

The distribution of caterpillar pests was determined in untreated Brussels sprout plots (50 x 75 plants) situated at four sites (HRI Kirton, HRI Stockbridge House, HRI Wellesbourne and ADAS Arthur Rickwood). These plots were sampled on up to five occasions during the summer to determine the spatial distribution of the species present. Pest distribution was assessed by examining every plant within transects taken in both directions across the plot, or within 5 x 5-plant blocks of plants.

1995

During 1995, further information on the distribution of the five species was obtained by taking samples from untreated Brussels sprout plots (50 x 75 plants) located at the same four sites. Each plant within a 10 x 40-plant block was inspected to obtain detailed information on pest distribution. Samples were taken when levels of target species exceeded 0.25-0.5 insects per plant. This was determined by monitoring 100 plants around the perimeter of the plot, once a week throughout the summer.

Sampling in commercial crops

1994

During 1994, Brussels sprout crops were sampled by teams based at HRI Kirton, HRI Stockbridge House and ADAS Arthur Rickwood, because although not considered to be the most susceptible to caterpillar attack, they are a long season crop and may be infested by all pest species. Infested crops were located by preliminary scouting. To assess the distribution of the various species, the samples taken in each field consisted of: 10 x 25-plant transects (from the edge of the crop inwards, inspecting every plant) and 20 x 25-plant samples from within the crop (5 x 5 blocks with 20-plant gaps between them). Thus a total of 750 plants were examined in each field on each occasion.

1995
During 1995, commercial fields were sampled by a team based at HRI Kirton. Sampling was done in all species of leafy brassica crop, rather than restricting it to Brussels sprouts. A total of 700-800 plants were examined in each field. The samples consisted of 105 plants from a 64 x 13-plant block on the headland and 93 plants from three 200-plant transects into the crop. One of these samples was taken from each side of the field. The composition of the field boundary (e.g. plant species and height) adjacent to each set of samples was recorded in detail.

1996
Sampling data collected during the first two years of the project indicated that although most species could be found some distance into the crop, there was often an 'edge effect' with larger numbers being found close to the field boundaries. Therefore, it seemed likely that, to detect the worst scenario, growers should examine the edges of the crop rather than the middle. To test this hypothesis, during 1995 and 1996, samples were taken from specified areas of each commercial crop; either the edge, corner or middle. These data were then used to test sampling strategies within a simulation program.

During 1996, commercial fields were sampled by a team based at HRI Kirton and a team based at ADAS Arthur Rickwood. Between 11 July and 23 October, 21 commercial crops of brassicas (20 sites in South Lincolnshire and 1 site in Bedfordshire) were sampled intensively to determine the numbers of plants infested with caterpillars.

Plants were sampled from nine locations within each field. The locations and numbers of plants sampled in each crop were as follows:

Edges	50 plants from each edge
Corners	50 plants from each corner
Middle	150 plants from the centre of the crop

Thus a total of 550 plants were sampled in each field.

Sampling plan
Edges - 10 plants were sampled from each of rows 6-10 from the outside edge. Within a row the sampled plants were 5 paces apart and the rows were staggered to avoid sampling adjacent plants in neighbouring rows.

Corners - 5 plants were sampled from each of rows 6-15 in each corner. Within a row the sampled plants were 3 paces apart and the rows were staggered to avoid sampling adjacent plants in neighbouring rows. The sampling plan was adapted for corners, which had not been planted completely.

Middle - 10 plants were sampled from each of 15 alternate rows in the centre of the crop. Within a row the plants were 5 paces apart and the rows were staggered.

1997

Between 1 August and 29 October 1997, 16 commercial *Brassica* crops in Lincolnshire and 1 crop in Bedfordshire were sampled intensively to determine the numbers of plants infested with caterpillars. Plants were sampled from five locations within each field. The locations and numbers of plants sampled in each crop were as follows:

Edges	50 plants from each edge (in some crops an additional 250 plants were sampled along one edge)
Middle	100 plants from the centre of the crop

Thus totals of 300 or 550 plants were sampled in each field.

Sampling plan

Edges - 10 plants were sampled from each of rows 6-10 from the outside edge. Within a row the sampled plants were 5 paces apart and the rows were staggered to avoid sampling adjacent plants in neighbouring rows. In some fields a further 250 plants were sampled from one edge. These samples were also taken from rows 6-10 but were taken over a longer distance. In general, the edge with the most diverse field boundary was chosen.

Middle - 10 plants were sampled from each of 10 alternate rows in the centre of the crop. Within a row the plants were 5 paces apart and the rows were staggered.

Results

Examples of transects taken from the 50 x 75-plant untreated Brussels sprout plots in 1994 and 1995 are shown in Figures 1a and 1b. 'Edge' effects were apparent for some species on some occasions. When pest numbers were low it was difficult to detect any spatial pattern.

Various statistical approaches were used to describe the within-crop distribution of caterpillars. Using the transect data (examples shown in Figures 1a & 1b), a smoothed pattern of infestation was produced for each species in each transect by calculating 5-plant running means. Figure 1c shows frequency distributions for the plant with the maximum number of caterpillars. The maximum number of caterpillars was found more frequently on plants 1-5 (running mean 3) than on any other plant. However, for all species there were still a considerable number of occasions when the maximum number of caterpillars was not found at the edge of the crop and even when it was, the change in numbers of insects per plant from edge to middle was often not very great.

Curves were fitted to those sets of data where there was an apparent edge effect. The parameters of the fitted curves provide estimates of the maximum infestation level (at the edge), the mean infestation level across the middle of the field, and the rate of decrease of infestation level into the crop (Figure 1d).

The data collected from commercial crops in 1995 were used to examine the levels of variation between and within the different edges of the crop. Plants were sampled from a 64 x 13-plant block on each edge of the crop and from three 200-plant transects going into the crop from each edge. Comparison of mean squares showed that variation was usually greatest between edges and least within transects. However, there was sometimes considerable variation between transects on the same edge.

Various discrete distribution functions were fitted to the observations on plants from the middle of crop. This was to determine whether pests were distributed evenly, randomly, or in clumps. The mean-variance relationships showed that all species were more aggregated than a random distribution (Figure 1e) but *P. rapae* and *P. xylostella* were less clumped than *E. forficalis* and *M. brassicae*. A similar result was shown by fitting negative binomial distributions. Species with a smaller value of k are more aggregated (Figure 1f). k also increased with the mean size of the infestation indicating that there was less appearance of clumping when infestations were greater.

For each set of data collected in 1994-95, estimates were obtained of the proportion of plants infested. Grouping all species together, there was a strong relationship between the proportion of plants infested and the mean infestation level (Figure 1g). There was, however, a good deal of scatter. The data collected in 1995 were grouped by sampling date (early season, mid-season, late season) to determine whether there was a temporal effect on the relationship (Figure 1h). No temporal effect was evident.

Assessment of spatial patterns of infested plants
Data collected from the wide transects (10 x 40 plant blocks) sampled in the untreated plots at the four experimental sites in 1995 were used to assess whether the distribution of infested plants displayed any spatial pattern.

Two approaches were developed to determine whether or not infested plants were likely to occur near to other infested plants, i.e. whether or not infested plants occurred in clusters. The results of these analyses can be used to determine the minimum distance between sampling locations in the adaptive sampling scheme. If infested plants do occur in clusters, it is important to avoid examining plants from the same cluster since these observations may not be of independent infestation events. By selecting an inter-plant distance that avoids sampling the same cluster when the overall infestation level is low, it will still be possible to estimate high infestation levels. However, the probabilities of either overestimating the infestation level (by observing the same cluster more than once) or of underestimating the infestation level (by failing to observe clusters when the sampling area is too small) will be reduced.

Approach 1 – Black-White Join-Count Statistic
This approach is based on counting the number of times an infested plant is the neighbour of a non-infested plant. The identification of a first neighbour (adjacent plant) can be extended to second neighbours (one intermediate plant), third neighbours (two intermediate plants), and so on. Counts of neighbouring plants in different states (infested and non-infested), for each type of neighbour, can then be compared with the expected count if the distribution was entirely random. A much lower count than expected indicates clustering of infested (or non-infested) plants (depending on the overall density), whilst a higher count than expected indicates a uniform distribution. The extent of the clustering (size of clusters) can be determined by considering the significance of the comparisons for the first, second, third, etc neighbours. Where the proportion of plants infested is high, the test is of clustering of non-infested plants and a lack of spatial correlation or a limited number of significant neighbourhoods indicates

that these non-infested plants are randomly distributed.

Table 1b shows the plant neighbourhoods showing significance levels of $p < 0.05$ for the Black-White Join-Count Statistic for samples taken in untreated plots at the four sites (HRI Wellesbourne, HRI Kirton, HRI Stockbridge House and ADAS Arthur Rickwood) during 1995. Significance levels of $p < 0.05$ indicate that there is spatial correlation between infested plants or non-infested plants. Although there is some variability, there is evidence that, in some instances, spatial correlation persisted up to the ninth neighbouring plant.

Approach 2 – Probability of infested plants within neighbourhood
This approach is based on calculating, for each infested plant, the probability of finding another infested plant within a defined neighbourhood. In contrast to the first approach, where neighbourhoods are defined as rings of plants around each focus plant, the neighbourhoods for this second approach contain all plants within a certain distance of one focus plant. The rationale for this approach is that if infested plants occur in clusters, then the probability of finding more infested plants within the neighbourhood of an infested plant will be higher than if infested plants are randomly distributed.

To assess the degree of clustering of each observed spatial pattern, the observed proportion of infested neighbours was compared with a distribution of similar values generated through 1000 computer simulations of patterns with the same overall infestation level. An observed value that is significantly greater than the mean obtained from the simulations indicates that the observed pattern exhibits more clustering of infested plants than would be expected if the distribution was random. Table 1c shows the plant neighbourhoods showing significance levels of $p < 0.05$ for this second approach. A similar pattern of clustering was obtained to that observed in the first approach.

1996 and 1997
The overall mean level of caterpillar infestation in the 21 intensively sampled fields in 1996 was 15.2% plants infested. In the 16 fields sampled in 1997, an average of 29.1% of plants were infested with *P. xylostella* and 6.3% with *P. rapae,* the next most numerous species. Caterpillars were found in every field sampled. The numbers of plants infested with each species in 1996 and 1997 are shown in Table 1d. *P. xylostella* was the most numerous species by far. A summary of the data collected from commercial crops in 1996 and 1997 is given in Appendix 1.

Corners, edges and middle
On average, plants sampled at either the edges or the corners of the field were equally infested (Figure 1i). In most cases, plants on the edges of the field were more infested than plants in the middle of the field, particularly when the worst affected edge was compared with the middle (Figures 1j & 1k).

Variation between edges and corners
There were often differences between the edges and the corners of an individual field in the percentage of plants infested. The orientation (N, S, E, W) of the most heavily infested edge(s) in each field was determined (Table 1e). No pronounced trend was evident, although more caterpillars were found along the SW/NE axis.

Similarly, the heights of the field boundaries were compared with the percentage of plants infested and again no pronounced trends were evident. However, most of the field boundaries were low and few of the fields were consistently bounded by very tall hedges or trees; which may be important factors in determining caterpillar distribution in more sheltered fields.

Caterpillar distribution also did not appear to be affected consistently by crop species in the fields that were planted with more than one crop.

2. To develop an adaptive sampling protocol to provide a cost effective and accurate estimate of pest populations based on the distribution of caterpillars in crops.

Simulation of crop sampling strategies

A program was developed in the computer package MATLAB to simulate a range of crop sampling strategies using the data sets collected from commercial fields during 1996 and 1997. The development of the program was funded by HDC Project FV 194.

Options, which can be selected within the program, include:

1) Crop

Currently the 37 data sets collected in 1996 and 1997 are available, covering a range of brassica crops sampled at different times of year.

3) Areas of the field to be sampled

Data are available on pest infestation levels in the 4 corners of the field (1996 only), along the 4 edges of the field, and from the middle of the field. Any combination of areas can be selected, and the number of edges or corners to be sampled must also be chosen where appropriate. Presently, where multiple corners or edges are selected these are chosen at random within each simulation run. In a future version of the program it would be possible to select specific corners or edges.

4) Sample size

Limits on the possible sample size are set according to the areas selected. Having selected the overall sample size it is possible to sample equally from each of the selected areas, or according to a range of pre-defined ratios (e.g. two thirds of the samples from one area and one third from another area).

5) How plants are chosen within the sampling areas

Plants can either be sampled completely at random, along pre-defined transects, or from clumps. The same approach is used in each of the sampling areas.

6) Number of replicate simulations

A default setting of 100 is provided - the more simulations the longer it takes to produce results, but the more accurate the picture of potential variability.

The results of the repeated runs for each sampling strategy are summarised both numerically and graphically, demonstrating the potential variability in the estimate of the level of pest infestation (see Results (Figure 2a) and Appendix 2). By running simulations of a number of different sampling strategies the benefits of selecting a suitable sampling strategy can be seen. Future developments of the program could incorporate the decision making process mentioned above and the use of a sequential sampling approach.

The simulation program allows an infinite number of sampling strategies to be tested and can be used to indicate trends associated with, for example, changes in sample size or in sampling area. Figure 2a shows the graphical output from 100 repeated simulations of one such sampling strategy, where only one edge of the selected crop (cauliflower sampled on 23 October 1996) was examined and 10 plants were selected along a transect (print of simulation run is in Appendix 2). The mean infestation level was 9.5% and the range of estimates of the level of infestation was from 0-40%.

Sample size
Figure 2b shows the effect of sample size on the coefficient of variation (CV) when repeated (100) simulations were made of a sampling strategy including all four edges of the crop. The CV is the ratio of the standard deviation to the mean and if, for example, the CV is 5% of the mean, 95% of estimates made will be within approximately $\pm$ 10% of the true infestation level; although this will also be influenced by the absolute size of the infestation.

As the sample size increased, repeated estimates of the percent plants infested became more reproducible and the CV was reduced. The CV was affected also by the overall level of caterpillar infestation within the crop and when caterpillar numbers were high, the sampling strategy was reproducible (low CV) even at quite low sample sizes.

Sampling areas
Choice of sampling area(s) will also determine the variability of the estimate of the population. If samples are taken only from the middle of the crop then this will often indicate a level of infestation which is lower than that in the field edges. If only one of the edges or corners is sampled then this estimate may not necessarily indicate the worst scenario. Figure 2c shows the effects on the CV of sampling from 1 to 4 edges or from 1 to 4 corners in two crops where the distribution of caterpillars was uneven. In general the CV was reduced and estimates became more reproducible as more edges or corners of the crop were sampled.

Current methods of crop walking
When crop walking, growers are prepared to spend at least 15-20 minutes in individual crops looking for pests, disease and other problems. They will look at a number of plants (possibly 20-30), although usually not as thoroughly as for experimental purposes. They generally look at several plants on the edge of the crop, usually in the edge nearest to the field entrance, and then walk a transect into the crop stopping to examine plants at intervals. They do not record what they find on individual plants but tend to make their decisions based on experience and a 'gut feeling'. Many of the growers keep records of their general impressions of the crop to support spray decisions. One of the greatest problems for growers is having enough time to walk all the crops at regular intervals and a system which would enable them to group fields

with respect to crop walking information would be very useful.

Comparison of grower practice with simulations
On 8 September 1997, a group of growers from OLGA visited a commercial calabrese crop near Friskney in south Lincolnshire and 21 members of the group walked the crop to determine the proportion of plants infested with aphids and with caterpillars. Each member of the group looked at a sample of 25 plants of their choice. The crop had been sampled earlier in the day by a team of scouts from HRI Kirton who obtained an estimate of the overall size of the infestation. The data were collated in the field for discussion with the group and compared subsequently with MATLAB simulations, using similar aphid and caterpillar infestation levels and a sample size of 25.

Aphid numbers were extremely low in the target crop, with an average of 5% of plants infested with either cabbage aphid or peach-potato aphid. However, 26% of plants were infested with caterpillars. Sampling by the 21 growers was compared with simulations based on similar levels of infestation. Although the growers' findings were broadly in line with the simulation, they were more variable and contained more zeros (Figure 2d).

3. To develop and validate forecasts that predict the timing of key events in the development of the five pest species, so crop monitoring can be targeted accurately.

Forecast development

There is some published information on the relationship between the rate of development and temperature for all species except *E. forficalis*. Most of the data were collected outside the UK (with the exception of some information on *P. rapae*, *P. brassicae* and *A. gamma*) and may not be applicable to UK populations. It was necessary, therefore, to collect data from UK populations to determine whether their response to temperature was similar to that recorded elsewhere. If so, it could be used in the construction of models in the UK.

Continuous development
Laboratory experiments were carried out to determine the temperature requirements for development of *E. forficalis*, *P. xylostella* and *M. brassicae*. Laboratory populations were established from insects collected in the field at ADAS Arthur Rickwood, HRI Wellesbourne and HRI Kirton. Individuals of each species were reared in containers kept in cooling incubators maintained at nine constant temperatures between 7.5 and 30°C. The duration of each stage (egg, caterpillar, pupa, oviposition period) at each temperature was determined for each species.

Diapause completion and post-diapause development
There is little information on the temperature requirements for post-winter development of the five species. This information is required to determine when temperature recording for forecasts should start each year and to obtain estimates of the temperature requirements for spring emergence.

Caterpillars of all species were collected from the field during September – November and maintained outside in cages at HRI Kirton and HRI Wellesbourne during the winters of 1995-

96, 1996-97 and 1997-98. However, there were only a few *P. brassicae* and these were all kept at HRI Kirton. Following collection from the field each year, most caterpillars (*P. rapae, M. brassicae, E.forficalis, P. brassicae*) formed pupae within a few weeks. However, relatively large numbers of *M. brassicae* collected as fourth and fifth instar caterpillars during late September-early November 1996 failed to pupate and spent much of the winter as fully-fed caterpillars, before dying in the spring.

During the first winter, batches of pupae (*M. brassicae, P.rapae, E. forficalis*) were brought into the laboratory and placed in an incubator at 17.5°C to determine the progress of diapause and post-diapause development. Pupae were brought into the laboratory on 18 December 1995, and on 9 January, 2 February, 6 March and 4 April 1996. On 2 February and 6 March 1996, batches of pupae were also placed at nine temperatures between 7.5 and 30°C to determine the temperature requirements for post-diapause development. Further batches of pupae were allowed to remain outside at both sites and adult emergence was recorded in the spring. During the following two winters, batches of insects were again maintained outside in cages. They were brought into the laboratory in late January – early February to obtain further data to confirm the duration of diapause and the temperature requirements for spring emergence.

It is thought that *P. xylostella* is principally a migrant pest in the UK and may not be able to survive the winter. Cages of *P. xylostella* were maintained outside at HRI Wellesbourne and HRI Kirton and the insects were observed at weekly intervals to see whether this species would be able to survive the winter.

Results

Continuous development

Data on the relationship between the rate of development and temperature have been obtained for *P. xylostella, M. brassicae* and *E. forficalis*. The rate of development was calculated as 100/time to complete a particular development stage and is expressed as percent development/day. Figure 3a shows the relationships between the rates of egg, caterpillar and pupal development and temperature. The relationships between oviposition and temperature for all three species are also shown.

Where appropriate information was available, comparisons were made also with data collected elsewhere. Further data on *P. xylostella* were obtained from Choi *et al.* (1992), Chung *et al.* (1989), Li Tao & Jue-Lian (1979) and Yamada & Kawasaki (1983). Data on *M. brassicae* were obtained from Johansen (1997).

Much of the previous work on development of *P. rapae* was done in the UK and no further data were collected during this project. Published data from Davies & Gilbert (1985), Gilbert (1988), Jones *et al.* (1982), Jones *et al.* (1987), Richards (1940) and Tatchell (1981) were used to develop the forecast for *P. rapae*.

Diapause completion and post-diapause development

Pupae maintained outside

Emergence of adults from overwintering pupae maintained outside throughout the winter and spring occurred during May and June. Dates of 50% emergence are shown in Table 3a.

Emergence of *P. rapae* occurred almost three weeks earlier at Kirton than at Wellesbourne in 1996 and two weeks earlier in 1998. Emergence times at Kirton and Wellesbourne of both *M. brassicae* and *E. forficalis* did not differ as much.

One freshly emerged adult *P. xylostella* was found on 29 April 1996 in the cage at Kirton. None survived at Wellesbourne in 1995-96. *P. xylostella* taken from the laboratory culture were maintained outside at Wellesbourne during the winter of 1996-97. There were live caterpillars and adults in the cage throughout the winter period.

Pupae taken into the laboratory at intervals throughout the winter and spring

The cumulative adult emergence curves of insects brought into the laboratory on 18 December 1995, and on 9 January, 2 February, 6 March and 4 April 1996, and then kept at 17.5°C are shown in Figure 3b. The mean emergence time decreased gradually as the series of samples were taken (Figure 3c). To compare the progress of diapause development between the three years, mean emergence times for pupae overwintered in 1996-97 and 1997-98 are also shown.

E. forficalis

In 1995-96, the mean emergence time at 17.5°C decreased from 46 days in mid-December to 37 days by early February (36-37 days in 1997, 41-48 days in 1998) (Figure 3c) indicating that diapause development was still occurring during this period. Each batch of moths emerged over a relatively short period of time and the CV of the rate of development did not vary greatly throughout the winter and spring period.

P. rapae

In 1995-96, the mean emergence time at 17.5°C decreased from 49 days in mid-December to 41 days by early February (42 days in 1997; 23-28 days in 1998) again indicating that some diapause development was occurring during this period (Figure 3c). At the beginning of the winter/spring period, the spread of emergence of each batch of butterflies was greater than for *E. forficalis* but by the time pupae were sampled on 4 April, the butterflies were emerging over a very short period of time.

M. brassicae

In 1995-96 the mean emergence time at 17.5°C decreased from 77 days in mid-December to 43 days in early February (42 in 1997;46 in 1998), showing that diapause development was occurring during this period (Figure 3c). The spread of emergence was also greater than for *E. forficalis* but had decreased by early March.

Results from the three years showed that diapause was completed at a similar rate each year by *M. brassicae* and *E. forficalis* and that 1 February would be a suitable date from which to begin temperature accumulation. The emergence time at 17.5° of *P. rapae* was more variable and was shorter in 1998 than in the previous two years.

No moths or butterflies emerged at 7.5°C from batches of pupae placed at a range of constant temperatures on 2 February and on 6 March 1996. Some *E. forficalis* and *M. brassicae*, but no *P. rapae*, emerged at 10°C (Table 3b). No *E. forficalis* emerged at 30°C. Linear regressions of the rate of development versus temperature (using the samples collected in late January – early February each year) are shown in Figure 3d.

Forecast validation

Adult trapping

1994

During 1994, insect traps were run at the four monitoring sites (HRI Kirton, HRI Stockbridge House, HRI Wellesbourne and ADAS Arthur Rickwood) to determine the pattern of adult activity. At each site, four yellow water traps were used to capture the two species of butterfly and pheromone traps were used to capture the three species of moth.

Since Oecos, the supplier of pheromone traps, could not recommend an optimum combination of trap, lure and lure replacement regime for the three species of moth, several combinations were evaluated to determine the most effective for each species. These are shown in Table 3c. Trap types included large and small Delta traps, Pagoda traps and plastic 'bucket' traps (all supplied by Oecos). The pheromones were dispensed either from a polyethylene (poly) vial, a polymer lure or a rubber septum and the lures were replaced at from 2-12 week intervals. Several different combinations were tested for each species. Each 'treatment' was replicated twice at each of the four sites. All the traps were serviced twice-weekly.

1995

In 1995, insect traps were run at the same four sites. Four yellow water traps were again used to monitor the butterflies. Pheromone traps and lures were obtained from Agralan. To monitor moth activity, at each site, five widely-separated trap locations were chosen, near or within brassica crops, and one pheromone trap for each of the three species of moth was placed at each location, with a 10 m gap between neighbouring traps. The traps were again serviced twice-weekly.

1996

In 1996, pheromone traps were run at the same four sites and four yellow water traps were again used to monitor the butterflies.

Most pheromone traps and lures were obtained from Agralan but because their traps for *M. brassicae* performed very badly in 1995, pheromone traps for this species were also obtained from Oecos. To monitor moth activity, at each site, five widely-separated locations were chosen, near or within brassica crops, and one pheromone trap for each of the three species of moth (two traps for *M. brassicae*) was placed at each location, with a 10 m gap between neighbouring traps. The traps were serviced twice-weekly and numbers of target and non-target species were recorded.

1997

In 1997 the sites and methods used for collecting forecast validation data were similar to 1996 with two exceptions:

1. A single pheromone trap for *Autographa gamma* was located at each site.

2. Orange/yellow sticky traps and yellow water traps were used to monitor butterflies at HRI Kirton and HRI Wellesbourne and just sticky traps at HRI Stockbridge House

and ADAS Arthur Rickwood.

Monitoring immature stages
During 1995, 1996 and 1997, the development of caterpillar infestations was monitored in untreated plots of Brussels sprouts (50 x 75 plants) at the four sites. One hundred marked plants, from around the perimeter of each plot, were inspected each week. On each occasion the eggs, caterpillars and pupae observed on each plant were identified and their numbers (+ estimated length of caterpillars) recorded.

Results
Figures 3e and 3f show examples of pheromone trap catches of *P. xylostella* and *E. forficalis* respectively.

Total catches by the different combinations of pheromone trap and lure used in 1994 are summarised in Table 3c. Similar numbers of *M. brassicae* were captured by all the trap/lure combinations. However, very few adult *M. brassicae* were captured at either HRI Wellesbourne or HRI Kirton. The *M. brassicae* pheromone was also relatively non-specific and large numbers of other moth species were captured by all the *M. brassicae* traps.

Few *P. xylostella* were captured by Pagoda traps, while polymer lures in small delta traps were the most effective. Similarly, few *E. forficalis* were captured in Pagoda traps, polymer lures in large delta traps being the most effective.

In 1995, very few adult *M. brassicae* were captured in pheromone traps at any of the four sites although large numbers of caterpillars were observed in the untreated plots at ADAS Arthur Rickwood and caterpillars were also found at HRI Wellesbourne and HRI Stockbridge House. This suggests that in 1995, the pheromone lures used for *M. brassicae* were ineffective. The lures for *M. brassicae* were also not very selective since several other species were trapped throughout the summer.

During 1996 when both Agralan and Oecos lures for *M. brassicae* were compared. The Oecos lures captured almost 8 times more *M. brassicae* moths than those from Agralan (Table 3d).

Water traps captured adult *P. rapae* at some sites in all years (example shown in Figure 3g) but few *P. brassicae* were trapped. *P. brassicae* caterpillars were also relatively uncommon, indicating that this may be a relatively unimportant pest of commercial brassica crops. Although easier to manage, vertical orange/yellow sticky traps caught fewer butterflies than the water traps.

Caterpillar infestations
Of the five species of caterpillar, *P. xylostella* was the most numerous in the four seasons studied, followed by, in decreasing order of importance, *P. rapae*, *M. brassicae*, *E. forficalis* and *P. brassicae*. Figure 3h shows the numbers of caterpillars of each species found each week on 100 untreated Brussels sprout plants at each site.

P. xylostella
In 1996, there was a particularly large infestation of *P. xylostella* and the moths were first captured in mid-June. Data collected at HRI Kirton showed that peak numbers of eggs were laid as peak numbers of moths were captured (Figure 3i). Peak numbers of caterpillars were found at the beginning of July, 2-3 weeks after peak moth activity (Figure 3j). A second peak of adult *P. xylostella* activity was most apparent at HRI Kirton, occurring at the end of July. Table 3e shows the dates when peak numbers of *P. xylostella* were found at each site in each year.

At HRI Kirton, samples of newly formed pupae were taken from the field on 11 July 1996 and maintained in the laboratory to determine the proportion of insects emerging successfully. Of these pupae, 49% emerged as adult *P. xylostella*, 26% were parasitised by *Diadegma* spp. and 25% were dead.

Other species
In general, numbers of the other caterpillar species were relatively low. Of these, *P. rapae* was the dominant species at HRI Wellesbourne and HRI Stockbridge House and Table 3f shows the dates when peak numbers of caterpillars were found at each site. The relatively large numbers of *P. brassicae* found on a few occasions were usually all on one plant.

E. forficalis was relatively common at ADAS Arthur Rickwood and HRI Wellesbourne. *M. brassicae* was most numerous at ADAS Arthur Rickwood and HRI Stockbridge House

Development of computer models

Forecast models were developed using the technique described by Phelps *et al.* (1993). The models were written in FORTRAN and were run on the VAX computer at HRI Wellesbourne. Insect development was described by a series of equations relating the rate of insect development to temperature for each stage of development of each the species. The equations were derived from experimental work within this project (Figures 3a & 3d) and from published data. At each stage of development, intra-population variability was included in the model by using the average CV of the development rates measured at constant temperatures in the laboratory (Phelps *et al.*, 1993). The CV's for continuous development of *P. rapae* were estimated from published data.

The models were run using weather data collected at the meteorological stations at HRI Wellesbourne, HRI Kirton, HRI Stockbridge House and ADAS Arthur Rickwood during the four years (1994-1997) of the project. The forecasts were validated using monitoring data collected at these four sites. The best control strategy for caterpillars is to apply treatments after they have hatched, but whilst they are still small and before they have caused large amounts of damage. Some species, such as *M. brassicae*, are also more susceptible to *Bacillus thuringiensis* in the first instar. Thus for validation purposes the period from egg hatch until pupation has been considered mainly in this report.

Results
P. xylostella
Large numbers of *P. xylostella* do not overwinter successfully in the UK and major

infestations are caused by the migration of adults from the continent. Therefore, the models were initiated using captures of adult male moths by pheromone traps and were used to predict egg-laying, egg hatch, pupa formation and adult emergence by the subsequent generations.

In Figure 3k, forecasts of the hatching of small caterpillars are compared with observations of caterpillars of all sizes made each week on untreated Brussels sprout plants at the four monitoring sites. Table 3g shows comparisons between the date when peak numbers of first generation caterpillars were found on plants and forecasts of peak hatching. On average, the week when peak numbers of caterpillars were found on the plants was 11 days after the week when peak hatching was forecast.

Although the forecasts indicated that temperatures were sufficiently high for the development of up to four generations each year, the numbers of caterpillars found on plants usually declined after the first generation.

P. rapae

Both the forecasts and monitoring data indicated that there were between two and three generations each year (Figure 3l, Table 3h). Relatively few first generation caterpillars were found in the untreated monitoring plots and no attempt was made to validate forecasts for the first generation. Larger numbers of caterpillars were found during the second and third generations, which usually overlapped. Second generation forecasts were validated by comparing the dates between which caterpillar numbers rose to >10% of the maximum number found, with the forecast date of 10% hatching (Table 3h). In general, predictions were within a week (the sampling interval for the untreated plots). The one exception was at ADAS Arthur Rickwood in 1996.

M. brassicae

Pheromone trap catches of *M. brassicae* were very variable and fewer than 10 moths were captured each year at most sites. The largest numbers were captured at ADAS Arthur Rickwood (64) and HRI Stockbridge House (71) in 1994, with peak numbers trapped in early July at both sites and a second peak at ADAS Arthur Rickwood in early September. Relatively high numbers of moths (25) were also captured at ADAS Arthur Rickwood in 1997 and peaks were evident in late June and late August. The spread of each 'generation' was relatively wide and moths were captured over a period of 40 or more days. Moths were occasionally captured very early, during May.

Batches of eggs were found on only 13 sampling occasions throughout the whole study. Eggs were found from mid-June to mid-July on 8 occasions and in late August – mid September on 3 occasions.

Caterpillars were found at most sites in most years, but numbers were sometimes low. The *M. brassicae* forecast was validated by determining the numbers of caterpillars found on untreated plants within and outside the period when the forecast predicted that caterpillars would be present (10% hatch of small caterpillars until 90% pupation by each of the two generations). An average of 8% (100/1279) of caterpillars were observed outside this forecast period (Table 3i). Figure 3m compares forecasts of hatching of small caterpillars and of pupation, with the numbers of caterpillars of all sizes found on the untreated monitoring plots at the four sites.

E. forficalis
The monitoring data and forecasts both indicated clearly that there were two generations each year. However, the first generation of caterpillars appeared to cause little damage to Brussels sprouts even at sites such as Arthur Rickwood, where they were relatively common during the second generation.

The *E. forficalis* forecast was validated by determining the numbers of caterpillars found on untreated plants within and outside the periods when the forecast predicted that caterpillars would be present (10% hatch of small caterpillars until 90% pupation by each of the two generations). An average of 3% (55/1704) of caterpillars were observed outside this period (Table 3j). Figure 3n compares forecasts of hatching of small caterpillars and pupation with the numbers of caterpillars of all sizes found on the untreated monitoring plots at the four sites.

4. To quantify the relative susceptibility of the different caterpillar species to different selective products.

Laboratory bioassays

The objective of this work was to quantify the relative susceptibility of different caterpillar pest species to *Bacillus thuringiensis* (*Bt*) products.

Bt products

1. Dipel WP (Abbot Laboratories) contains the strain HD1 subsp. *kurstaki*, used in all currently available *Bt* products registered in the UK.

2. Bactospeine WP (Novo Nordisk) contains the strain HD1 subsp. *kurstaki*.

3. Turex/Agree (CIBA), a new product based upon a transconjugant strain of *Bt* belonging to subsp. *aizawai*. The strain produces a different range of toxins to HD1.

Bioassay procedure

The activity of the *Bt* products was determined using neonate caterpillars that were allowed to feed on an agar based artificial diet into which a series of dilutions of *Bt* had been included. The bioassays were performed using 5 doses with a minimum of 25 insects per dose. Mortalities were recorded after 6 days at 25°C.

In 1995, laboratory bioassays were performed to determine the entomocidal activity of the *Bt* product Dipel and the two products (Agree and Bactospeine) used in field experiments during the summer. The insect species tested were *M. brassicae*, *P. brassicae*, *P. rapae*, *P. xylostella* and *E. forficalis*.

Differences between the activity of the *Bt* products (Bactospeine, Dipel and Agree) and the susceptibility of the pest species were found (Table 4a). *M. brassicae* was confirmed as the least susceptible of the species tested, with Agree more active than Dipel against *M. brassicae* and *E. forficalis*. The batch of Bactospeine used appeared to be much less active against *M. brassicae* than it should have been and this was possibly due to plasmid loss. This was taken up with the suppliers.

5. To assess the effectiveness of current and novel selective agents for the control of caterpillars as compared to broad-spectrum insecticides.

Insecticide efficacy field experiments

A series of four field experiments was done to assess the efficacy of novel and existing selective insecticides compared to a broad spectrum product and to quantify the relative susceptibility of the different caterpillar species to different selective products. To provide adequate data for statistical analysis, the minimum infestation level required at a suitable site was considered to be 0.5 caterpillars per plant.

1995
Four field efficacy experiments were done at ADAS Arthur Rickwood between July and October 1995. There were five treatments:

1. Untreated

2. Pyrethroid standard. Deltamethrin 2.5% EC applied at 7.5g ai per ha (300 ml per ha of Decis).

3. Diflubenzuron 24% WP applied at 100g ai per ha (400g per ha of Dimilin).

4. *B. thuringiensis* as Bactospeine applied at 1000g per ha.

5. AGC product GC91 (Agree) applied at rate advised by manufacturer (1125g/ha) (crop destroyed after experiment complete).

Spray treatments were applied in 1000 l/ha water, using a medium spray as defined by the BCPC Nozzle Selection System. Bactospeine, Agree and Dimilin were applied with added wetter (0.5l Agral/1000l water).

Each of the four experiments was targeted at a different species. Two or three species were included in some experiments, which were timed to coincide with high levels of natural infestation. In two experiments, one for *P. xylostella* (Experiment 1) and one for *P. rapae* (Experiment 2), pest numbers were increased by seeding the plots with caterpillars collected from nearby untreated areas. In the third and fourth experiments the plots were already heavily infested with either *P. rapae*, *E. forficalis* or *M. brassicae* and no seeding was done. Attempts to establish an infestation of *P. brassicae* using eggs obtained from the laboratory culture maintained at HRI Littlehampton/Wellesbourne were unsuccessful.

There were five replicates of each of the five treatments arranged in a randomised block design. Plots consisted of 4 x 5-plant or 4 x 6-plant blocks of Brussels sprouts with at least two guard rows at the perimeter of each plot, to give at least four guard rows between plots.

To obtain an estimate of mortality, the numbers of each species were recorded on each plot immediately before treatment, and then recorded 2-3 and 7-10 days after treatment. Numbers of live, dead and moribund caterpillars and pupae were recorded.

The results of the field experiments are shown in Figure 5a. The data were analysed using a log-linear model, allowing the following specific comparisons to be made:

1. Between diflubenzuron (Dimilin) and the other insecticide products (deltamethrin (Decis) and the two *Bt* products (Bactospeine and Agree)).

2. Between deltamethrin and the two *Bt* products.

3. Between the *Bt* products (Bactospeine and Agree).

These comparisons are summarised in Table 5a and the overall results are summarised by product below:

Diflubenzuron (Dimilin)
Overall this was the least effective of all the products tested and levels of control achieved were often significantly worse when compared with the other products.

Deltamethrin (Decis)
This product gave maximum control within 2-3 days of treatment and was usually more effective than either of the two *Bt* products at the first assessment.

Bt (Bactospeine)
This product was more active against *P. xylostella* and *P. rapae* than it was against *M. brassicae* and *E. forficalis*, confirming the results of the laboratory bioassays.

Bt (Agree)
This product was similar to Bactospeine in its activity against *P. xylostella* and *P. rapae* but was sometimes more active against the other two species, again confirming the laboratory bioassay results. Both *Bt* products acted more slowly than Decis but usually gave similar levels of control against *P. xylostella* and *P. rapae* by the time of the second assessment.

6. To draw together the forecasts and crop sampling methods, derived from knowledge of caterpillar distributions, with selective methods of control in an adaptive sampling and control system.

Development of a preliminary system of managed control for caterpillar pests of brassicas

1996
A preliminary system of managed control for caterpillar pests of Brussels sprouts was developed and tested in field experiments at ADAS Arthur Rickwood, HRI Kirton and HRI Stockbridge House. The objectives were to:

1. Use information on pest activity (forecasts/monitoring) to target crop walking.

2. Use crop walking to estimate the proportion of plants infested.

3. Use previously-determined pest tolerance levels to decide whether to **spray** immediately, **not to spray**, or to return to re-assess the crop at a later date (**no decision**).

4. Compare, within the managed system, the performance of a selective insecticide (Agree) with a broad spectrum pyrethroid (Decis).

5. Compare the managed system with conventional routine use of a broad spectrum pyrethroid insecticide in terms of sampling and control inputs and crop quality.

Plots were 20 x 30 plant blocks of Brussels sprouts (cv Corinth). There were seven treatments in total using different management regimes, insecticides, pest tolerance levels or systems of crop walking.

Monitoring records were used to trigger crop walking. These were collected using pheromone traps, water traps and by making counts of eggs on untreated plants.

The standard system of crop walking used 25 plants per plot. These plants were located within a central block of 10 x 20 plants (leaving a 5-plant guard around the perimeter). Plants were selected using random numbers and decisions were based on the numbers of plants infested with caterpillars.

The pest tolerance levels had been determined previously in work funded by MAFF and the HDC. They were reduced as the plants grew and the buttons started to form:

Age of crop	Caterpillar tolerance level
0-10 weeks	40%
11-15 weeks	5 or 10%
16 weeks onwards	0.5 or 5%

Decisions were based on a probability of 0.15 for spraying when the actual infestation was less than the pest tolerance level and a probability of not spraying of 0.05 when the actual infestation level was greater than the pest tolerance level.

Decisions for 25-plant samples were as follows:

Tolerance level (%)	No. infested plants		
	No spray	No decision	Spray
40	0-5	6-13	14-25
10	-	0-4	5-25
5	-	0-2	3-25
0.5	-	0	1-25

For most treatments the action following 'no decision' was to re-sample at a later date, either after a week, or after a shorter interval if insect development was likely to be rapid (mean air temperatures > 22°C). However in one treatment, the action following a 'no decision' was to take a further sample of 35 plants immediately, to increase sampling precision, so that the decision was then based on a total sample of 60 plants. Decisions for 60-plant samples were as follows:

Tolerance level (%)	No. infested plants		
	No spray	No decision	Spray
40	0-17	18-28	29-60
5	0	1-5	6-60
0.5	-	0-1	2-60

Treatments
The treatments are listed below and are described in detail in Appendix 3.

A Untreated
B Routine sprays of deltamethrin (Decis) every two weeks
C Standard managed treatment using *Bt* (Agree)
D Managed treatment using deltamethrin
E Managed treatment with increased sample size (Agree)
F Managed treatment with routine assessments
G Managed treatment with higher tolerance levels

N.B. Double rate Agree was applied when the tolerance level was exceeded by the total number of plants infested by *M. brassicae, E. forficalis* and *A. gamma* caterpillars.

Location of treatments

ADAS Arthur Rickwood A, B, C, D, E, F
HRI Kirton A, B, C, D, G
HRI Stockbridge House A, B, C

Assessments
At the beginning of each month, 20 plants per plot (all treatments) were sampled and numbers of eggs, caterpillars, pupae of each species were recorded. At harvest, samples of buttons were taken from each plot and assessed for caterpillar damage. Records of marketable yield were also taken.

1997
A revised system of managed control for caterpillar pests of Brussels sprouts was tested in field experiments at ADAS Arthur Rickwood, HRI Kirton and HRI Stockbridge House in 1997. The main difference was that the tolerance levels used from 11 weeks onwards in the 'standard' managed treatment were increased to those used in the 'Managed with higher tolerance levels' treatment in 1996 (40, 10, 5% vs 40, 5, 0.5%). This was because the 1996 experiments showed that there was no difference between the effects of the lower and higher tolerance levels. Further treatments were used to examine the effects of a lower tolerance level from planting for *P. xylostella* (10% vs 40%) and an even higher tolerance level for all species from 16 weeks onwards (10% vs 5%).

Plots were 20 x 48 plant blocks of Brussels sprouts (cv Corinth). There were eight treatments in total using different management regimes, insecticides, pest tolerance levels or systems of crop walking.

Monitoring records were used to trigger crop walking. These were collected using pheromone traps, water traps and by making counts of eggs on untreated plants.

The standard system of crop walking used 25 plants per plot. These plants were located within a central block of 10 x 20 plants (leaving a 5-plant guard around the perimeter and a 20 x 18 plant harvest area at one end of each plot). Plants were selected at random and decisions were based on the numbers of plants infested with caterpillars.

Pest tolerance levels were revised (see treatment details below) and were as follows:

Age of crop	Pest tolerance level
0-10 weeks	**40% or 10%**
11-15 weeks	**5% or 10%**

16 weeks onwards	**0.5% or 5% or 10%**

Decisions were based on a probability of 0.15 for spraying when the actual infestation was less than the pest tolerance level and a probability of not spraying of 0.05 when the actual infestation level was greater than the pest tolerance level.

Decisions for 25-plant samples were as follows:

Tolerance level (%)	**No. infested plants**		
	No spray	**No decision**	**Spray**
40	**0-5**	**6-13**	**14-25**
10	**-**	**0-4**	**5-25**
5	**-**	**0-2**	**3-25**
0.5	**-**	**0**	**1-25**

Re-sampling interval
If a positive decision was made (**'spray' or 'no spray'**) then plots were re-sampled after 1 week (if there was a risk of *P. xylostella*) or 2 weeks (other species). Plots were re-sampled at these intervals until no moths/butterflies/eggs had been found for two weeks. There was a risk of *P. xylostella* if 5 or more moths are captured in any of the five pheromone traps. If **'no decision'** was made then the plots were re-sampled after 1 week (or 3 days if mean maximum temperature > 22° C) if there was a risk of *P. xylostella* and after 1 week for other species.

In Treatment E, the action following a 'no decision' was to take a further sample of 35 plants immediately, to increase sampling precision, so that the decision was then based on a total sample of 60 plants.

Decisions for 60-plant samples were as follows:

Tolerance level	**No. infested plants**		
	No spray	**No decision**	**Spray**
40	**0-17**	**18-28**	**29-60**
10	**0-1**	**2-8**	**9-60**
5	**0**	**1-5**	**6-60**

Treatments are shown below and are described in detail in Appendix 4.

A. Untreated
B. Routine deltamethrin
C. Standard managed
D. Standard managed with deltamethrin
E. Increased sample size
F. Lower tolerance level at start for *P. xylostella*
G. Same triggers as in 1996
H. Higher tolerance level at end

N.B. Double rate Agree was applied when the tolerance level was exceeded by the total number of plants infested by *M. brassicae, E. forficalis* and *A. gamma* caterpillars.

Location of treatments

ADAS Arthur Rickwood A, B, C, D, E, H
HRI Kirton A, B, C, F, G
HRI Stockbridge House A, B, C

Assessments

Samples of 25 plants were taken in untreated and routinely-treated (Decis) plots at the beginning of each month to record the numbers of caterpillars, eggs, and pupae.

Destructive damage assessments were made on 20 plants on three occasions. These were taken from a separate area of plot (18 x 20 plants).

At harvest, samples of buttons were taken from each plot and assessed for damage. Records of marketable yield were also taken. The results are summarised in the next section.

7. To compare the effectiveness of the adaptive sampling and control programme with current routine treatments of broad-spectrum products to provide a marketable crop.

Results

Analyses of the 1996 experimental data are shown in Figures 7a-d. All of the insecticide treatments (managed and routine) were effective when compared with the untreated control. In addition, there were no statistically significant differences between any of the insecticide treatments in terms of levels of caterpillar control; all were equally effective. Thus managed treatments with either Agree or deltamethrin gave the same levels of control as routine fortnightly sprays of deltamethrin. Pest pressure due to *P. xylostella* was extremely high at all three sites and the treatments did not achieve complete caterpillar control. This was particularly evident on the lower buttons.

Caterpillar infestations in 1997 were light compared with the previous year (Table 7a). Analyses of the 1997 experiment data are shown in Figures 7e-g. There were no statistically-significant differences between any of the treatments, even between insecticide treatments (managed and routine) and the untreated control. This was because the overall infestation level was so low that treatment differences could not be detected.

The numbers of sprays applied to the standard managed treatment at the three sites in 1996 and 1997 are shown in Table 7b. On average, nearly seven more sprays were applied in 1996 than in 1997 showing that, as a result of the managed treatments, there was a considerable reduction in the number of sprays applied when the caterpillar infestation was low.

TECHNOLOGY TRANSFER

Presentations

COLLIER, R.H. Managing caterpillar pests of *Brassica* crops. IOBC/WPRS meeting on Integrated Control in Field Vegetable Crops 6-8 November 1995.

MEAD, A. From sequential sampling charts to the development of a practical protocol for managed pest control. 18th International Biometrics Conference in Amsterdam, 1-5 July 1996.

EMMETT, B. Keynote lecture on pests, parasites and pathogens. CSL York, Institute of Biology. 6 November 1996.

COLLIER, R.H. Development of integrated pest management systems for field vegetable crops. BCPC Symposium - Crop Protection and Food Quality: Meeting Customer Needs. 16-19 September 1997.

COLLIER, R.H. Simulating sampling strategies for aphid and caterpillar pests of *Brassica* crops. IOBC/WPRS meeting on Integrated Control in Field Vegetable Crops 6-9 October 1997.

Publications in scientific journals

COLLIER, R.H., BLOOD SMYTH, J. & JARRETT, P. (1997). Managing caterpillar pests of *Brassica* crops. Integrated Control in Field Vegetable Crops. IOBC/WPRS Bulletin 1996, **19 (11)**, 81-88.

MEAD, A. & COLLIER, R.H. (1996). From sequential sampling charts to the development of a practical protocol for managed pest control. XVIIIth International Biometrics Conference Amsterdam July 1-5. Contributed papers volume, p 34.

COLLIER, R.H. (1997). Development of integrated pest management systems for field vegetable crops. Crop Protection and Food Quality: Meeting Customer Needs. BCPC Symposium, University of Kent, 16-19 September 1997, 473-8.

COLLIER, R.H. *et al.* (1999). Simulating sampling strategies for aphid and caterpillar pests of *Brassica* crops Integrated Control in Field Vegetable Crops. IOBC/WPRS Bulletin, In press.

Grower articles

EMMETT, B. (1994). Wanted: caterpillar rich crops. Grower July 28, 1994.

COLLIER, R.H. (1995). Managing aphid and caterpillar pests of brassica crops. HDC Project News, September 1995.

COLLIER, R.H. (1998). Caterpillar counter attack. Grower April 23, 1998.

Several articles about the work appeared in the Horticultural Press following a Horticultural Research Association meeting at HRI Kirton in 1995 and other grower days at HRI Kirton in 1996 and 1997.
There was a photograph plus caption of J Blood Smyth in the Grower in September 1997.

There was an article in Farmers Weekly after Veg Focus in September 1997

Grower walks and Open Days

The project was demonstrated to the industry at HDC grower days at HRI Kirton on 2 July, 6 August and 26 September 1996, at the ADAS Arthur Rickwood Open Day on 4 July 1996 and at a grower meeting/walk at HRI Kirton on 11 November 1997

The project is referred to in HORIS manuals

The project was described in a poster at the Royal Show 1995

CONCLUSIONS

1. Of the six species of caterpillar included in this study, diamond-back moth (*Plutella xylostella*) appears to have been the most damaging commercially. This was followed by, in decreasing order of importance, small white butterfly (*Pieris rapae*), cabbage moth (*Mamestra brassicae*), garden pebble moth (*Evergestis forficalis*) large white butterfly (*Pieris brassicae*) and silver Y moth (*Autographa gamma*). Attacks by all six species of caterpillar were sporadic and they did not occur in every crop each year.

2. Data were collected on the within-crop distribution of the immature stages of all six species. 'Edge' effects were apparent for some species on some occasions and plants on the edges of the field were often more infested than plants in the middle of the field, particularly when the worst affected edge was compared with the middle. There was also often considerable variation along and between edges.

3. The distributions of *M. brassicae* and *E. forficalis* were more aggregated than those of *P.*

xylostella and *P. rapae*. Considering all species together, there was a strong relationship between the proportion of plants infested and the mean infestation level. This relationship did not change during the season. Therefore, the same sampling approach can be used throughout the life of the crop.

4. Pheromone traps were used to determine the pattern of adult moth activity. The pheromone lures used for *M. brassicae* were relatively non-specific and not very effective. Very few adult *M. brassicae* were captured although caterpillars were observed in untreated plots at several sites. Water traps captured adult *P. rapae* at all sites, but few large white butterflies were captured. Vertical yellow/orange sticky traps did not capture as many butterflies as water traps.

5. Preliminary forecasts were developed for *P. xylostella, P. rapae, M. brassicae* and *E. forficalis* and were validated using monitoring data collected at four sites during 1994-1997. *P. xylostella* completed up to four generations each year, *P. rapae* up to three generations and *E. forficalis* and *M. brassicae* two generations. The forecasts require further validation and refinement before they can be used on a commercial scale.

6. Laboratory bioassays showed a wide range in the susceptibility of pest species to the *Bt* products tested (Dipel/Bactospeine and Agree). *M. brassicae* was the least susceptible species to Bactospeine/Dipel but was more susceptible to Agree. *E. forficalis* was also more susceptible to Agree than to the other two products. However, Agree, Dipel and Bactospeine were equally effective against *P. xylostella* and *P. rapae*.

7. Four insecticide efficacy field experiments were done at ADAS Arthur Rickwood in 1995. There were five treatments: untreated, deltamethrin (Decis), diflubenzuron (Dimilin) and the two *Bt* products, Bactospeine and Agree. Diflubenzuron was the least effective of all the products tested. Deltamethrin gave maximum control within 2-3 days of treatment. Both *Bt* products acted more slowly that deltamethrin but usually gave similar levels of control against *P. xylostella* and *P. rapae* within 7-10 days. Agree was sometimes more active than Bactospeine against *M. brassicae* and *E. forficalis*.

8. In 1996, a preliminary management system for the control of caterpillars on Brussels sprouts was equally effective whether deltamethrin or the *Bt* product Agree was used. Both treatments were as effective as routine two-weekly sprays of deltamethrin. A revised management system was evaluated in 1997. Caterpillar infestations were considerably lower in 1997 and damage was low in all plots, including the insecticide-free controls. In 1996, an average of 8.3 sprays was applied to the managed plots whereas in 1997 this was reduced to 1.7 sprays in response to the low numbers of caterpillars.

ACKNOWLEDGEMENTS

We thank J. Davies, B. Emmett, W. Riggall, K. Reynolds, D. Ellis, J. Town and other colleagues for their assistance with this project. We also thank participating growers for allowing us to sample caterpillars within their crops and MAFF, HDC and MicroBio Limited for supporting this work.

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Table 1a Samples taken to determine the within-crop distribution of caterpillars.

	Untreated plots	Commercial crops
1994	Transects + blocks	Transects + blocks
1995	Transects	Transects + edges
1996	-	Edges, corners & middle
1997	-	Edges & middle

Table 1c The plant neighbourhoods showing significance levels of $p < 0.05$ for the second method of spatial analysis, for samples taken in untreated plots at four sites in 1995.

Species	Site	Sampling occasion	Date	Proportion plants infested	Neighbourhood plants where p < 0.05
P. xylostella	HRI Wellesbourne	1	21-Jul	0.83	None
		2	8-Aug	0.5	None
		3	23-Aug	0.27	None
	HRI Kirton	1	10-Jul	0.16	None
		2	18-Jul	0.53	1,2,3,4,5,6,7,8,9
		3	31-Jul	0.8	1,2
	HRI Stockbridge House	1	20-Jul	0.59	4,5,6,7,8
		2	2-Aug	0.26	1,2,3
		3	24-Aug	0.04	1,2
	ADAS Arthur Rickwood	1	13-Jul	0.28	None
		2	10-Aug	0.45	1,2,3,4,5,6,7,8,9
		3	31-Aug	0.35	1,2,3,4,5,6,7,8,9
		4	26-Sep	0.14	2,3
P. rapae	HRI Wellesbourne	1	21-Jul	0.32	None
		2	8-Aug	0.89	None
		3	23-Aug	0.43	None
	HRI Kirton	3	31-Jul	0.03	None
	HRI Stockbridge House	1	20-Jul	0.04	1,5,6
		2	2-Aug	0.55	1,3,4
		3	24-Aug	0.73	1,2,3,4,5,6,7,8,9
	ADAS Arthur Rickwood	1	13-Jul	0.1	None
		2	10-Aug	0.78	1,2,3,4,5,6,7,8,9
		3	31-Aug	0.44	2,3
		4	26-Sep	0.23	4
M. brassicae	HRI Stockbridge House	1	20-Jul	0.08	2
		2	2-Aug	0.11	2
	ADAS Arthur Rickwood	2	10-Aug	0.08	1,3,4,5,6
		3	31-Aug	0.16	1,2,3,8,9
		4	26-Sep	0.48	1,2,3,4,5,6,7,8,9
E. forficalis	ADAS Arthur Rickwood	3	31-Aug	0.25	None
		4	26-Sep	0.13	1,2

Table 1b The plant neighbourhoods showing significance levels of $p < 0.05$ for the Black-White Join-Count method of spatial analysis, for samples taken in untreated plots at four sites in 1995. Significance levels of $p < 0.05$ indicate that there was spatial correlation between infested plants.

Species	Site	Sampling occasion	Date	Proportion plants infested	Neighbourhood plants where $p < 0.05$
P. xylostella	HRI Wellesbourne	1	21-Jul	0.83	None
		2	8-Aug	0.5	None
		3	23-Aug	0.27	5,6
	HRI Kirton	3	31-Jul	0.8	1
	HRI Stockbridge House	1	20-Jul	0.59	3,4
		2	2-Aug	0.26	1,2,3,4,6
		3	24-Aug	0.04	1,2,4
	ADAS Arthur Rickwood	1	13-Jul	0.28	2,3,4
		2	10-Aug	0.45	1,2,3,4,5,6
		3	31-Aug	0.35	1,2,3,4,5,6,7,8,9
		4	26-Sep	0.14	2,4
P. rapae	HRI Wellesbourne	1	21-Jul	0.32	7
		2	8-Aug	0.89	7
		3	23-Aug	0.43	None
	HRI Kirton	3	31-Jul	0.03	None
	HRI Stockbridge House	1	20-Jul	0.04	9
		2	2-Aug	0.55	1,3,4,9
		3	24-Aug	0.73	1,2,3
	ADAS Arthur Rickwood	1	13-Jul	0.1	None
		2	10-Aug	0.78	1,2,3,4
		3	31-Aug	0.44	2
		4	26-Sep	0.23	3
M. brassicae	HRI Stockbridge House	1	20-Jul	0.08	8
		2	2-Aug	0.11	1,2,3,4
		3	24-Aug	0.07	1,2
	ADAS Arthur Rickwood	2	10-Aug	0.08	1,2,3,5,6,7
		3	31-Aug	0.16	1,2
		4	26-Sep	0.48	1,2
E. forficalis	ADAS Arthur Rickwood	3	31-Aug	0.25	None
		4	26-Sep	0.13	1,7

Table 1d The numbers of caterpillars of each species found in commercial crops during 1996 and 1997.

	1996 (11,500 plants)	1997 (5,300 plants)
P. xylostella	2006	1628
P. rapae	179	426
A. gamma	332	79
M. brassicae	3	47
E. forficalis	0	1
P. brassicae	3	39

Table 1e The orientation of the most heavily-infested edges of commercial fields sampled in 1996 and 1997 (fields with two equally infested edges were scored as 0.5 for each edge and three equally infested edges as 0.3 for each edge).

	N	NE	E	SE	S	SW	W	NW
1997[a]	1.5	3	1	0	0	5.5	0.5	2
1998[b]	0	3	1	2.5	2.5	6	2	1
1998[c]	1	3.5	0	3.5	3.5	2.5	2	2.5

1997[a] – all species but mainly *P. xylostella.*
1998[b] – *P. xylostella.*
1998[c] – *P. rapae.*

Table 3a Dates of 50% emergence of adult moths from pupae maintained outside during the winter at HRI Wellesbourne (W) and HRI Kirton (K).

	P. rapae	*M. brassicae*	*E. forficalis*	*P. brassicae*
1996	23 May (W)	31 May (W)	22 May (W)	4 Jun (K)
	4 May (K)	2 Jun (K)	27 May (K)	-
1997	4 May (W)	-	3 May (W)	-
	2 May (K)	12 May (K)	12 May (K)	-
1998	6 May (W)	-	-	-
	21 Apr (K)	18 May (K)	-	-

Table 3b Emergence of adults from overwintered pupae kept at a range of constant temperatures in the laboratory. Samples of pupae were maintained outside and placed into incubators on 2 February and 6 March 1996.

Evergestis forficalis

Temperature °C	Percent emergence (2/2/96)	Percent emergence (6/3/96)	Mean development time (days) (2/2/96)	Mean development time (days) (6/3/96)
7.5	0	0		
10	55	65	109	79
12.5	55	100	85	61
15	100	100	47	32
17.5	80	100	36	27
20	75	80	37	32
22.5	75	100	28	21
25	50	100	31	20
30	0	0		

Pieris rapae

Temperature °C	Percent emergence (2/2/96)	Percent emergence (6/3/96)	Mean development time (days) (2/2/96)	Mean development time (days) (6/3/96)
7.5	0	0		
10	0	20		76
12.5	15	67	90	60
15	25	67	48	26
17.5	25	67	37	20
20	40	60	32	18
22.5	50	27	17	12
25	20	27	11	9
30	15	73	11	7

Mamestra brassicae

Temperature °C	Percent emergence (2/2/96)	Percent emergence (6/3/96)	Mean development time (days) (2/2/96)	Mean development time (days) (6/3/96)
7.5	0			
10	27	27	147	113
12.5	60	80	94	73
15	87	80	56	40
17.5	67	80	39	28
20	87	67	32	28
22.5	87	93	26	19
25	67	27	18	18
30	7		14	

Table 3c. Performance of different types of pheromone trap - total numbers of moths trapped at all four sites

M. brassicae - 5 treatments (10 traps per site)

Trap type	**Large delta**			**Pagoda**	**Funnel**
Dispenser	Rubber septum	Polymer	Polymer	Rubber Septum	Rubber Septum
Replaced after:	6 wks	6 wks	12 wks	6 wks	6 wks
Total moths trapped	31	20	30	33	31

P. xylostella - 6 treatments (12 traps per site)

Trap type	**Small delta**					**Pagoda**
Dispenser	Poly vial	Poly vial	Polymer	Polymer	Polymer	Poly vial
Replaced after:	2 wks	4 wks	4 wks	8 wks	12 wks	2 wks
Total moths trapped	96	134	510	547	777	3

E. forficalis - 4 treatments (8 traps per site)

Trap type	**Large delta**			**Pagoda**
Dispenser	Rubber	Polymer	Polymer	Rubber
Replaced after:	6 wks	6 wks	12 wks	6 wks
Total moths trapped	178	340	356	7

Table 3d The total numbers of *M. brassicae* captured by five pheromone traps at each of the four sites during 1996. Lures were obtained either from Oecos or Agrisense and were placed in Delta traps obtained from Agrisense.

	Oecos lure	Agrisense lure
ADAS Arthur Rickwood	44	5
HRI Wellesbourne	50	10
HRI Kirton	20	0
HRI Stockbridge House	21	2
Total	**135**	**17**

Table 3e Dates when peak numbers of *P. xylostella* caterpillars were found in untreated plots in 1995, 1996 and 1997.

P. xylostella	**1995**	**1996**	**1997**
ADAS Arthur Rickwood	17 Jul	1 Jul	11 Aug
HRI Wellesbourne	17 Jul	8 Jul	3 Sep
HRI Kirton	7 Aug	1 Jul	1 Sep
HRI Stockbridge House	24 Jul	8 Jul	11 Aug

Table 3f Dates when peak numbers of *P. rapae* caterpillars were found in untreated plots in 1995, 1996 and 1997.

P. rapae	**1995**	**1996**	**1997**
ADAS Arthur Rickwood	7 Aug	2 Sep	11 Aug
HRI Wellesbourne	31 Jul	16 Sep	13 Aug
HRI Kirton	14 Aug*	8 Jul*	15 Oct
HRI Stockbridge House	14 Aug	26 Aug	11 Aug

* Very low numbers of caterpillars found.

Table 3g *P. xylostella* - comparisons between the date when peak numbers of first generation caterpillars were found on plants and forecasts of peak egg hatch.

Site	Year	First generation Date peak numbers observed	Date peak egg hatch forecast	Difference (days)
HRI Stockbridge House	1995	24-Jul	10-Jul	14
HRI Stockbridge House	1996	8-Jul	25-Jun	13
HRI Stockbridge House	1997	5-Jun	5-Jun	0
HRI Kirton	1995	17-Jul	10-Jul	7
HRI Kirton	1996	3-Jul	25-Jun	8
HRI Kirton	1997	28-Jul	10-Jul	18
ADAS Arthur Rickwood	1995	17-Jul	10-Jul	7
ADAS Arthur Rickwood	1996	1-Jul	25-Jun	6
ADAS Arthur Rickwood	1997	11-Aug	10-Jul	32
HRI Wellesbourne	1995	18-Jul	10-Jul	8
HRI Wellesbourne	1996	10-Jul	25-Jun	15
HRI Wellesbourne	1997	28-Aug	21-Aug	7
Mean				**11**

Table 3h *P. rapae* – Forecasts of the dates of 1% and 10% egg hatch and 90% pupation. Comparisons are made between the dates when second generation caterpillar numbers rose to >10% of the maximum number of caterpillars found, with the forecast date of 1% egg hatch.

Site	Year	First generation 1% hatched	10% hatched	90% pupae
HRI Stockbridge House	1995	18-Jun	21-Jun	1-Aug
HRI Stockbridge House	1996	14-Jun	17-Jun	16-Aug
HRI Stockbridge House	1997	9-Jun	13-Jun	10-Aug
HRI Kirton	1995	20-Jun	22-Jun	1-Aug
HRI Kirton	1996	10-Jun	16-Jun	10-Aug
HRI Kirton	1997	10-Jun	12-Jun	7-Aug
ADAS Arthur Rickwood	1995	3-Jun	9-Jun	26-Jul
ADAS Arthur Rickwood	1996	6-Jun	8-Jun	31-Jul
ADAS Arthur Rickwood	1997	5-Jun	7-Jun	29-Jul
HRI Wellesbourne	1995	5-Jun	10-Jun	24-Jul
HRI Wellesbourne	1996	6-Jun	7-Jun	28-Jul
HRI Wellesbourne	1997	3-Jun	6-Jun	30-Jul

Site	Year	Second generation 1% hatched	10% hatched	Maximum no.	Observed start*	Difference**	90% pupae
HRI Stockbridge House	1995	28-Jul	2-Aug	211	24 Jul - 1 Aug	4	7-Oct
HRI Stockbridge House	1996	8-Aug	16-Aug	192	12 Aug - 21 Aug	-4	1-Nov
HRI Stockbridge House	1997	7-Aug	11-Aug	68	4 Aug-11 Aug	3	14-Oct
HRI Kirton	1995	30-Jul	2-Aug	25	31 Jul - 8 Aug	-1	9-Oct
HRI Kirton	1996	2-Aug	12-Aug	3	5 Aug - 12 Aug	-3	27-Oct
HRI Kirton	1997	3-Aug	7-Aug	53	28 Jul - 4 Aug	6	14-Oct
ADAS Arthur Rickwood	1995	24-Jul	29-Jul	311	24 Jul - 31 Jul	0	27-Sep
ADAS Arthur Rickwood	1996	27-Jul	3-Aug	26	15 Jul - 22 Jul	12	17-Oct
ADAS Arthur Rickwood	1997	27-Jul	31-Jul	136	28 Jul - 4 Aug	-1	22-Sep
HRI Wellesbourne	1995	20-Jul	27-Jul	454	18 Jul - 25 Jul	2	20-Sep
HRI Wellesbourne	1996	26-Jul	31-Jul	81	30 Jul - 6 Aug	-4	4-Oct
HRI Wellesbourne	1997	27-Jul	1-Aug	236	23-31 Jul	4	19-Sep

* The observed start is the sampling dates between which > 10% of maximum number of caterpillars per plant were observed on the monitoring plot

** The difference is the number of days between forecast 1% hatching and the first date of the observed start.

Site	Year	Third generation 1% hatched	10% hatched	90% pupae
HRI Stockbridge House	1995	11-Sep	23-Sep	
HRI Stockbridge House	1996			
HRI Stockbridge House	1997	14-Sep	2-Oct	
HRI Kirton	1995	16-Sep	22-Sep	
HRI Kirton	1996	17-Sep	29-Sep	
HRI Kirton	1997	7-Sep	29-Sep	
ADAS Arthur Rickwood	1995	2-Sep	15-Sep	24-Nov
ADAS Arthur Rickwood	1996	11-Sep	28-Sep	
ADAS Arthur Rickwood	1997	30-Aug	11-Sep	10-Dec
HRI Wellesbourne	1995	25-Aug	10-Sep	14-Nov
HRI Wellesbourne	1996	11-Sep	24-Sep	
HRI Wellesbourne	1997	1-Sep	12-Sep	17-Nov

Table 3i *M. brassicae* - Forecasts of the dates of 1% and 10% egg hatch and 90% pupation. Also shown, are the numbers of caterpillars found on untreated plants within and the numbers found outside the period when the forecast predicted that caterpillars would be present (10% hatch of caterpillars until 90% pupation by first and second generations).

Site	**Year**	**First generation** 1% hatched	10% hatched	90% pupae
HRI Stockbridge House	1995	20-Jun	25-Jun	26-Aug
HRI Stockbridge House	1996	19-Jun	28-Jun	10-Sep
HRI Stockbridge House	1997	14-Jun	20-Jun	29-Aug
HRI Kirton	1995	21-Jun	26-Jun	26-Aug
HRI Kirton	1996	17-Jun	27-Jun	5-Sep
HRI Kirton	1997	12-Jun	18-Jun	24-Aug
ADAS Arthur Rickwood	1995	11-Jun	19-Jun	15-Aug
ADAS Arthur Rickwood	1996	9-Jun	14-Jun	25-Aug
ADAS Arthur Rickwood	1997	7-Jun	11-Jun	18-Aug
HRI Wellesbourne	1995	10-Jun	17-Jun	13-Aug
HRI Wellesbourne	1996	8-Jun	13-Jun	22-Aug
HRI Wellesbourne	1997	6-Jun	10-Jun	14-Aug

Site	**Year**	**Second generation** 1% hatched	10% hatched	90% pupae	**Total no. observed**	**No. outside 10-90% range**
HRI Stockbridge House	1995	1-Sep	12-Sep		257	20
HRI Stockbridge House	1996	28-Sep	5-Oct		236	21
HRI Stockbridge House	1997	9-Sep	24-Sep		3	2
HRI Kirton	1995	1-Sep	12-Sep		4	0
HRI Kirton	1996	17-Sep	29-Sep		13	8
HRI Kirton	1997	6-Sep	17-Sep		38	14
ADAS Arthur Rickwood	1995	25-Aug	1-Sep	3-Dec	556	9
ADAS Arthur Rickwood	1996	1-Sep	10-Sep		55	4
ADAS Arthur Rickwood	1997	20-Aug	30-Aug	18-Dec	80	10
HRI Wellesbourne	1995	19-Aug	23-Aug	27-Nov	20	0
HRI Wellesbourne	1996	27-Aug	5-Sep		No caterpillars	
HRI Wellesbourne	1997	22-Aug	28-Aug	4-Dec	17	12
Total					**1279**	**100**

Table 3j *E. forficalis* - Forecasts of the dates of 1% and 10% egg hatch and 90% pupation. Also shown, are the numbers of caterpillars found on untreated plants and the numbers found outside the period when the forecast predicted that caterpillars would be present (10% hatch of small caterpillars until 90% pupation by first and second generations).

Site	**Year**	**First generation**		
		1% hatched	**10% hatched**	**90% pupae**
HRI Stockbridge House	1995	1-Jun	5-Jun	27-Jul
HRI Stockbridge House	1996	5-Jun	9-Jun	6-Aug
HRI Stockbridge House	1997	30-May	3-Jun	31-Jul
HRI Kirton	1995	No caterpillars		
HRI Kirton	1996	4-Jun	6-Jun	1-Aug
HRI Kirton	1997	28-May	1-Jun	25-Jul
ADAS Arthur Rickwood	1995	26-May	30-May	22-Jul
ADAS Arthur Rickwood	1996	2-Jun	5-Jun	28-Jul
ADAS Arthur Rickwood	1997	20-May	27-May	20-Jul
HRI Wellesbourne	1995	26-May	30-May	19-Jul
HRI Wellesbourne	1996	2-Jun	5-Jun	23-Jul
HRI Wellesbourne	1997	18-May	27-May	19-Jul

Site	**Year**	**Second generation**			**Total no.**	**No. outside**
		1% hatched	**10% hatched**	**90% pupae**	**observed**	**10-90% range**
HRI Stockbridge House	1995	7-Aug	16-Aug	9-Nov	35	2
HRI Stockbridge House	1996	19-Aug	24-Aug	6-Nov	40	1
HRI Stockbridge House	1997	12-Aug	19-Aug	15-Nov	1	1
HRI Kirton	1995	No caterpillars				
HRI Kirton	1996	16-Aug	20-Aug	5-Nov	27	0
HRI Kirton	1997	9-Aug	14-Aug	28-Oct	71	2
ADAS Arthur Rickwood	1995	6-Aug	12-Aug	26-Oct	734	14
ADAS Arthur Rickwood	1996	9-Aug	16-Aug	1-Nov	114	7
ADAS Arthur Rickwood	1997	1-Aug	9-Aug	19-Oct	213	9
HRI Wellesbourne	1995	3-Aug	12-Aug	16-Oct	194	18
HRI Wellesbourne	1996	9-Aug	15-Aug	1-Nov	119	0
HRI Wellesbourne	1997	3-Aug	9-Aug	17-Oct	156	1
Total					**1704**	**55**

Table 4a. Activity of *Bacillus thuringiensis* products (LC 50 ug *Bt*/g diet) in laboratory bioassays against five species of caterpillar.

	Agree	Dipel	Bactospeine[1]
Mamestra brassicae	21.4	65.2	270.8
Pieris brassicae	2.0	2.1	5.8
Plutella xylostella	3.7	4.1	4.2
Pieris rapae	3.7	4.2	6.9
Evergestis forficalis	1.5	7.6	-

[1] This batch was less active that it should have been due to possible plasmid loss.

Table 5a Summary of analyses of field trials at ADAS Arthur Rickwood, comparing the activity of insecticides against four species of caterpillar.

Species (Expt. No.)	Assessment times in days after treatment	Other products more effective than diflubenzuron?		Deltamethrin more effective than Bt products?		Agree more effective than Bactospeine?	
		Assess 1	**Assess 2**	**Assess 1**	**Assess 2**	**Assess 1**	**Assess 2**
P. xylostella (1)	2,9	NS	Y	NS	NS	NS	NS
P. rapae (2)	3,7	Y	Y	Y	NS	NS	NS
(3)	3,9	Y	Y	NS	NS	NS	NS
(4)	3,10	Y	Y	Y	NS	NS	NS
M. brassicae (4)	3,10	NS	NS	Y	Y	Y	NS
E. forficalis (3)	3,9	Y	NS	Y	NS	Y	Y
(4)	3,10	Y	NS	Y	NS	NS	NS

Table 7a Percentage of Brussels sprout buttons damaged (by weight) in the untreated plots at the three sites in 1996 and 1997. Comparisons are made between the buttons taken from the bottom third of each stem where the damage was greatest.

	1996	1997
ADAS Arthur Rickwood	26	5
HRI Kirton	83	19
HRI Stockbridge House	29	10

Table 7b The mean numbers of sprays of *Bacillus thuringiensis* applied to the plots treated with the standard managed treatment in 1996 and 1997.

	1996	1997
ADAS Arthur Rickwood	8	2.7
HRI Kirton	10.7	1.3
HRI Stockbridge House	6.3	1

Figure 1a The distribution of *P. xylostella* caterpillars in an untreated plot of Brussels sprouts at HRI Kirton sampled on 18 July 1995. Numbers shown are the mean numbers of caterpillars found in ten adjacent 40-plant transects taken from the edge to the middle of the plot.

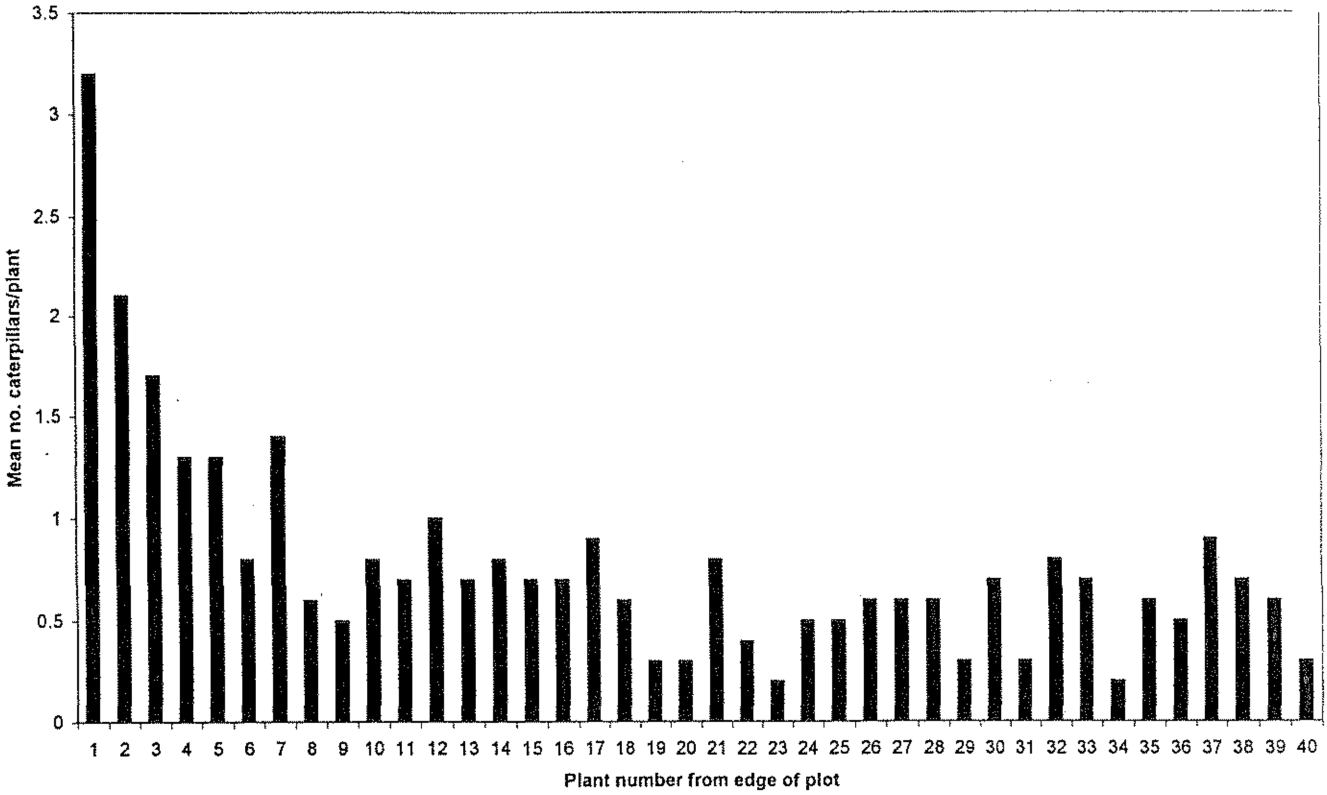


Figure 1b The distribution of *M. brassicae* caterpillars in an untreated plot of Brussels sprouts at HRI Stockbridge House, sampled on 2 August 1995. Numbers shown are the mean numbers of caterpillars found in ten adjacent 40-plant transects taken from the edge to the middle of the plot.

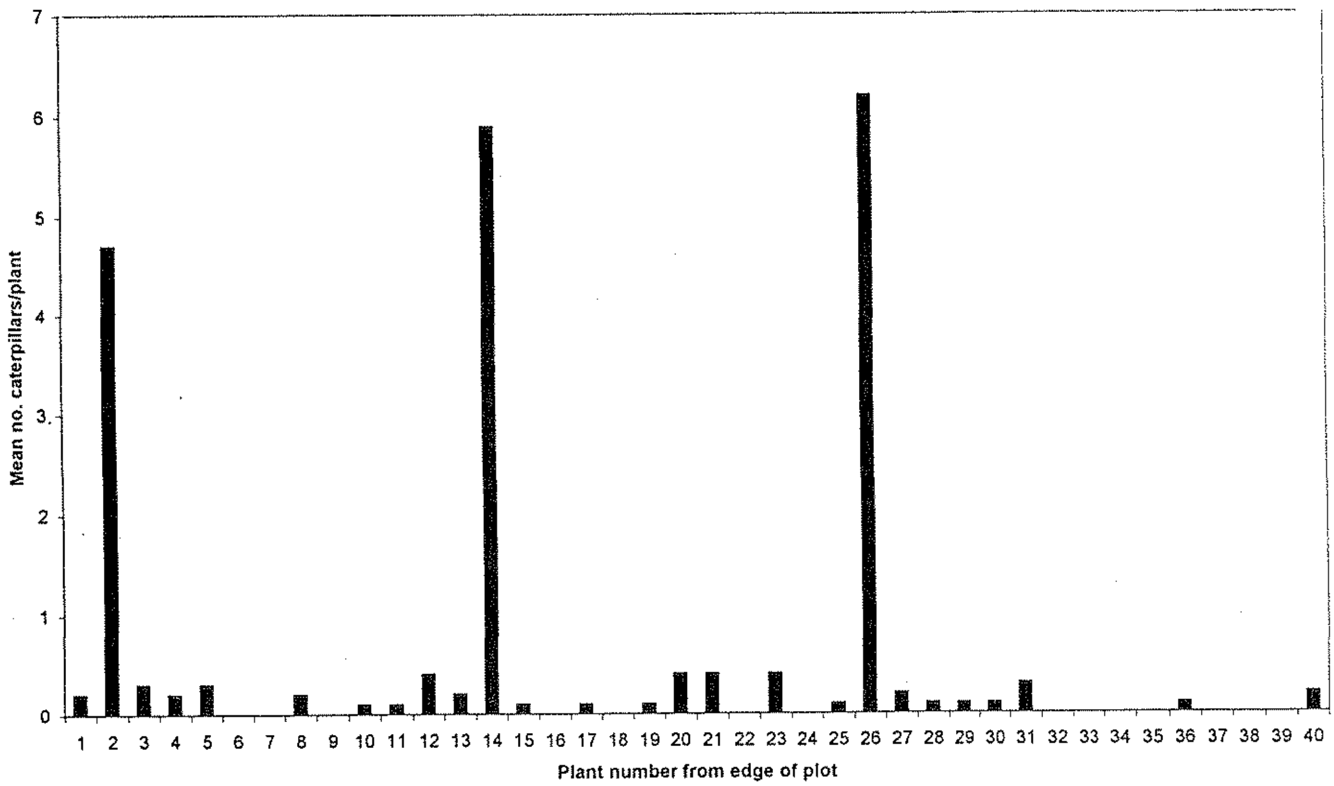


Figure 1c Frequency distributions showing the plant (plants numbered from the edge of the crop) on which the maximum number of caterpillars were found in transects taken in commercial crops and untreated plots during 1994 and 1995. The data were summarised using 5-plant running means.

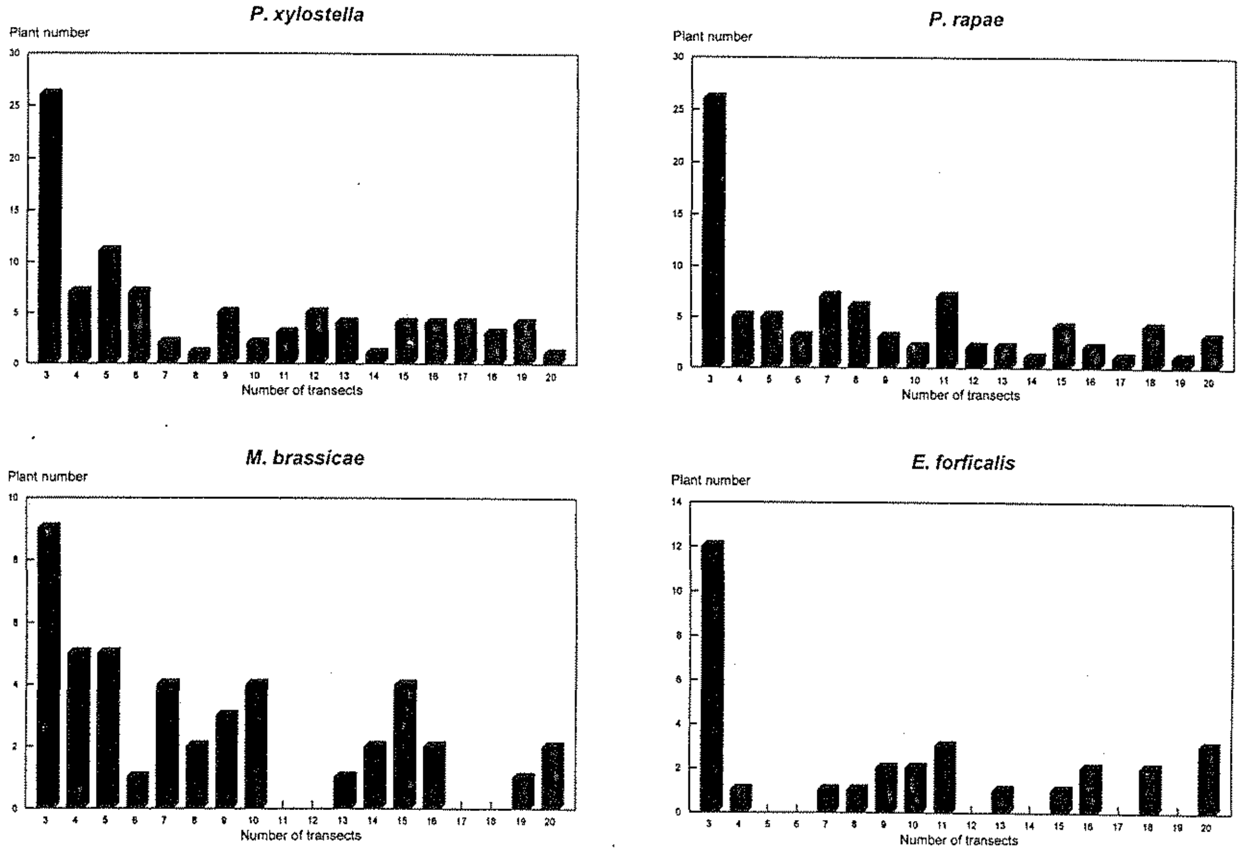


Figure 1d Fitted curves showing the distribution of *P. xylostella* in transects taken across 9 commercial fields in 1995.

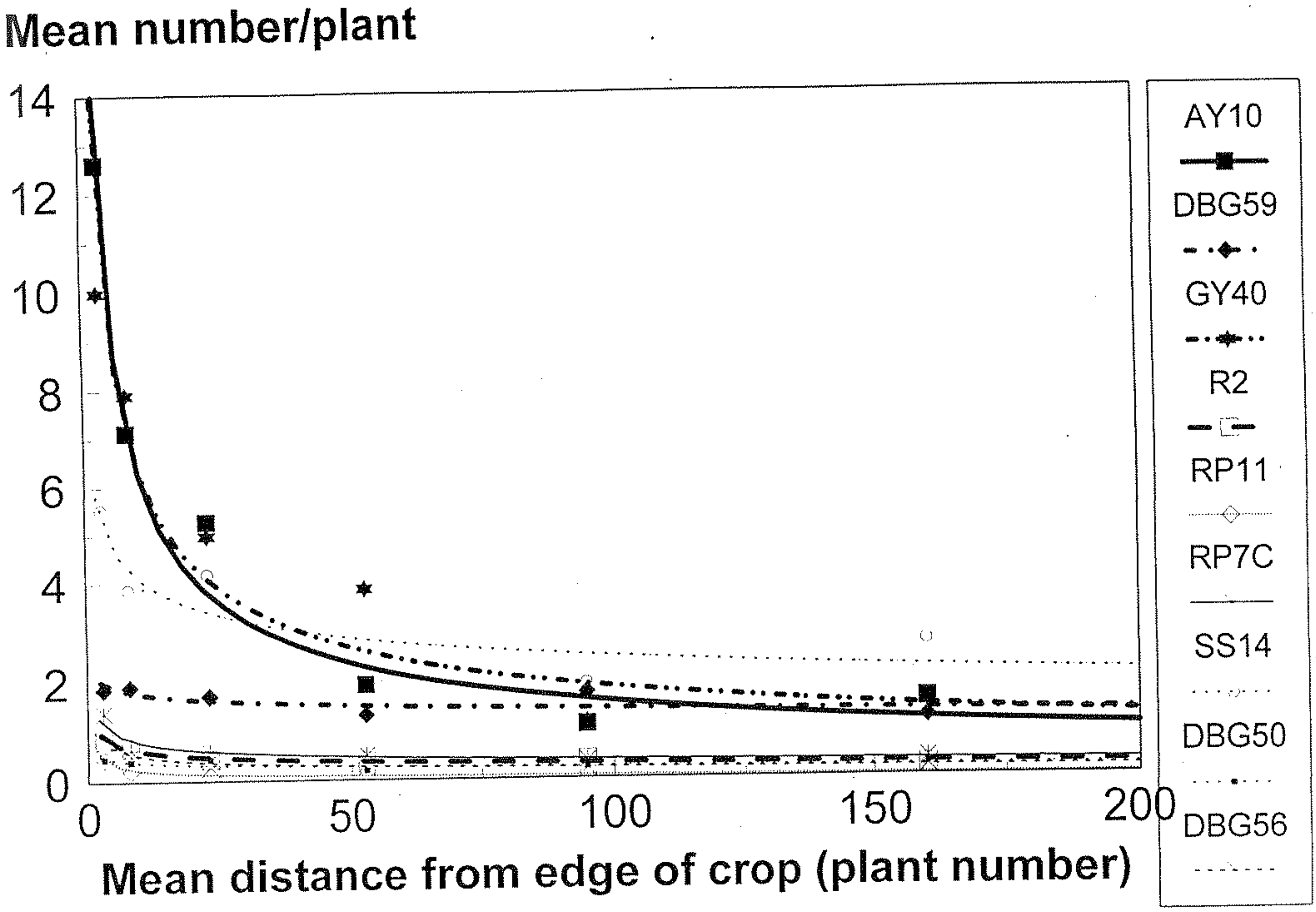


Figure 1e The relationship between the mean infestation size and the variance for the four species of caterpillar sampled in 1994 and 1995.

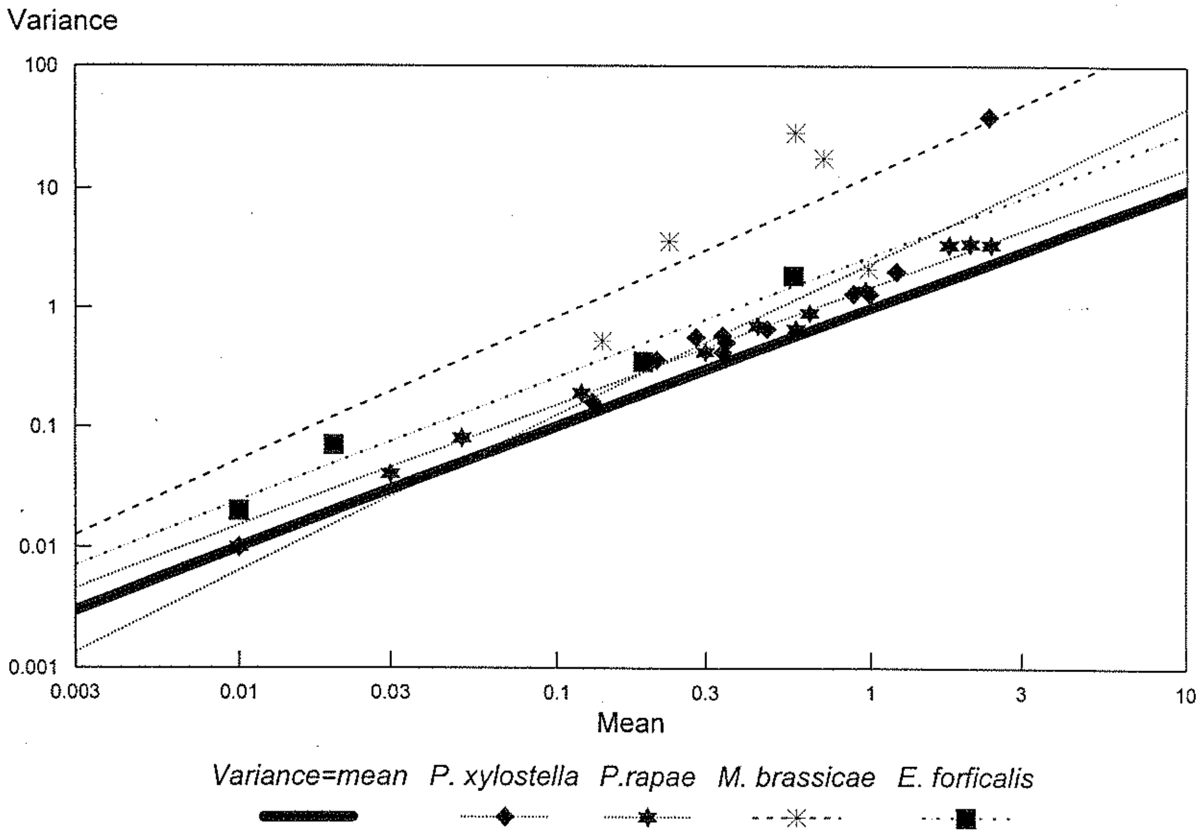


Figure 1f Relationship between the fitted parameter k from the negative binomial distribution and the mean infestation size for the four species of caterpillar sampled in 1994 and 1995.

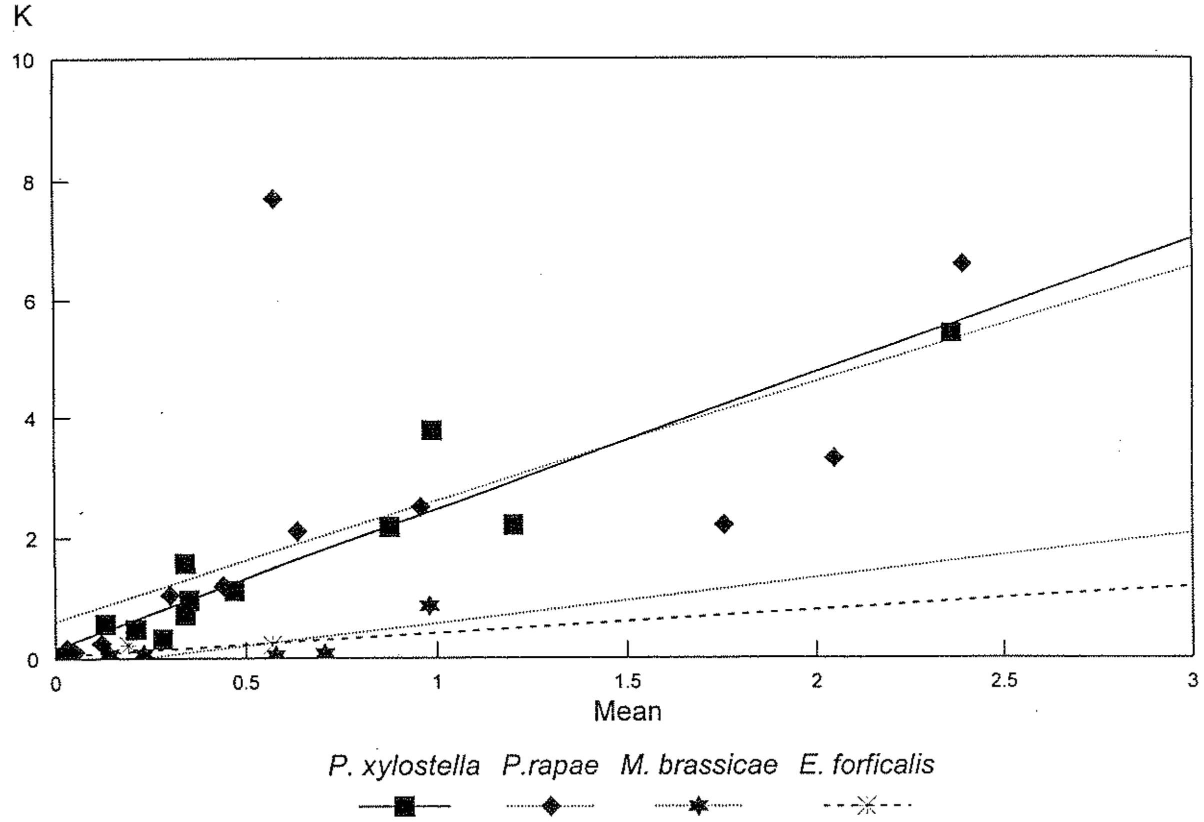


Figure 1g Relationship between the proportion of plants infested with caterpillars and the mean infestation level (using data for all species collected in commercial crops in 1995). The legend shows sampling dates in days from 1 January.

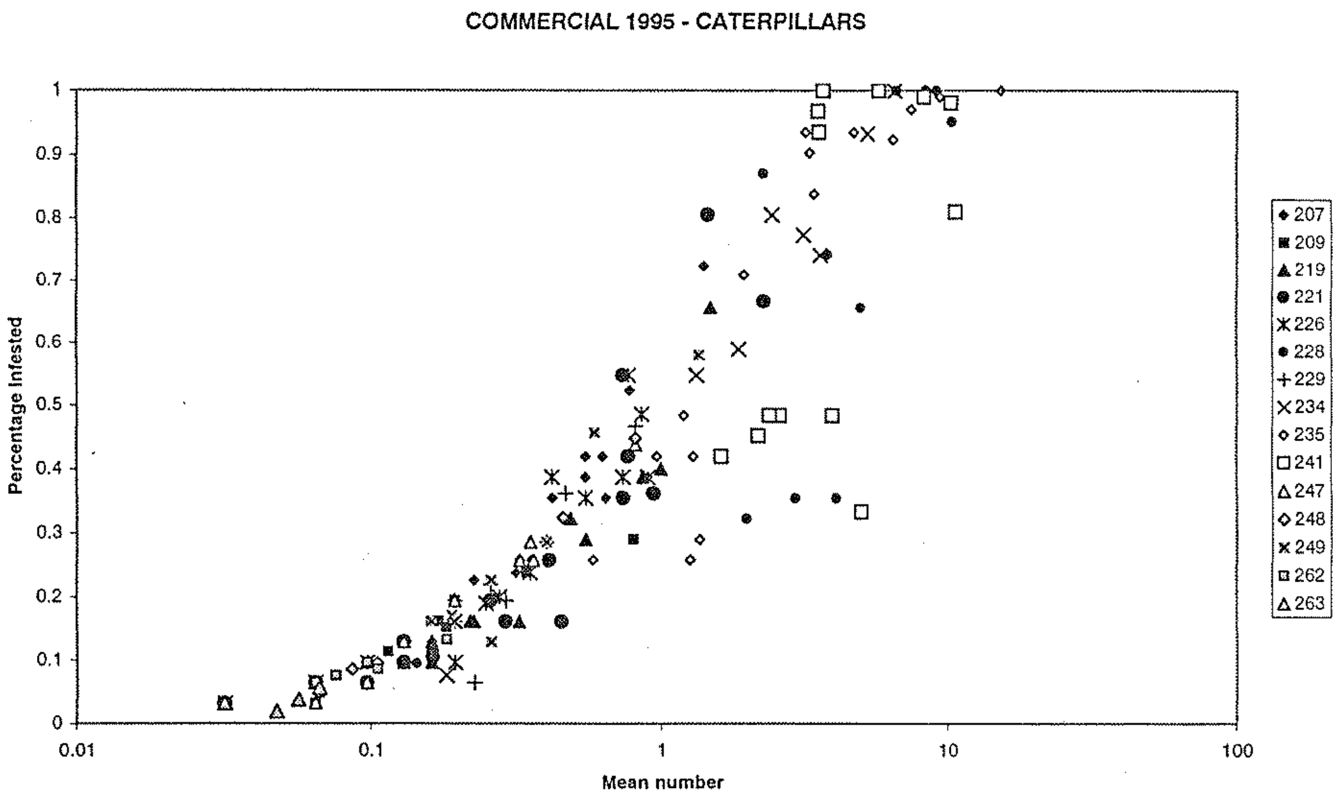


Figure 1h Relationship between the proportion of plants infested with caterpillars and the mean infestation level – data separated into three groups (crops sampled early, mid and late season). The legend shows sampling dates in days from 1 January.

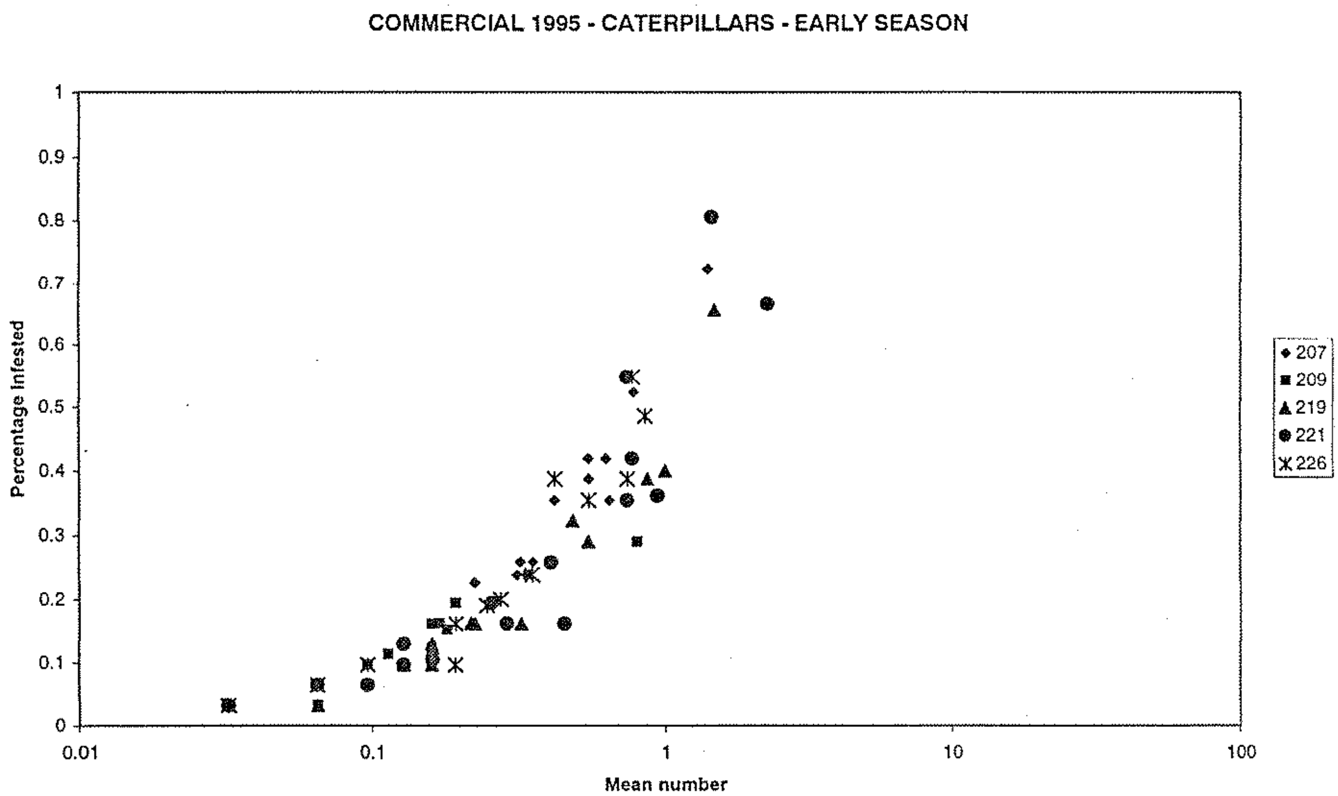
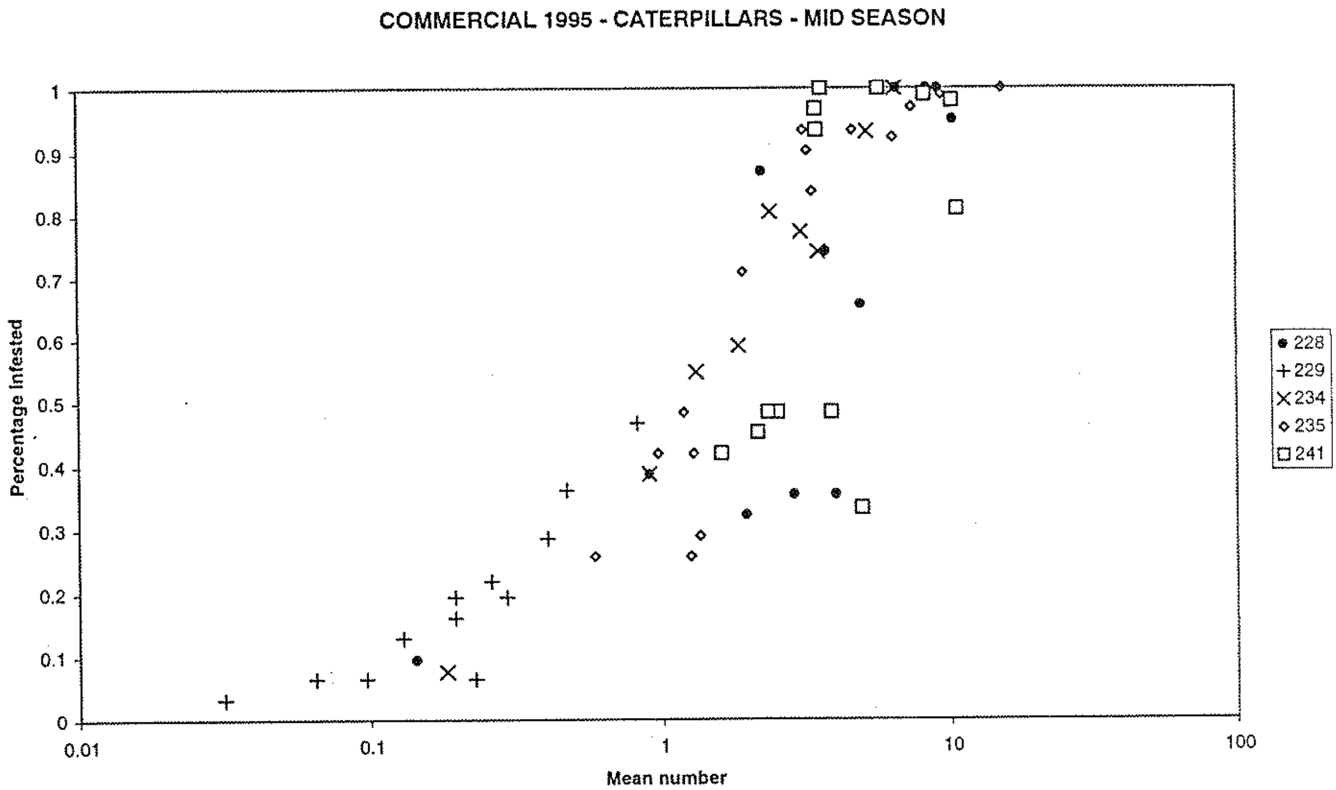


Figure 1h	Relationship between the proportion of plants infested with caterpillars and the mean infestation level – data separated into three groups (crops sampled early, mid and late season). The legend shows sampling dates in days from 1 January.



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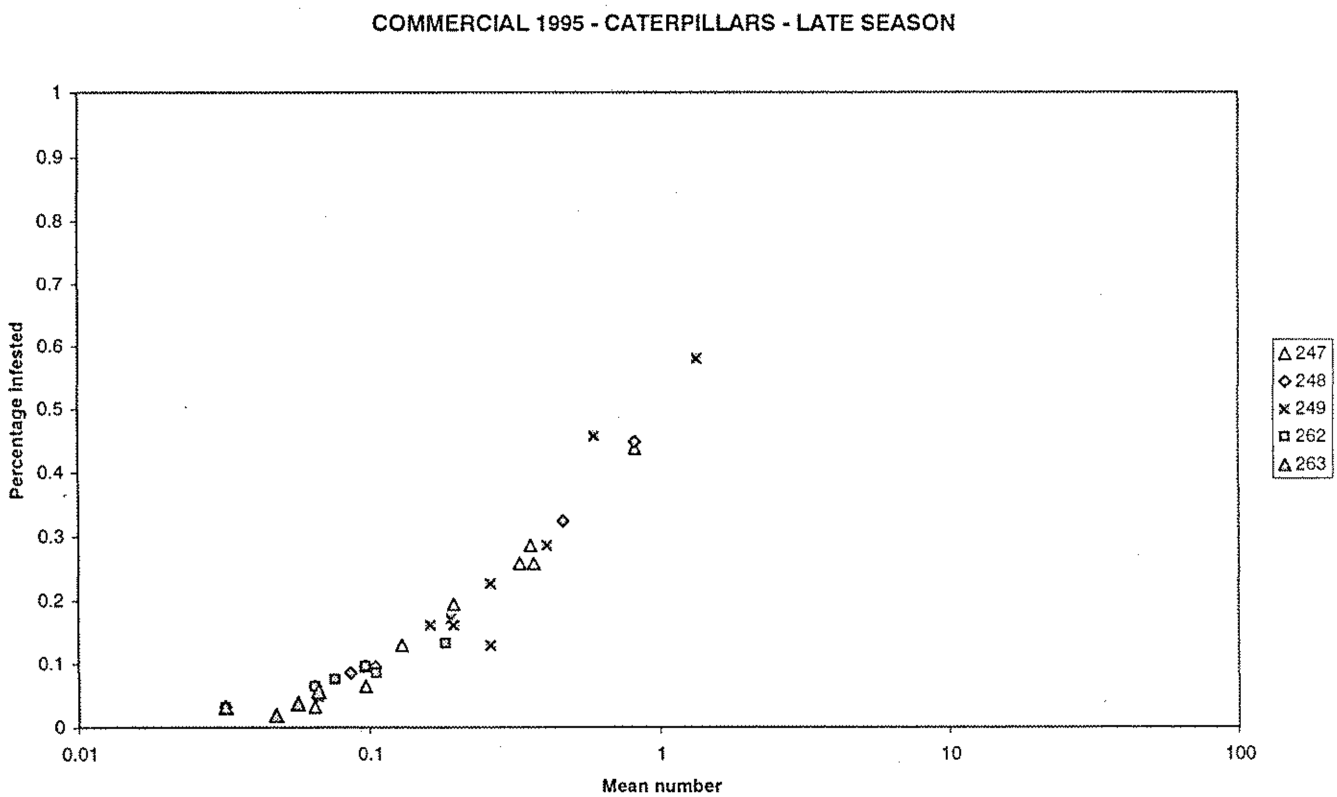


Figure 1i Relationship between the mean percentage of plants infested in the corners and the mean percentage of plants infested on the edges of commercial crops sampled in 1996.

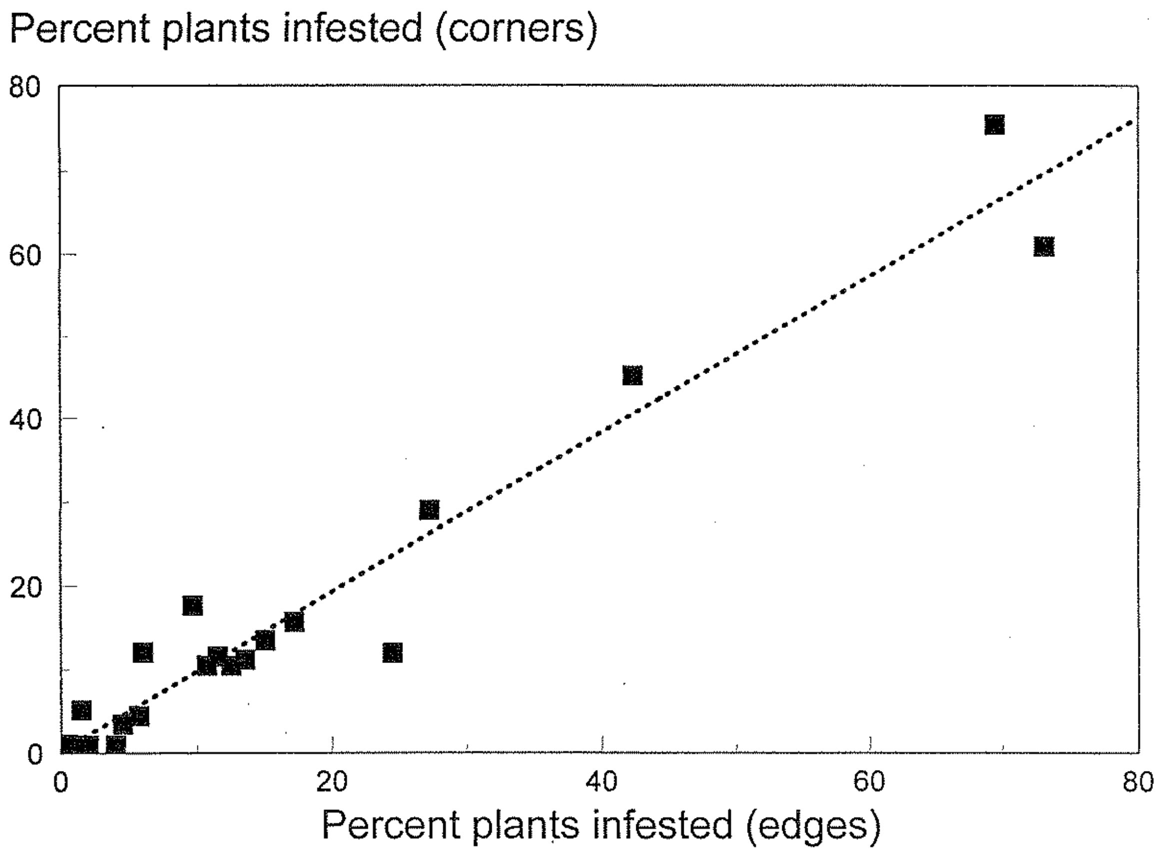


Figure 1j Relationship between the percentage of plants infested in the middle and the mean percentage of plants infested on the edges of commercial crops sampled in 1995 -1997.

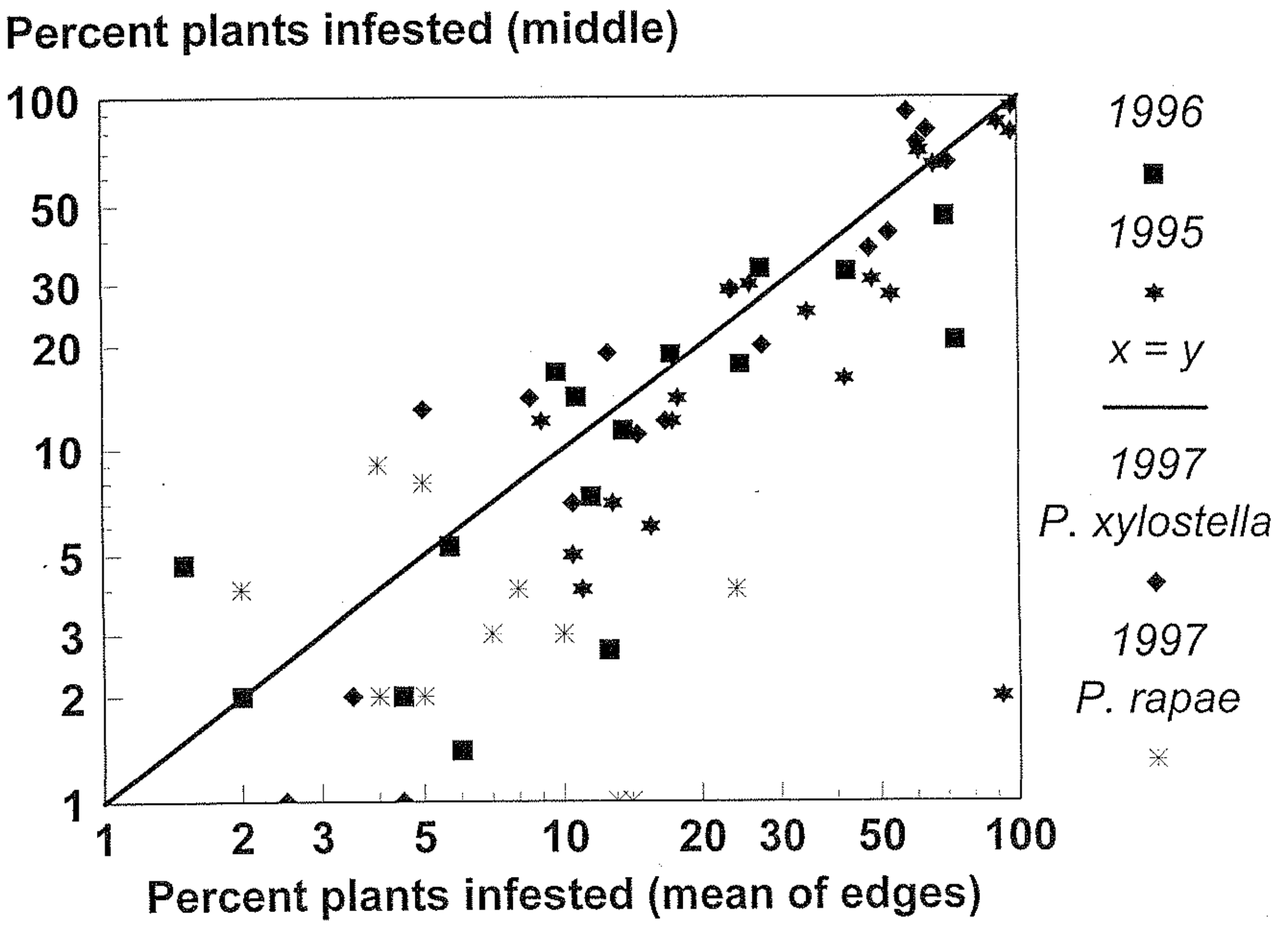


Figure 1k Relationship between the percentage of plants infested in the middle and the mean percentage of plants infested on the worst edge of commercial crops sampled in 1995-97.

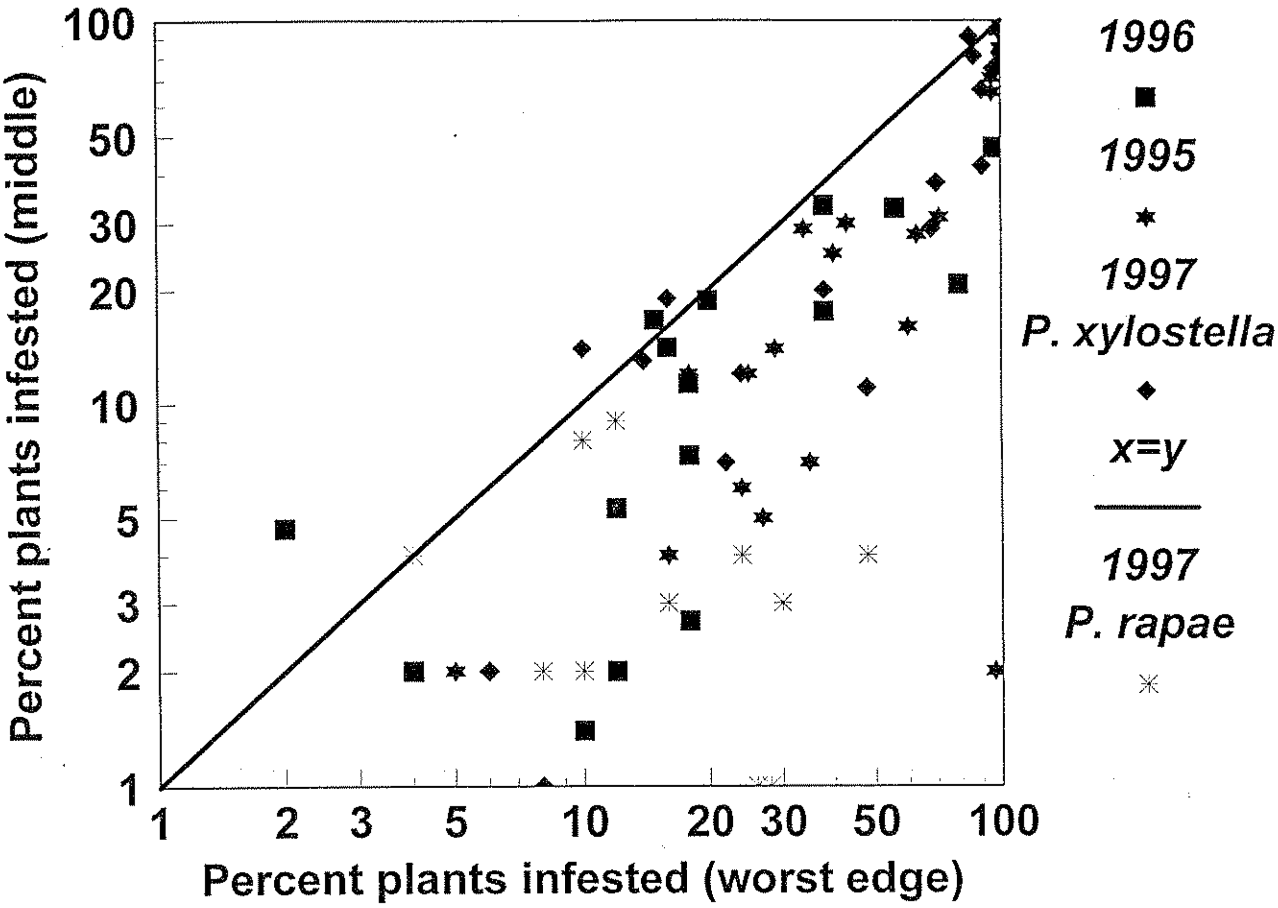


Figure 2a Output from 100 repeated simulations of a sampling strategy, where only one edge of a cauliflower crop (sampled on 13 August 1996) was examined and 10 plants were selected along a transect (print of simulation run is in Appendix 2). The mean infestation level was 14.1% and the range of estimated infestation levels was from 0 to 50%.

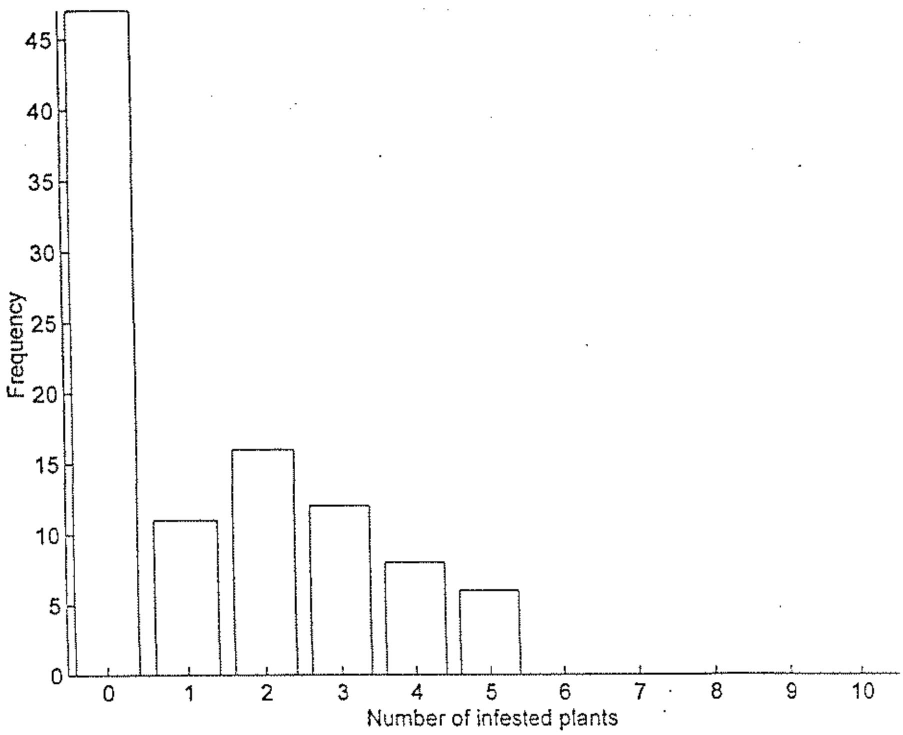
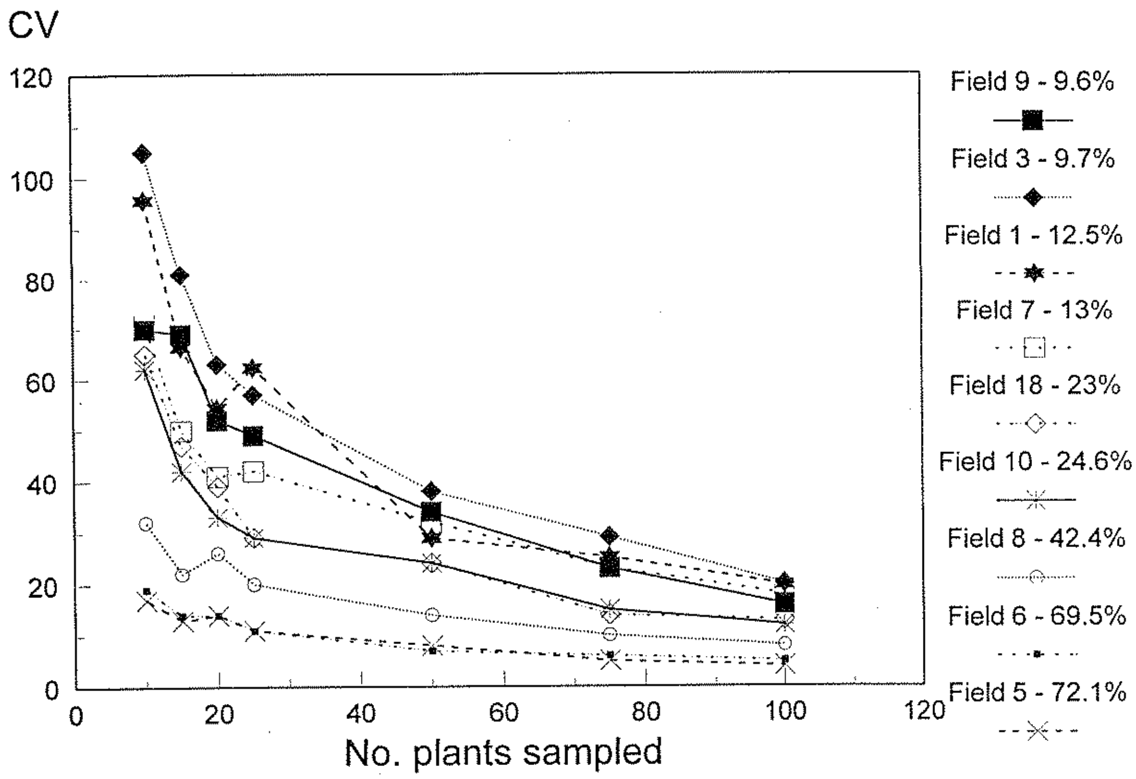


Figure 2b The effect of sample size on the coefficient of variation (CV) when repeated (100) simulations were made of a sampling strategy including all four edges of the crop.



Legend shows overall infestation level in each field

Figure 2c An example of the effects on the coefficient of variation (CV) of sampling from 1-4 edges/corners of a crop (25-plant samples).

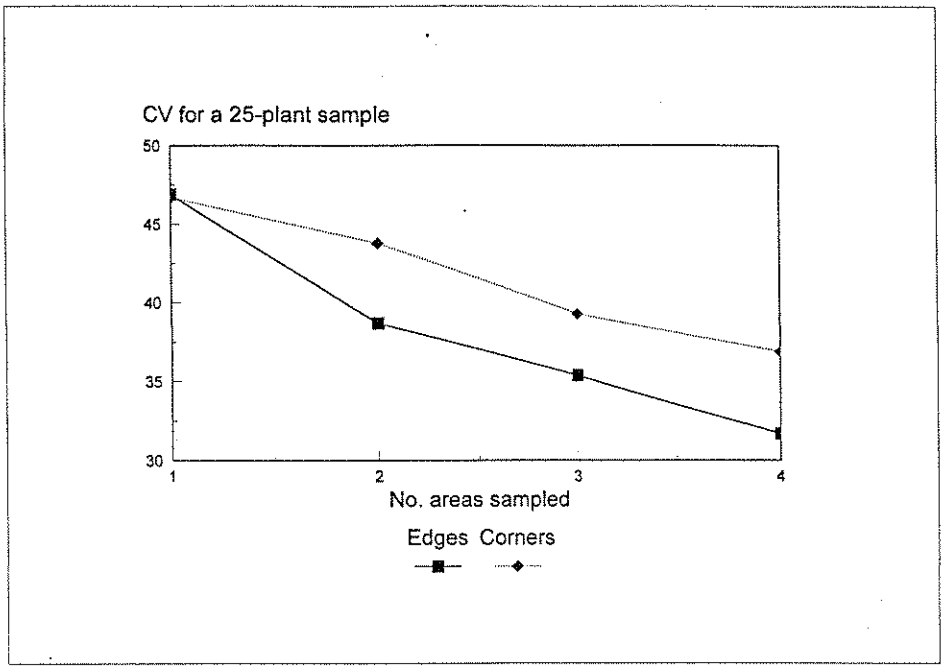


Figure 2d Comparison of MATLAB simulations with estimates made by 21 growers of the number of plants infested with caterpillars in a commercial crop of calabrese.

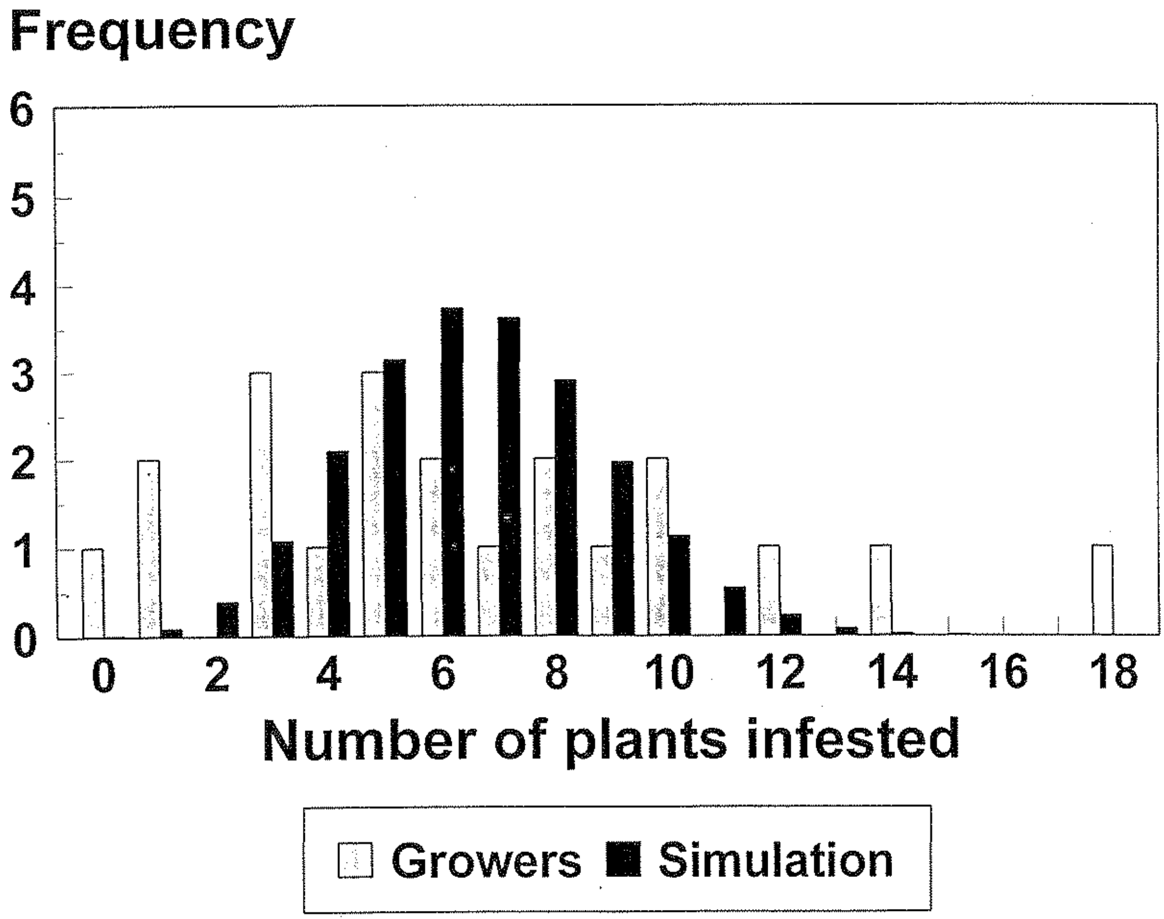
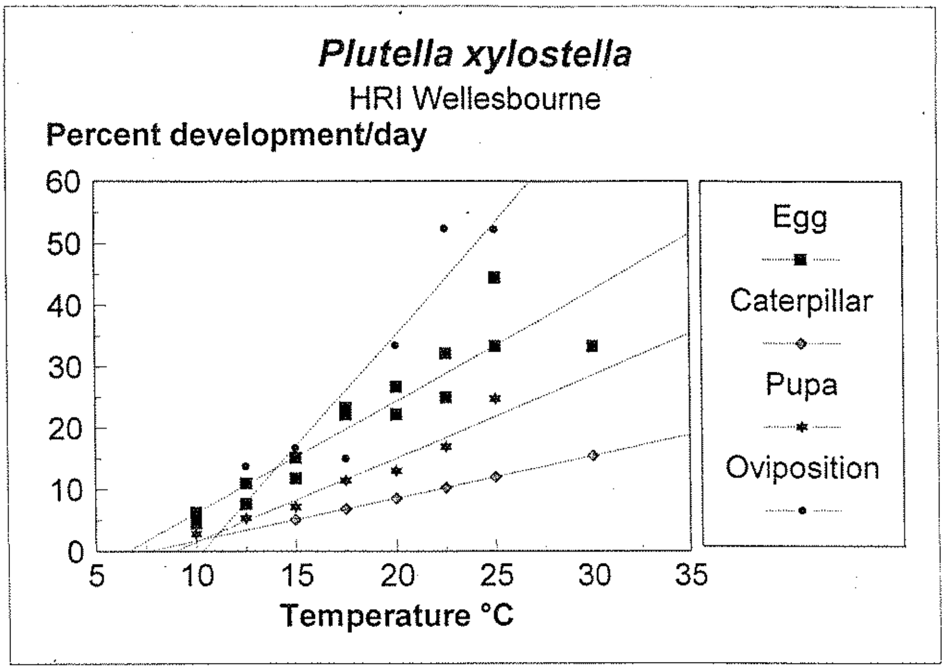


Figure 3a Relationship between the rate of development (100/time to complete development) for oviposition, egg, larval and pupal development of P. *xylostella*, *M. brassicae* and *E. forficalis*.



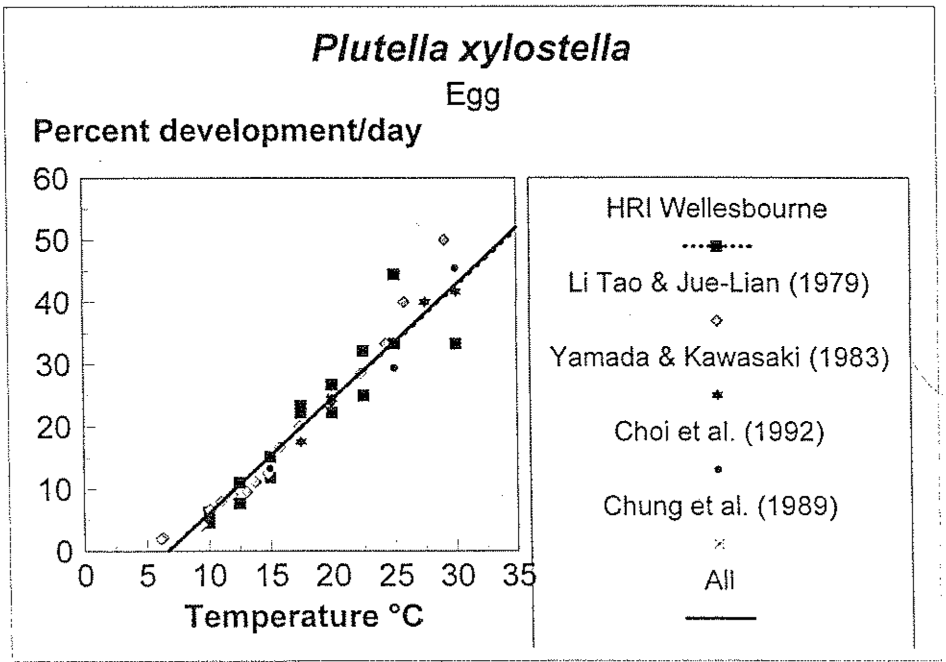
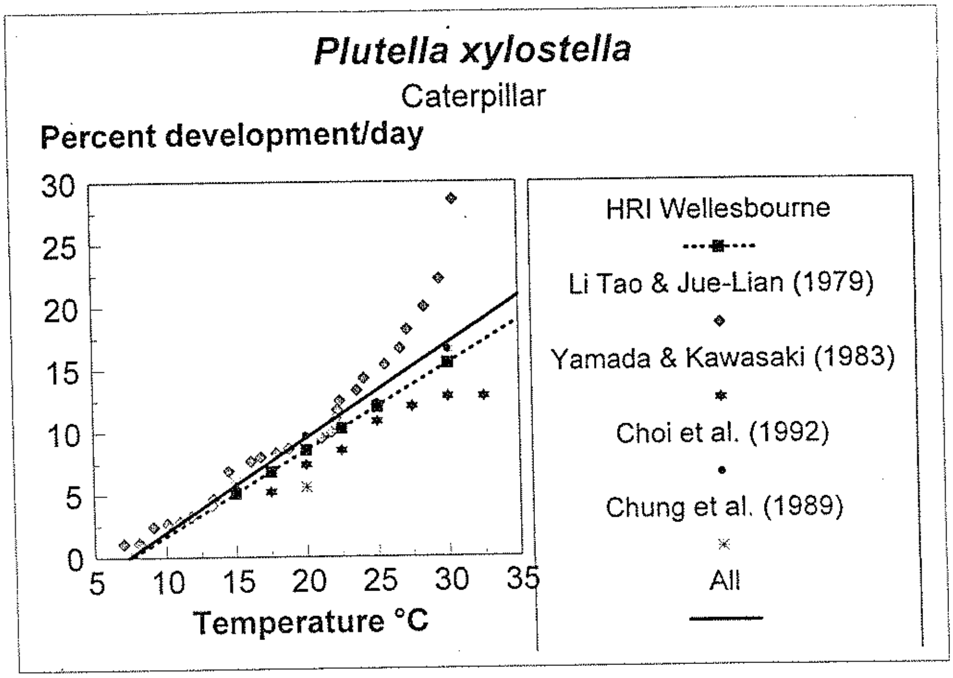
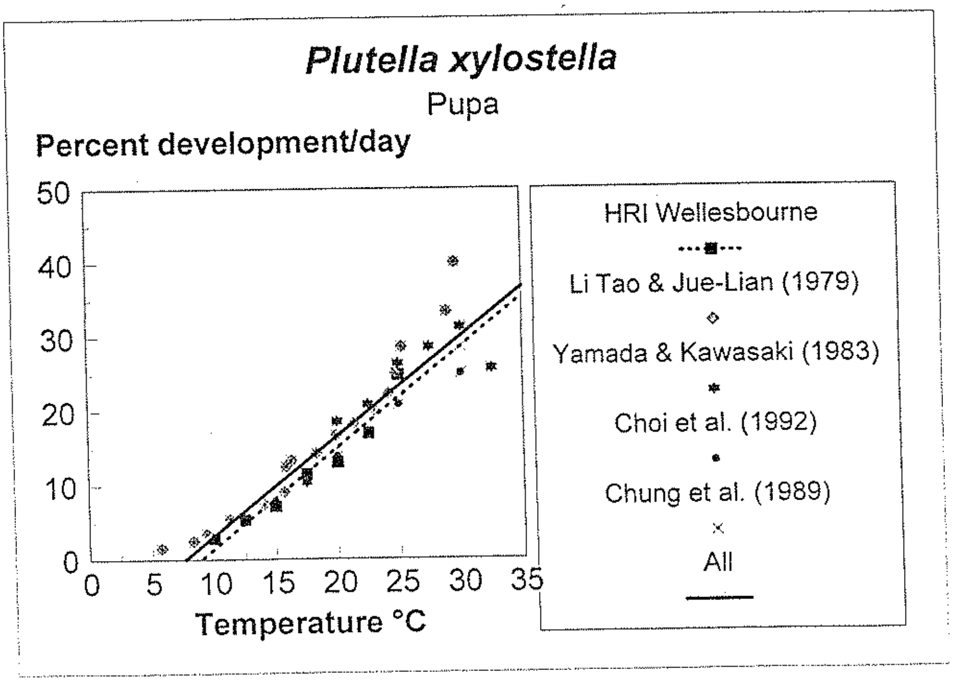


Figure 3a Relationship between the rate of development (100/time to complete development) for oviposition, egg, larval and pupal development of *P. xylostella, M. brassicae* and *E. forficalis.*





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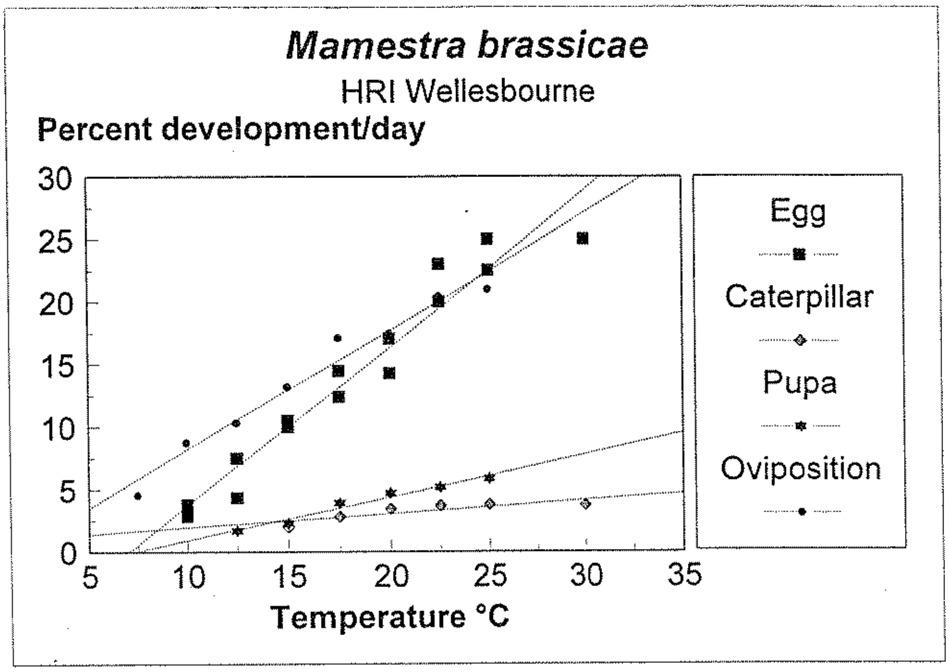

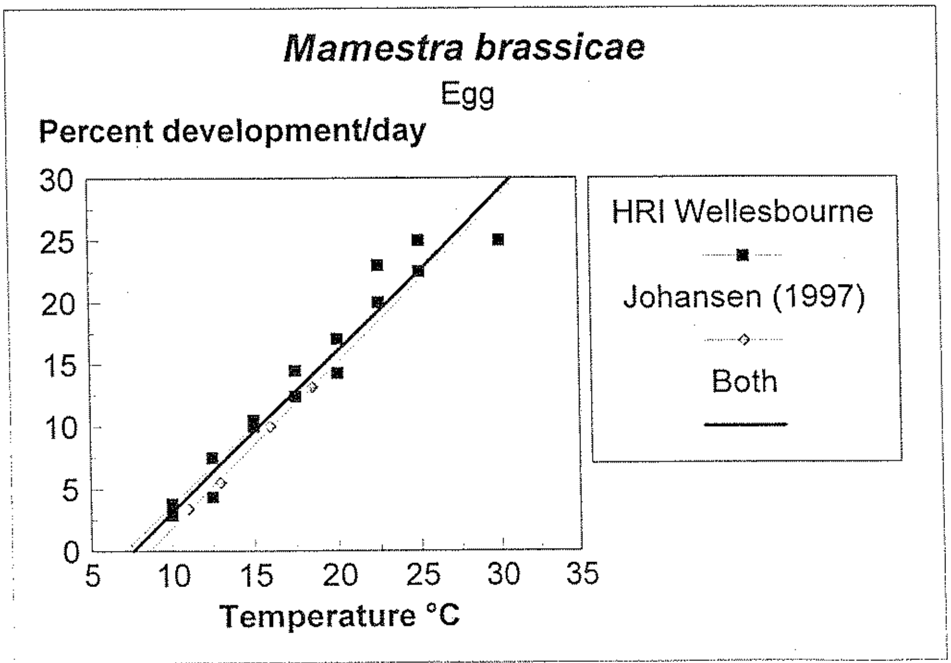

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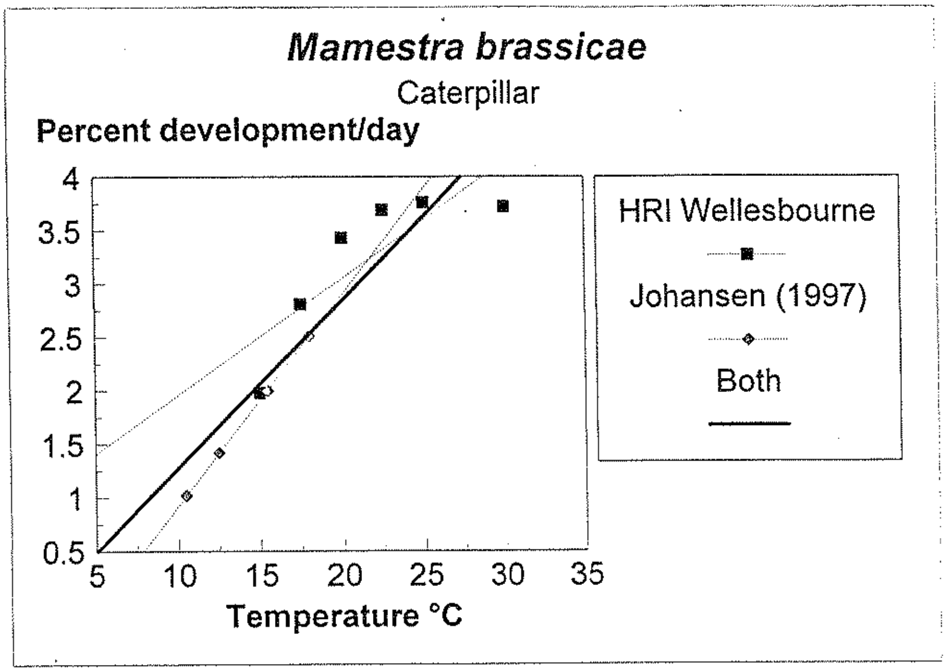

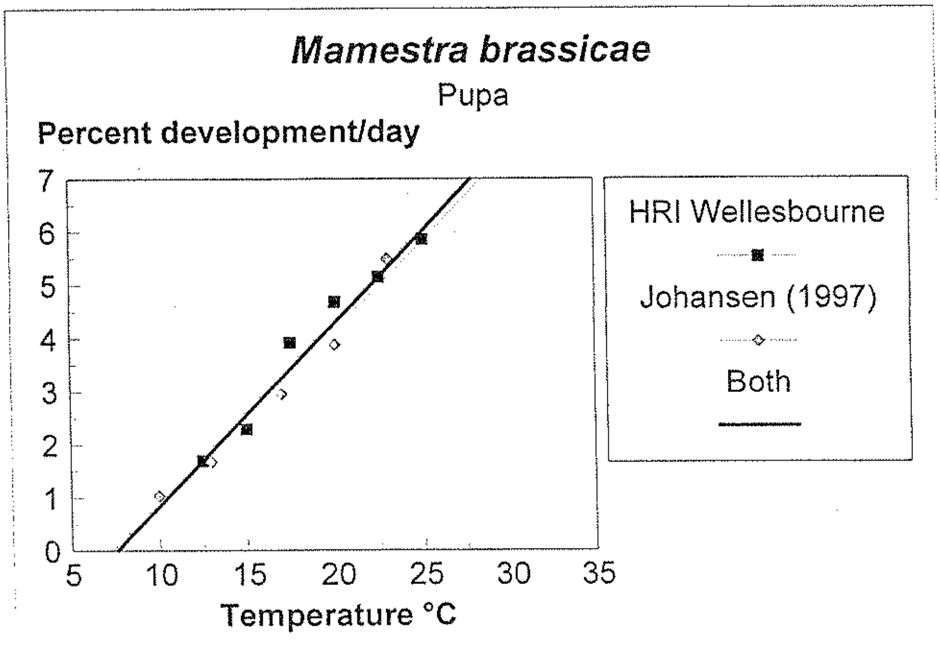

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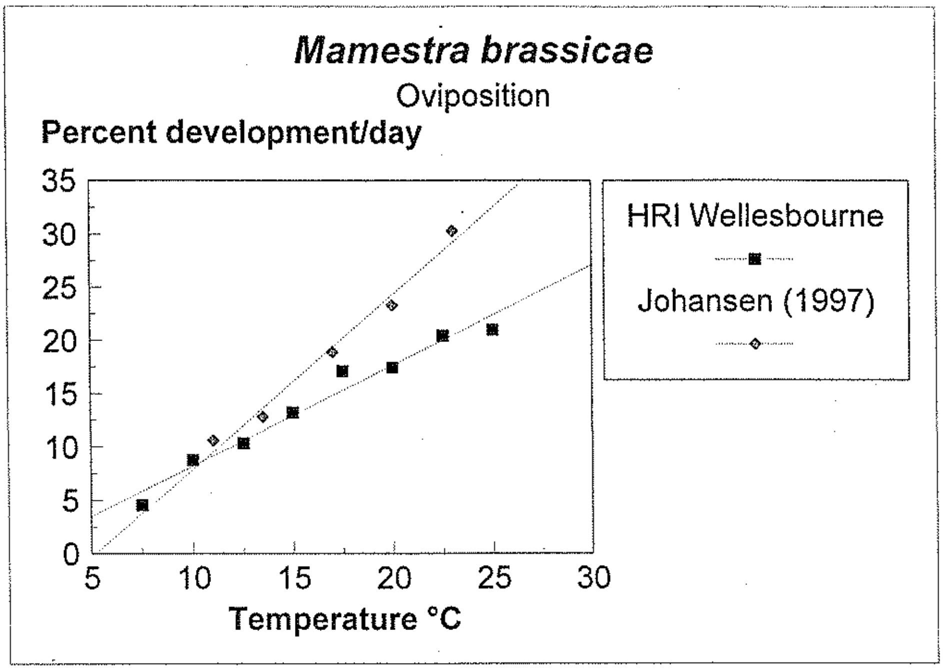


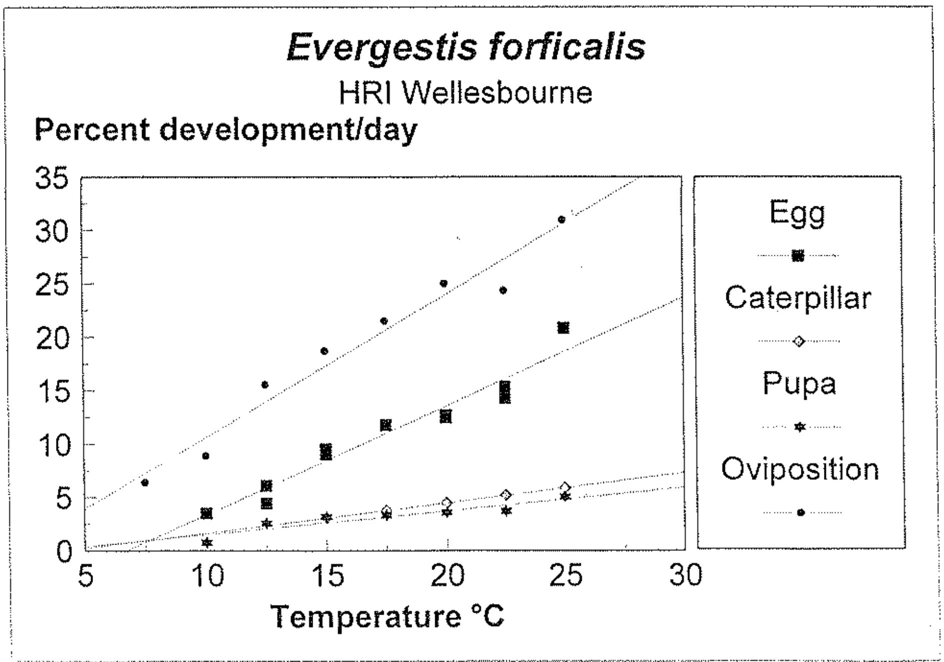
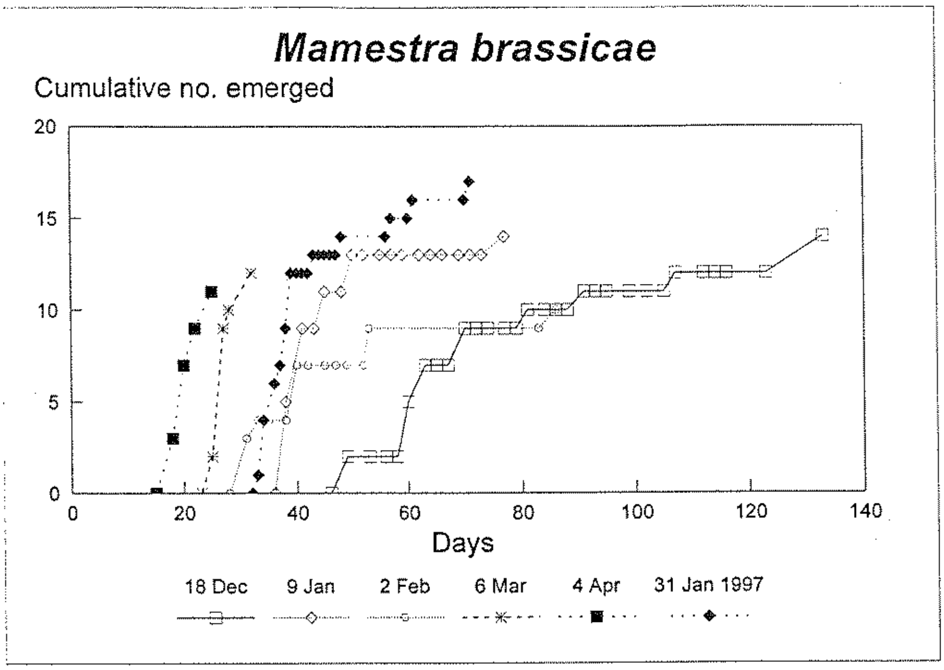
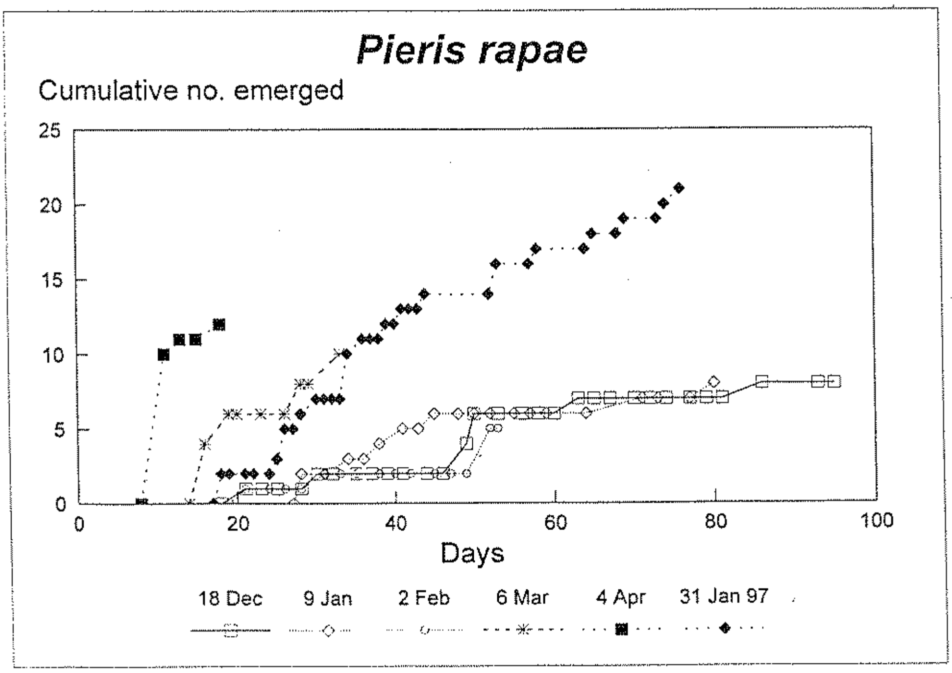


Figure 3b Cumulative adult emergence curves for three species of caterpillar. Overwintering pupae were maintained outside and samples were taken into the laboratory at regular intervals and kept at 17.5°C.





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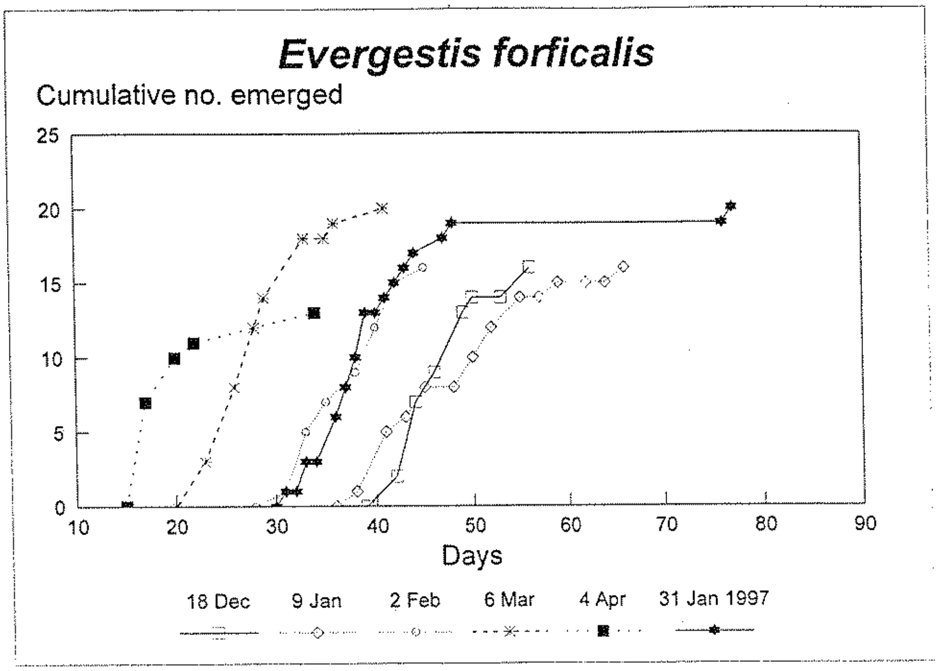
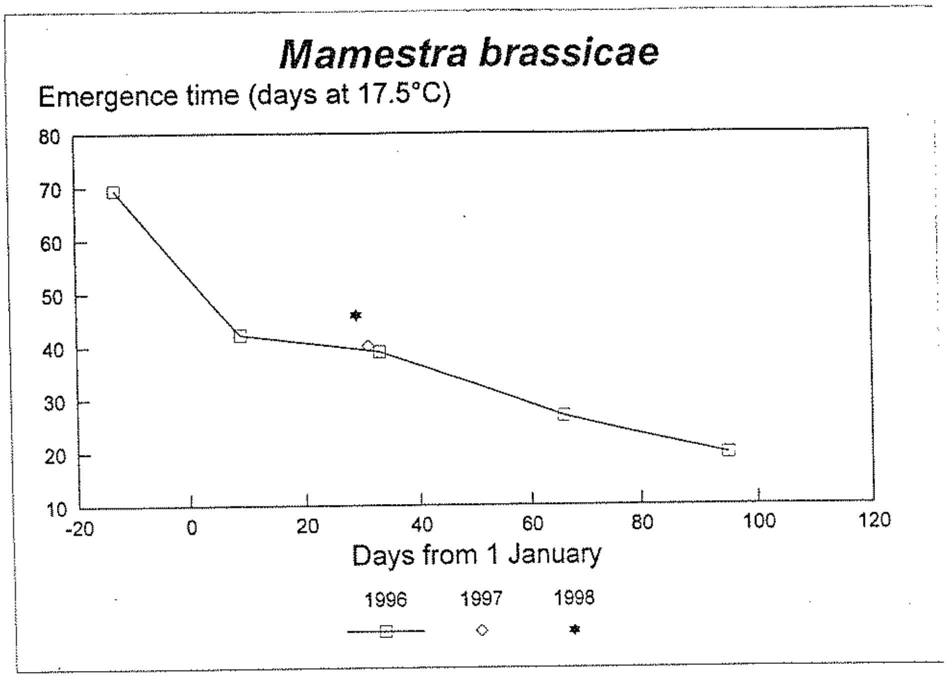
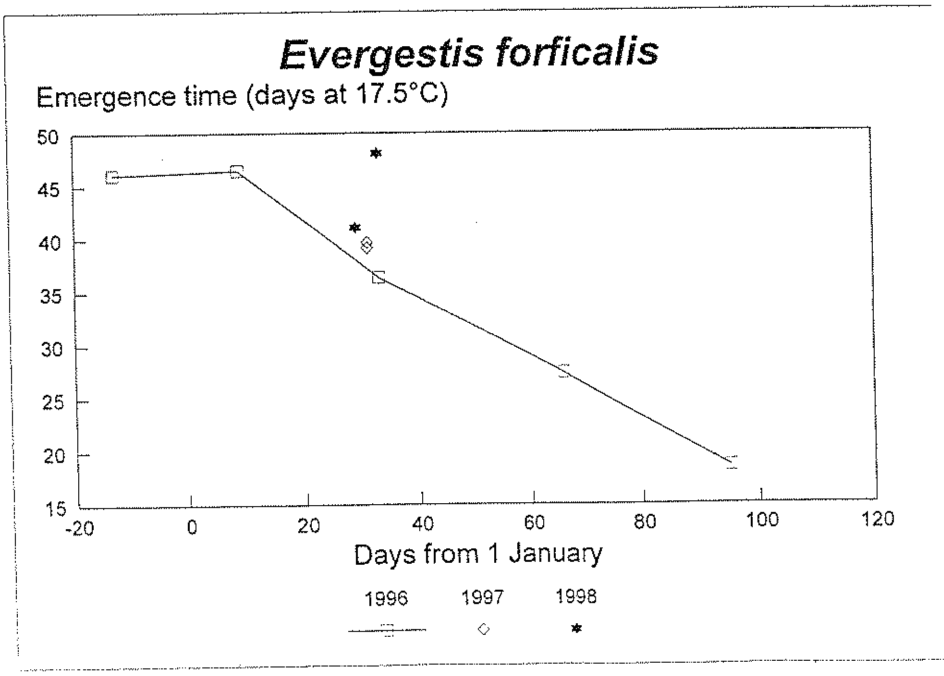


Figure 3c The mean emergence time when overwintering pupae of three species of caterpillar were brought into the laboratory at intervals throughout the winter and spring.





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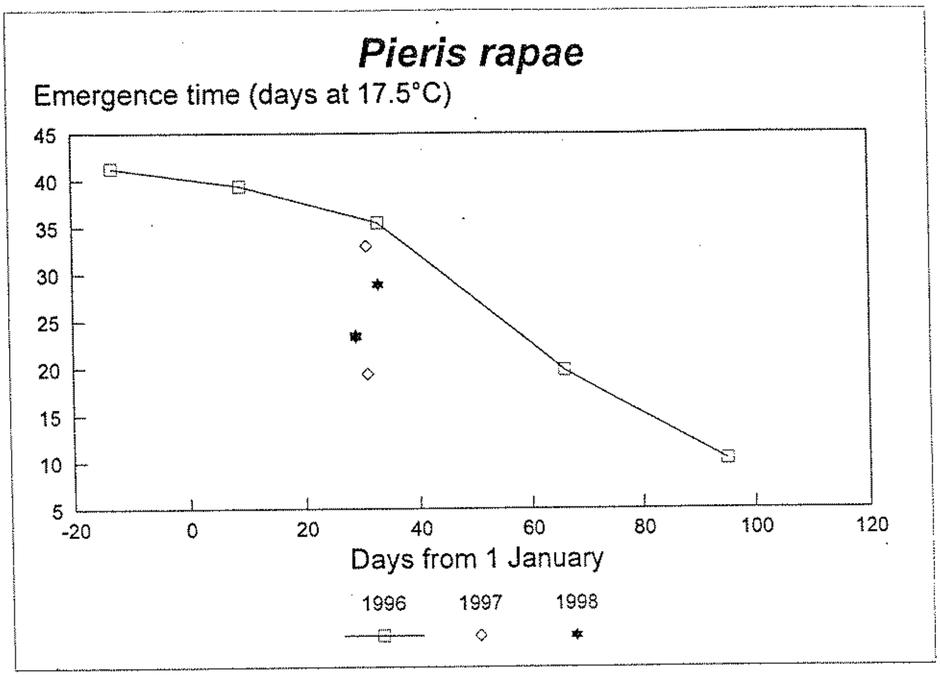
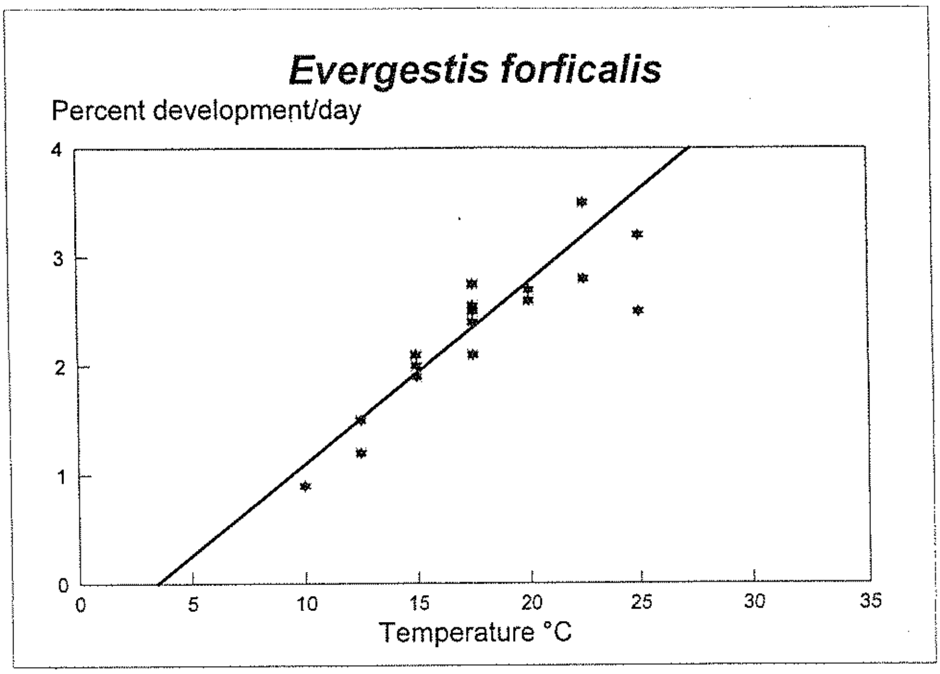
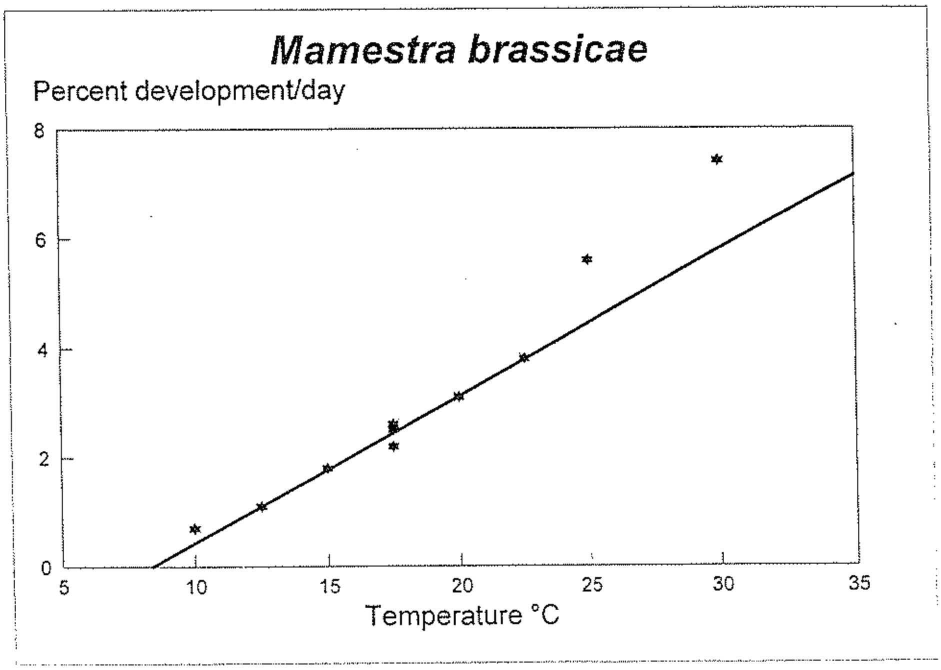


Figure 3d Relationship between the rate of post-winter development and temperature for the overwintering pupae of three species of caterpillar.





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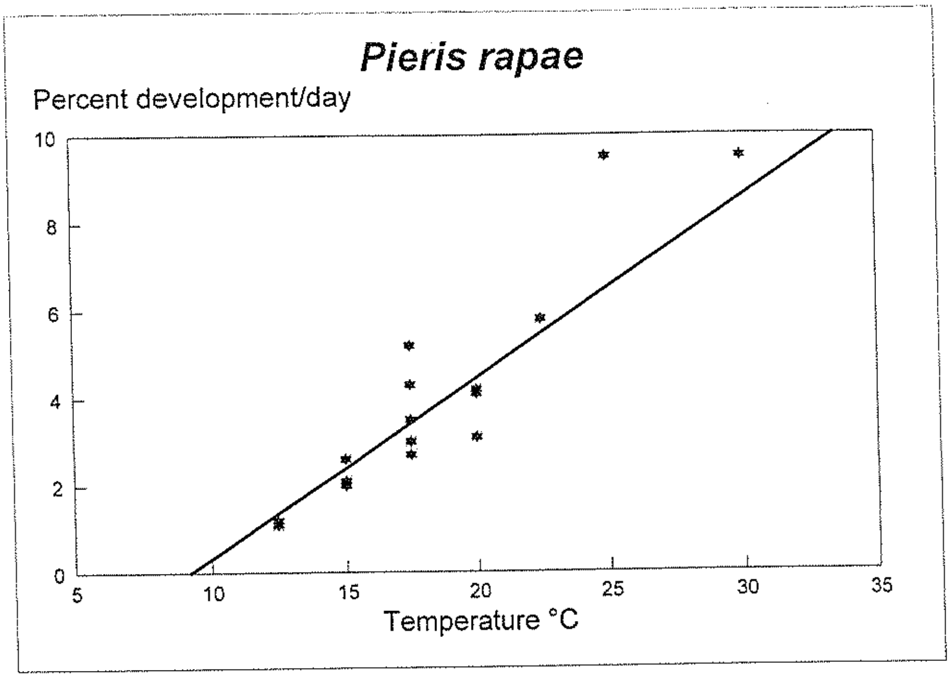


Figure 3e The numbers of male *P. xylostella* moths captured in pheromone traps at Kirton in 1996.

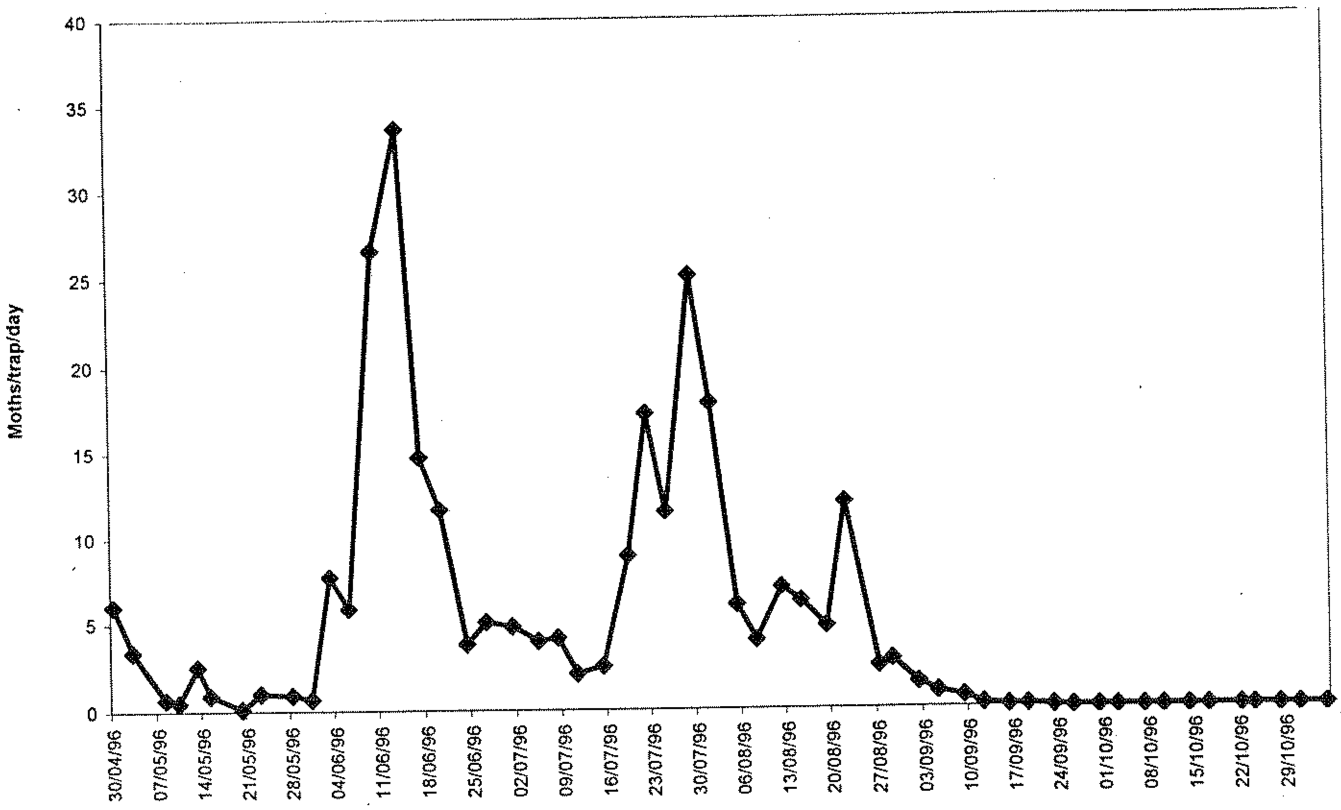


Figure 3f The numbers of male *E. forficalis* moths captured in pheromone traps at ADAS Arthur Rickwood in 1995.

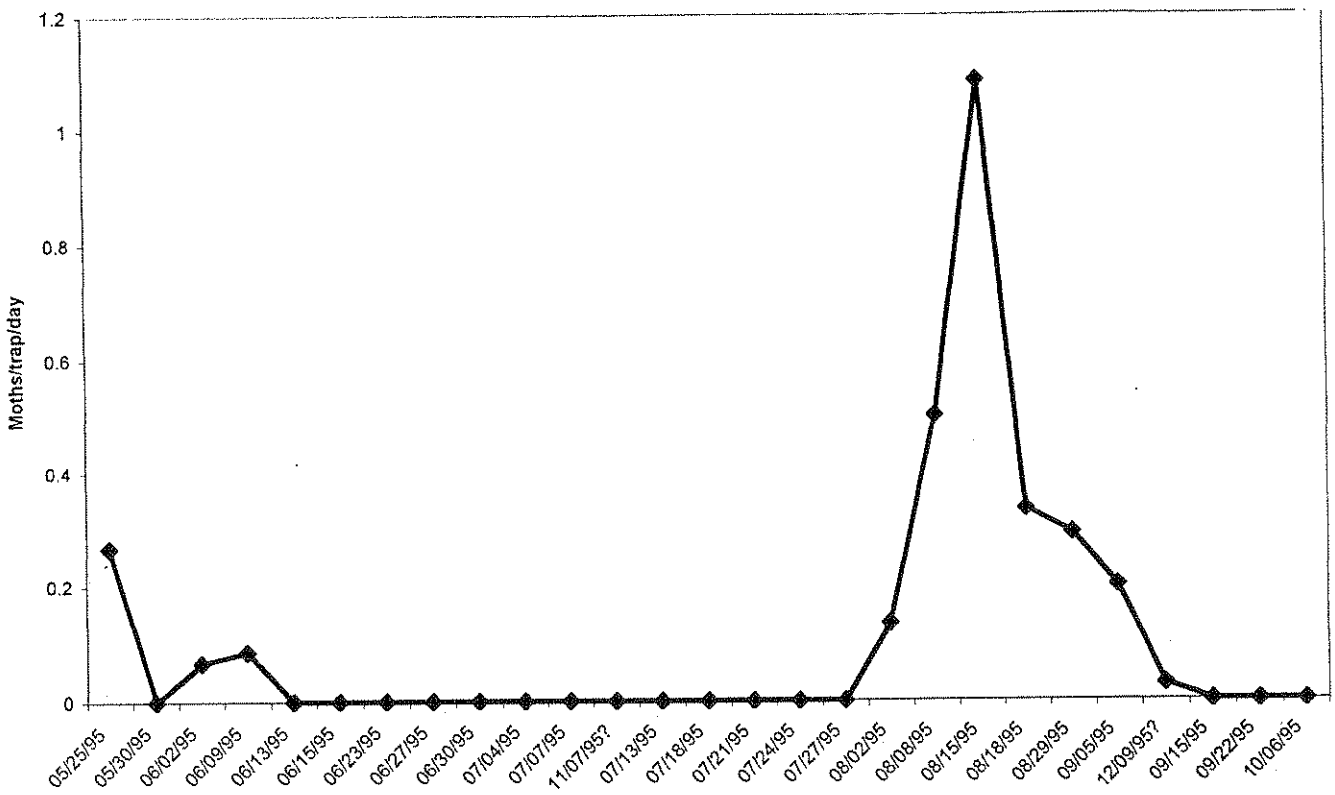


Figure 3g The numbers of *P. rapae* butterflies captured in water traps at HRI Wellesbourne in 1995.

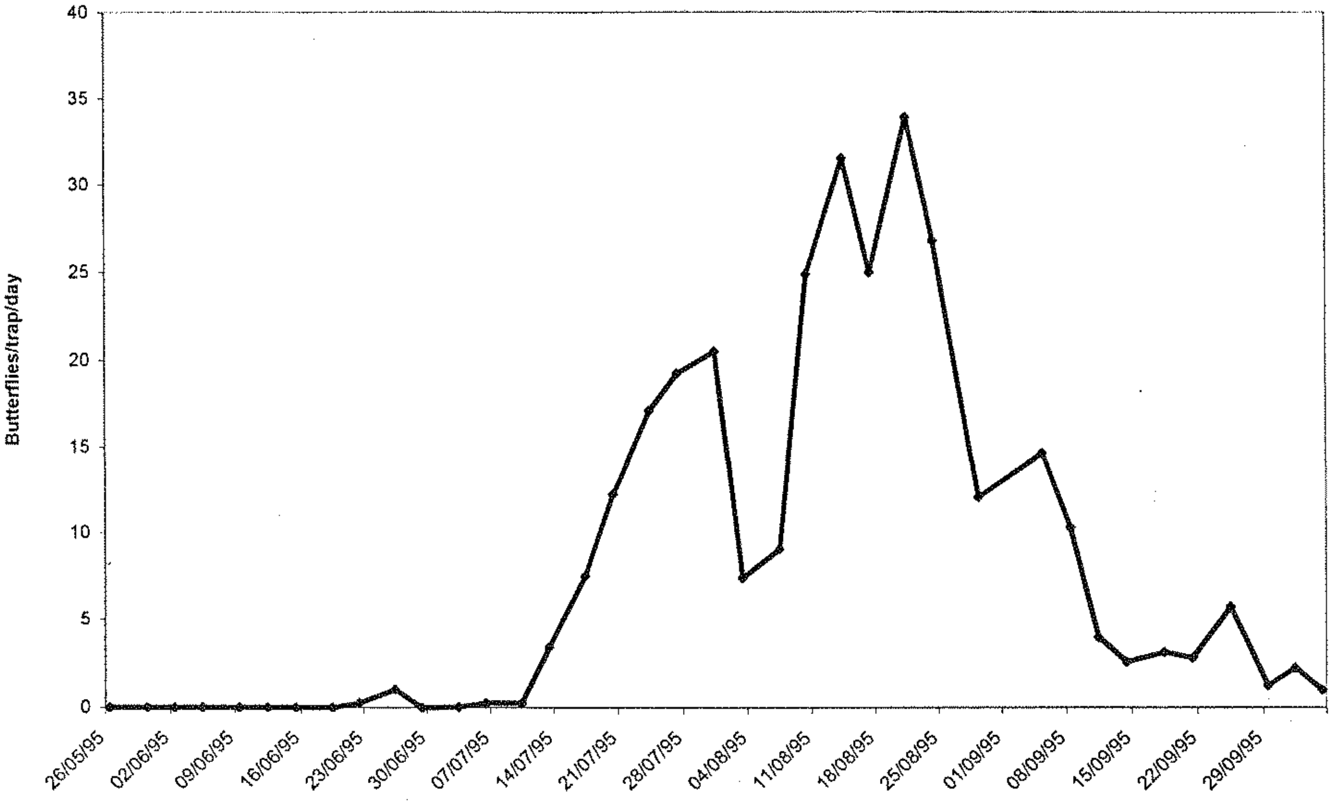
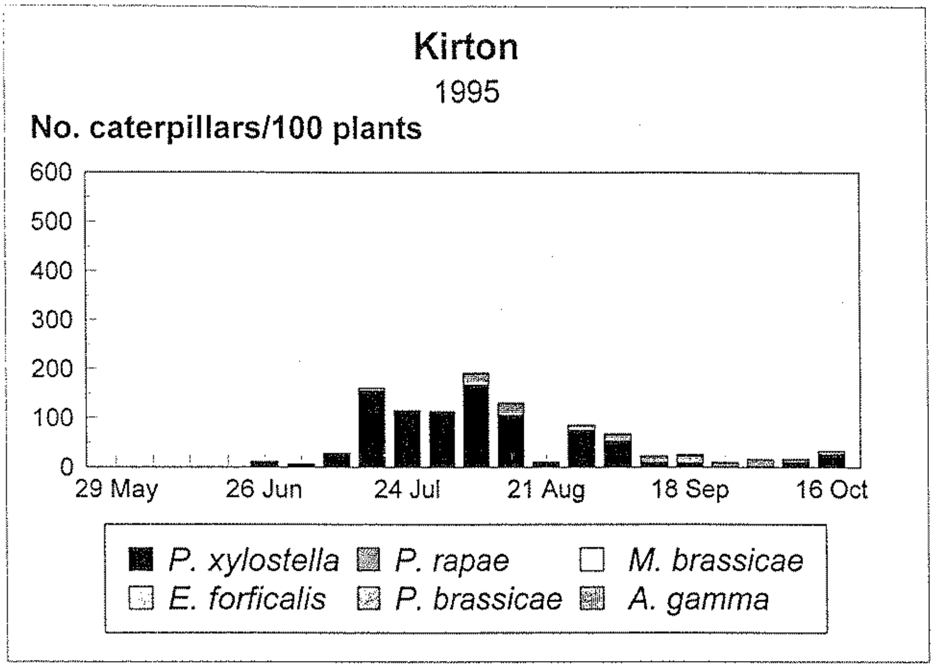


Figure 3h The numbers of caterpillars of each species found each week during 1995-1997 on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood.



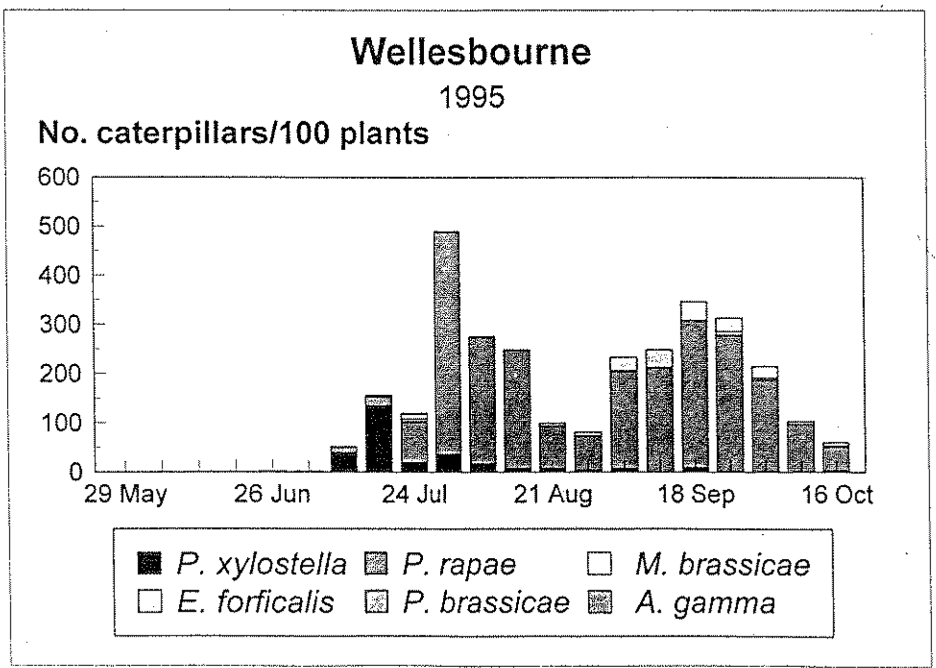
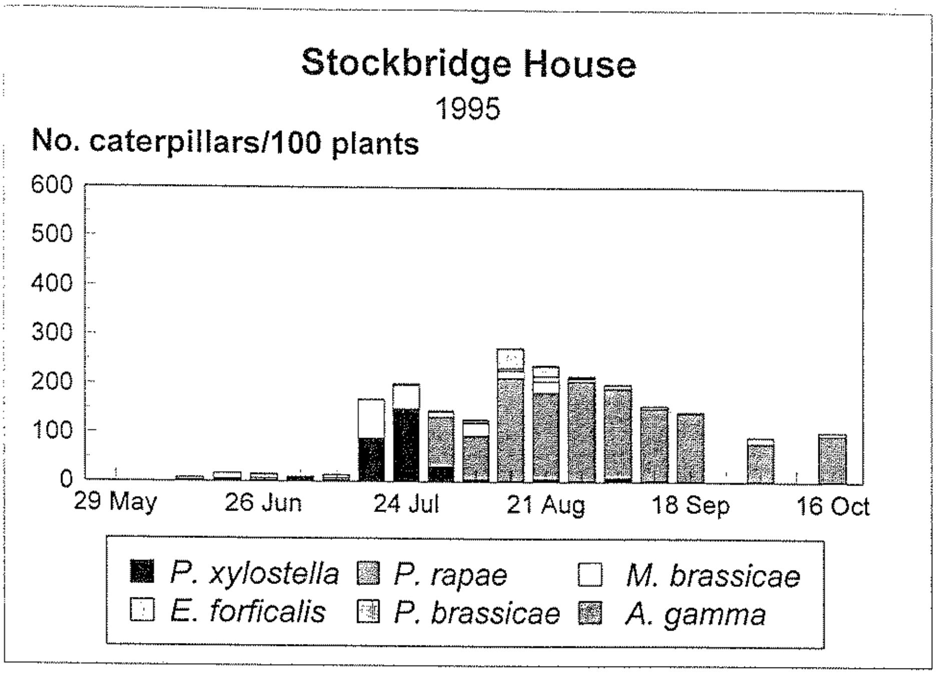


Figure 3h The numbers of caterpillars of each species found each week during 1995-1997 on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood.



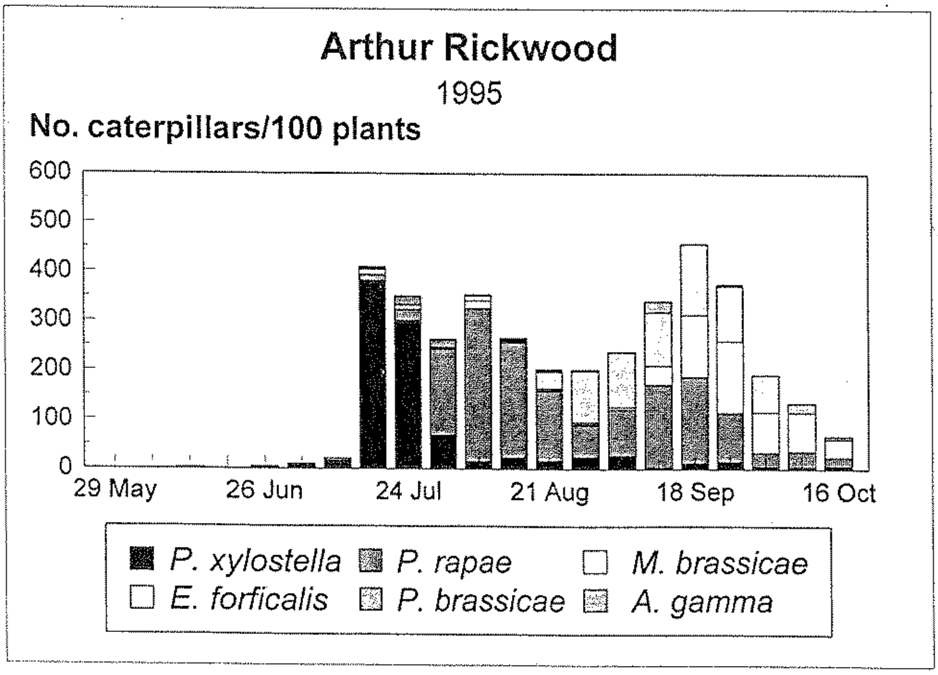
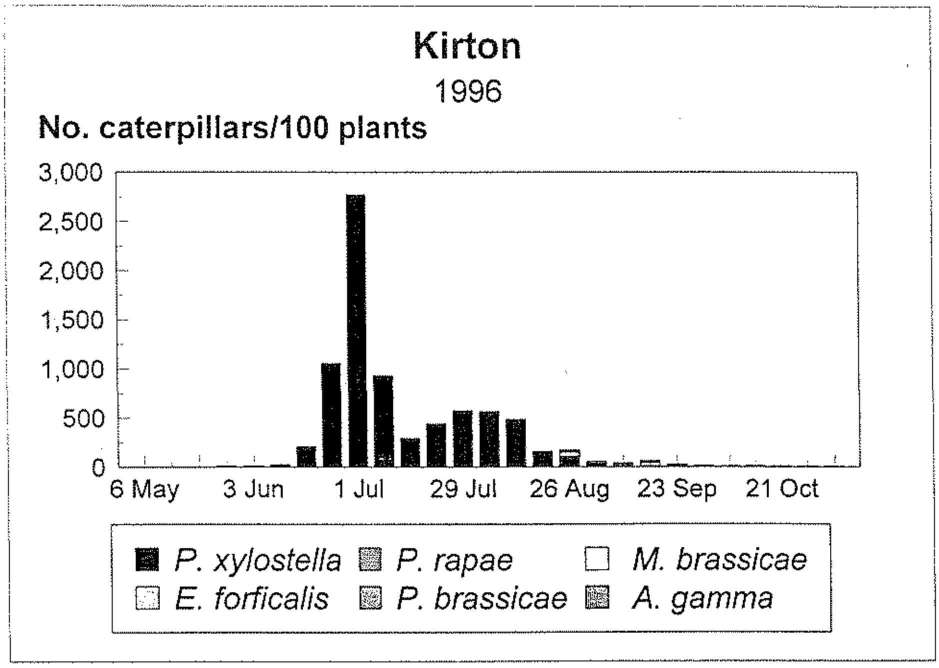


Figure 3h The numbers of caterpillars of each species found each week during 1995-1997 on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood.



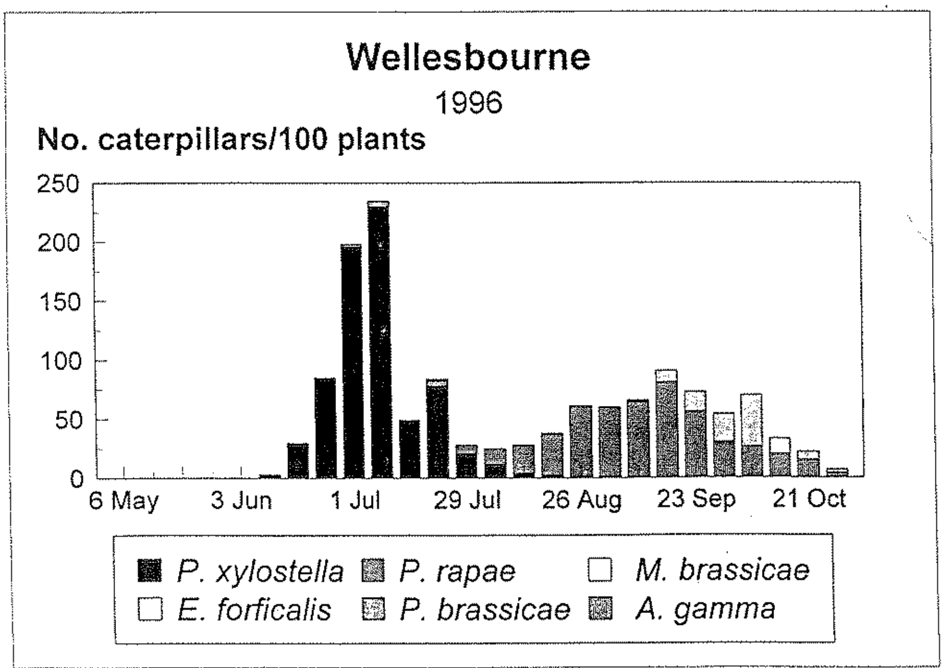
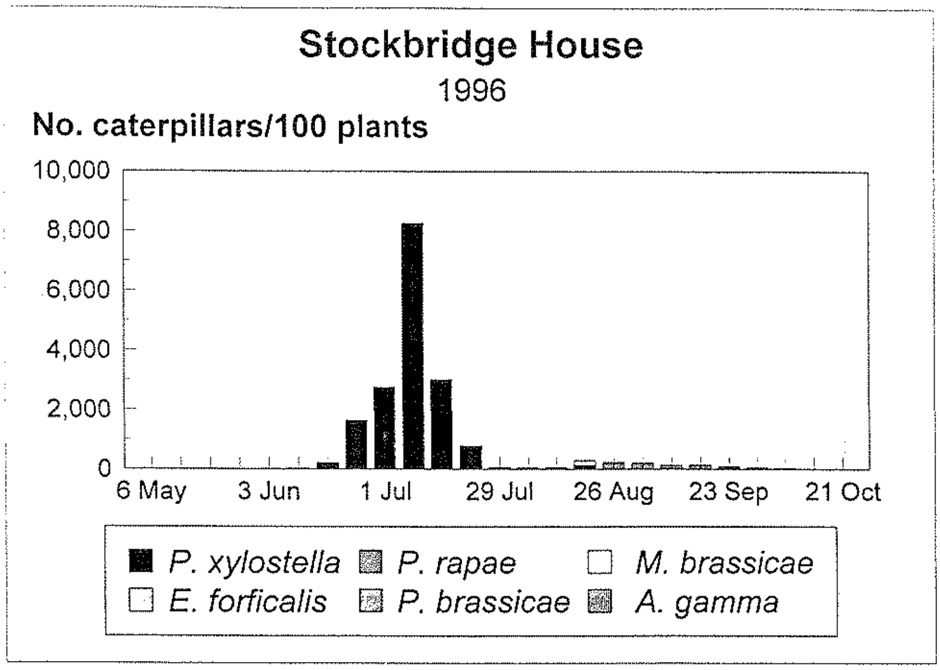


Figure 3h The numbers of caterpillars of each species found each week during 1995-1997 on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood.



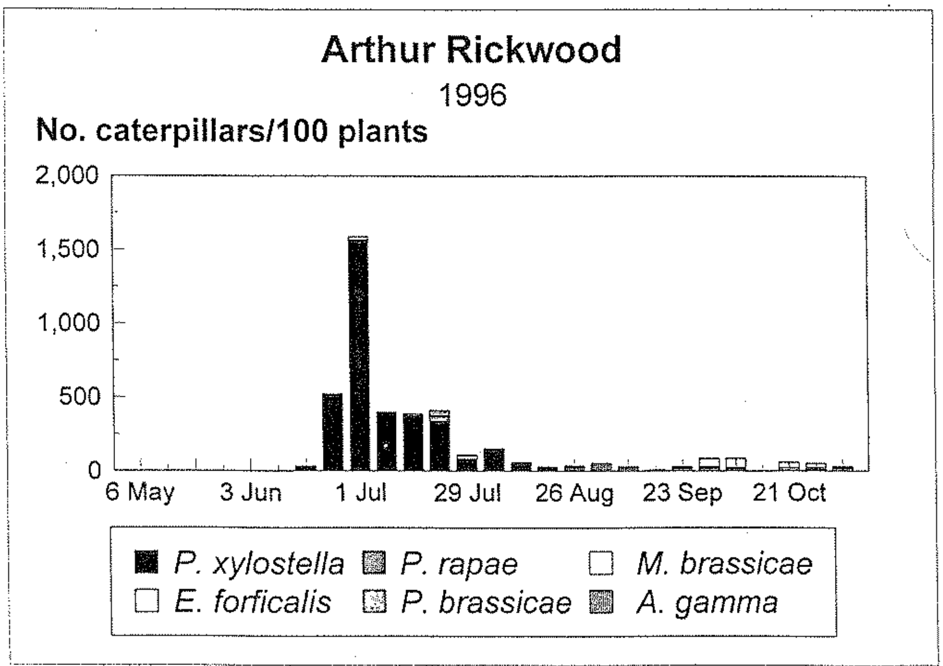
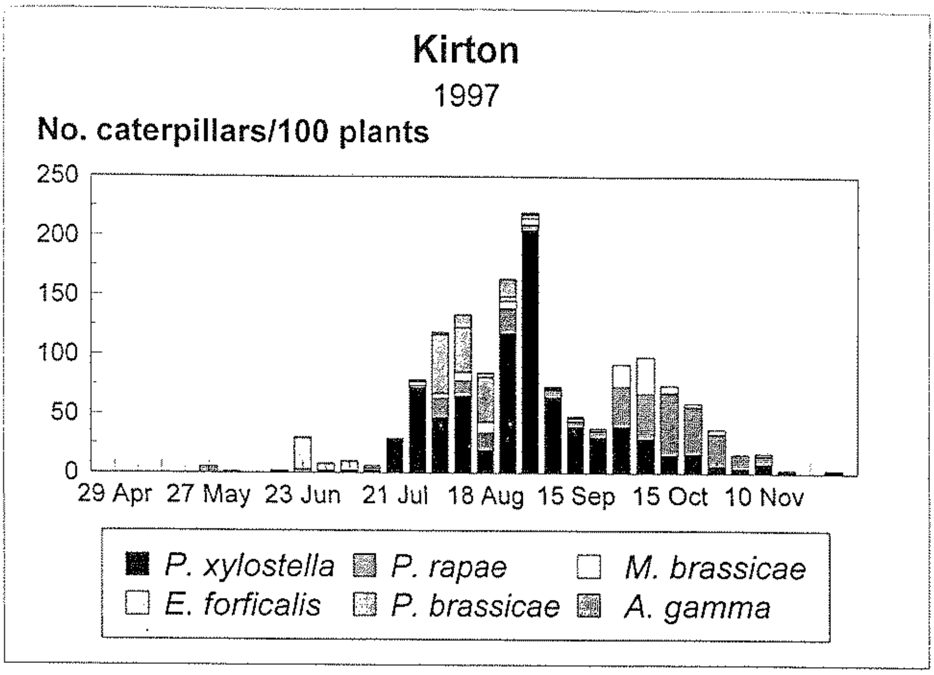


Figure 3h The numbers of caterpillars of each species found each week during 1995-1997 on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood.



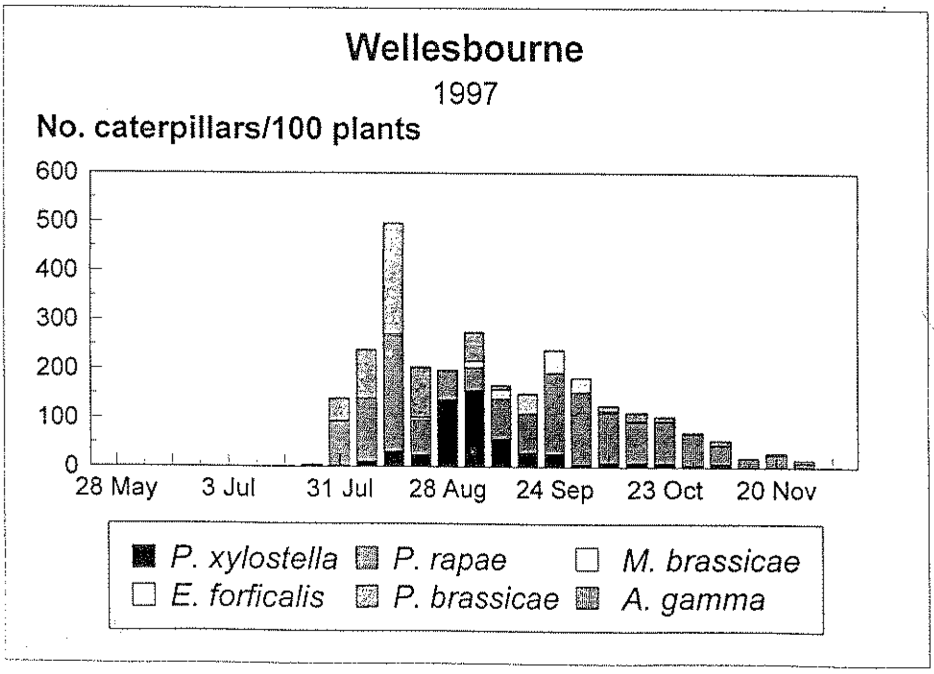
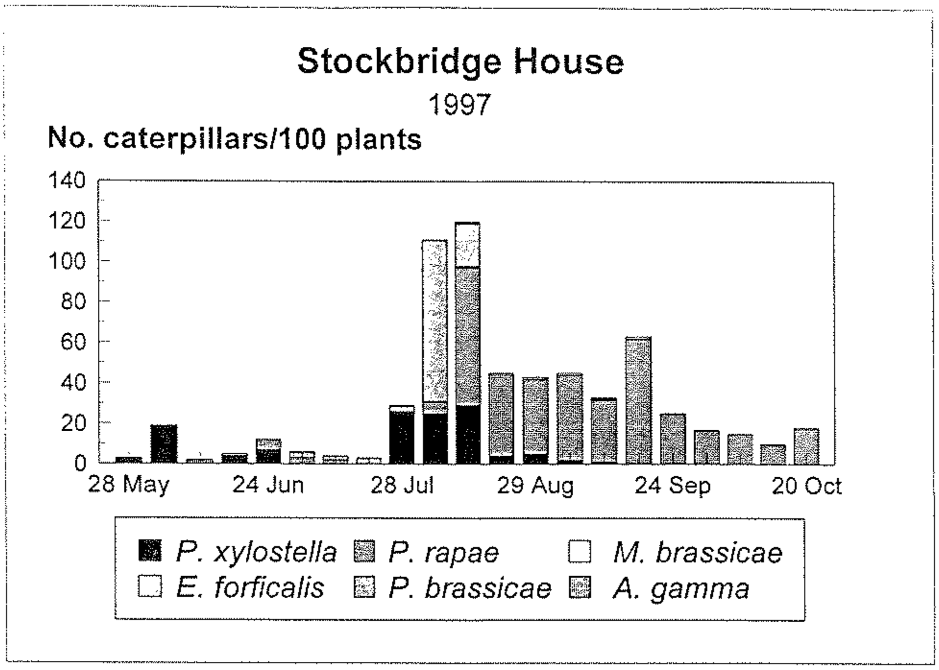


Figure 3h The numbers of caterpillars of each species found each week during 1995-1997 on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood.



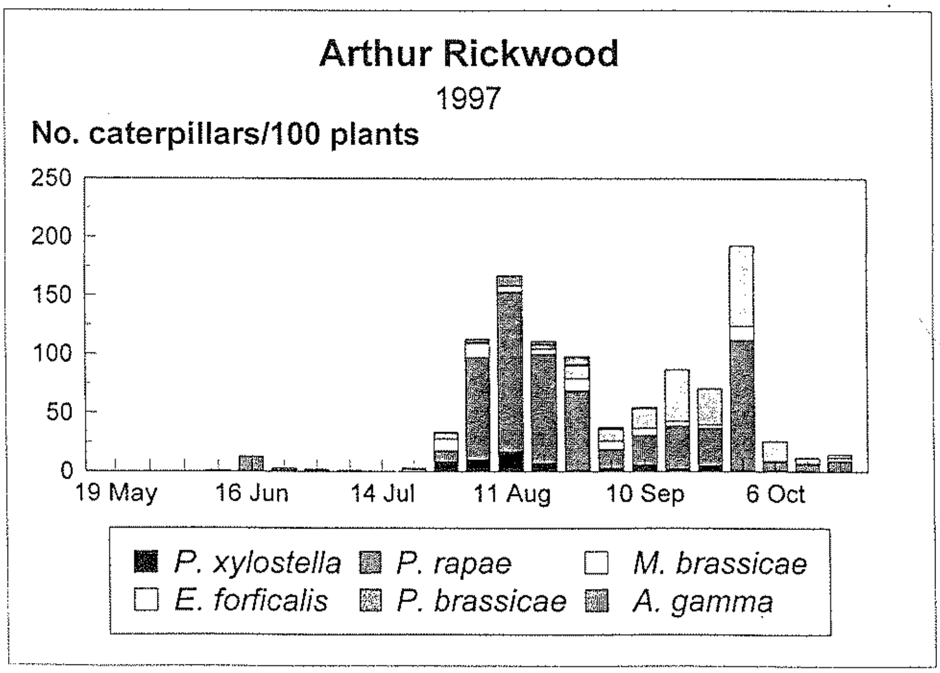


Figure 3i *P. xylostella* – the numbers of moths captured in pheromone traps and eggs found on untreated plants at HRI Kirton in 1996.

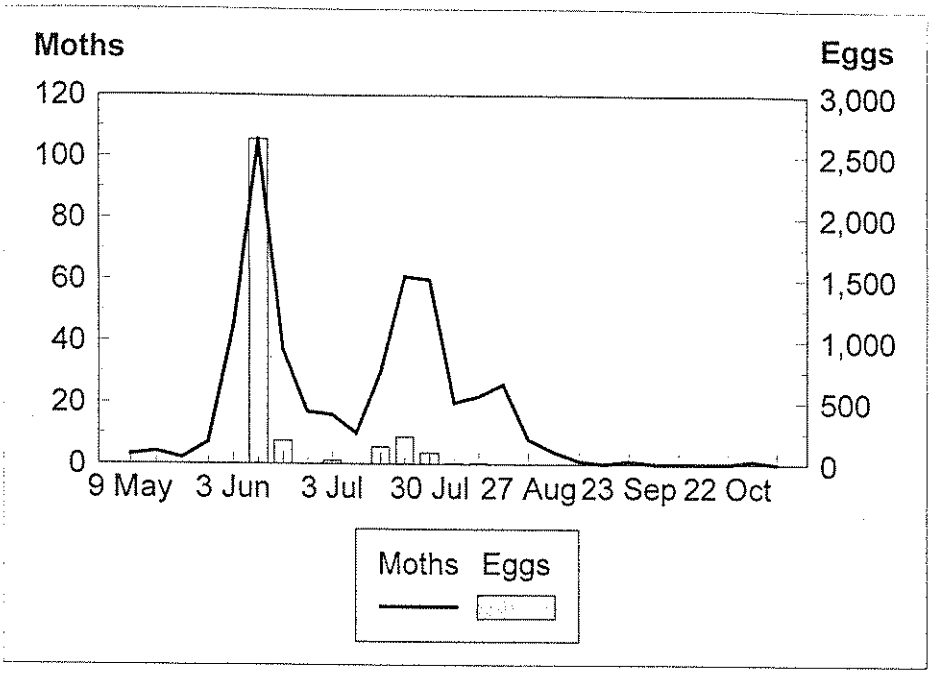


Figure 3j *P. xylostella* – the numbers of moths captured in pheromone traps and caterpillars found on untreated plants at HRI Kirton in 1996.

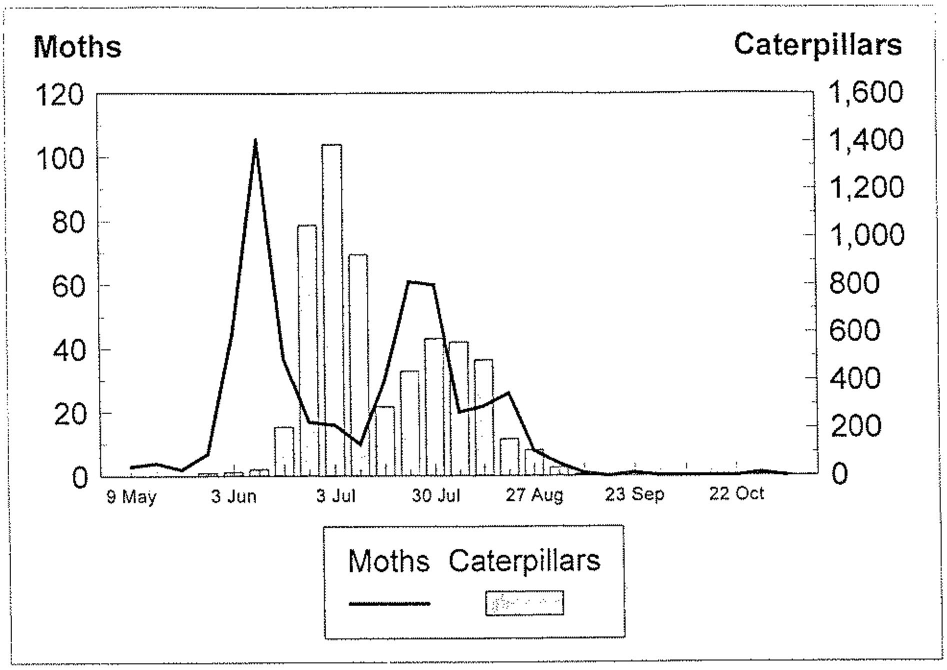
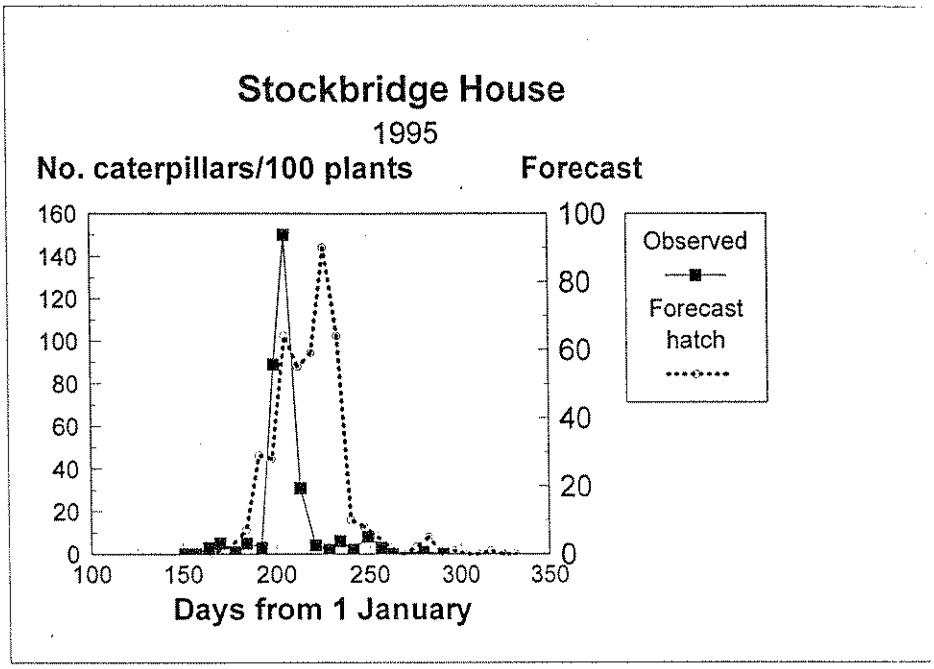


Figure 3k *P. xylostella* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



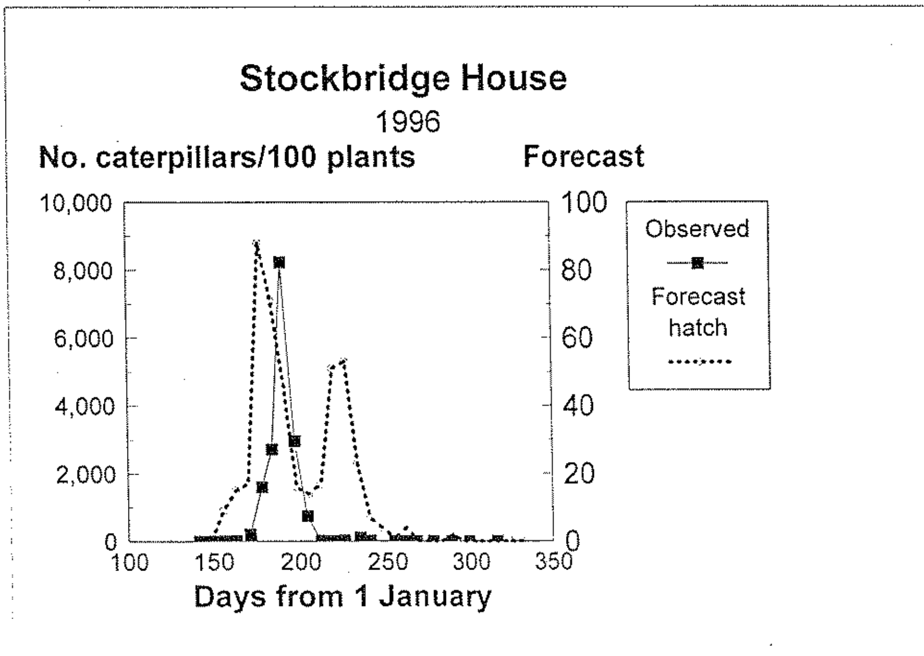
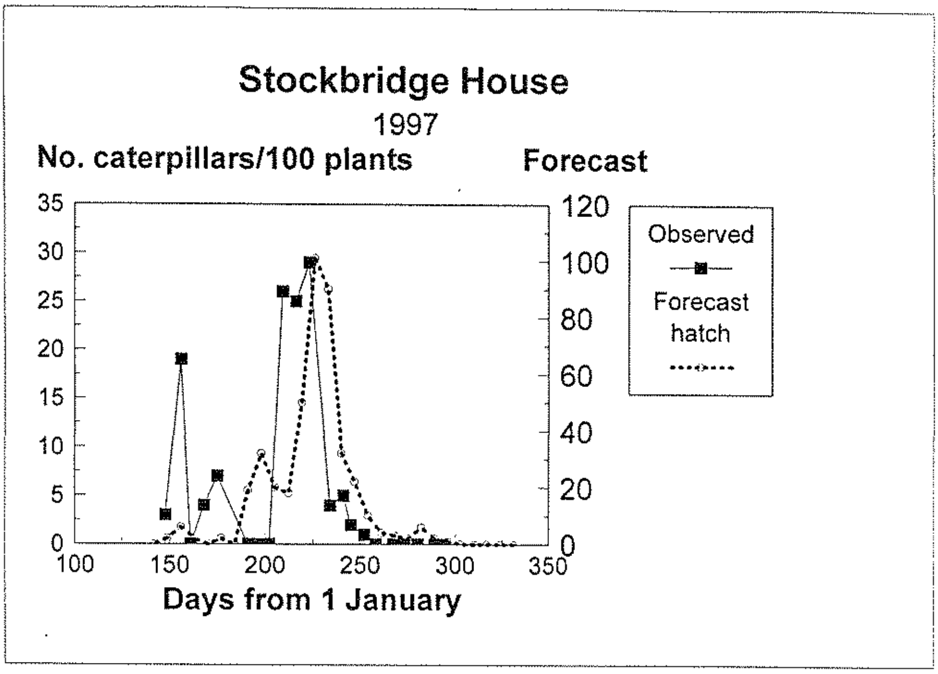


Figure 3k *P. xylostella* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



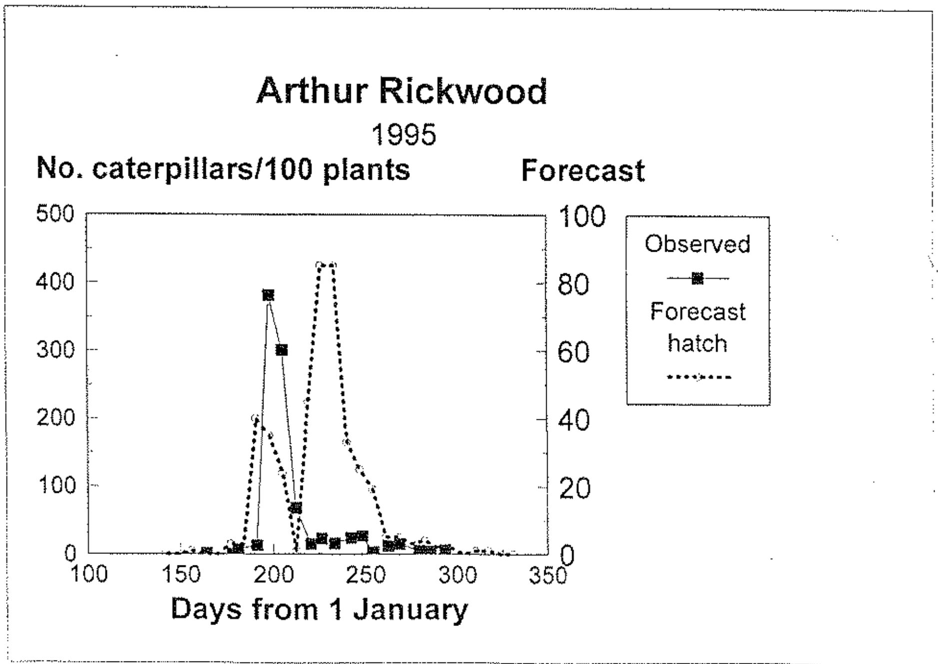
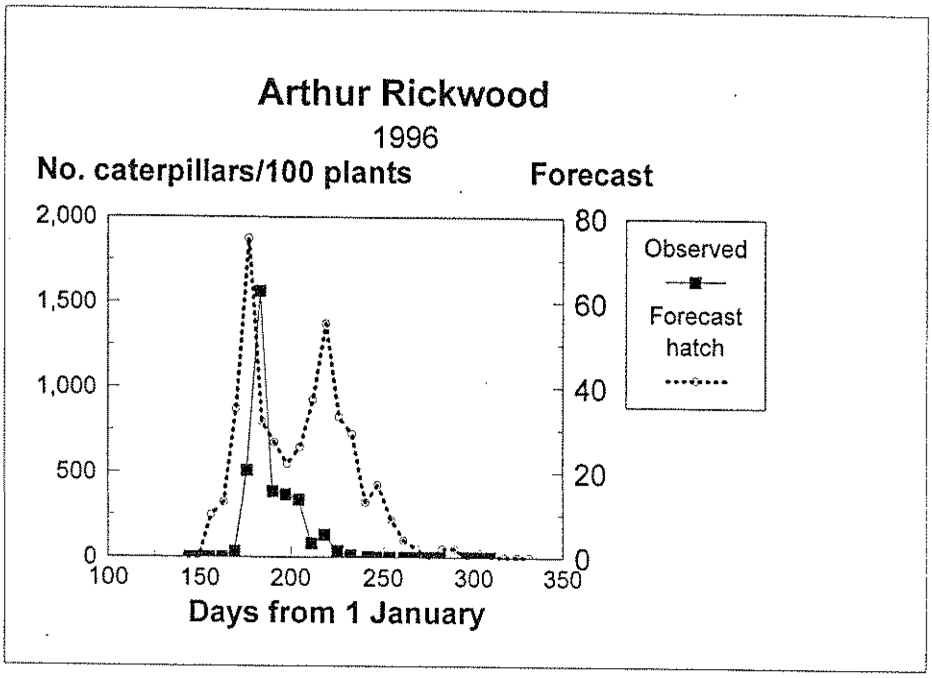


Figure 3k *P. xylostella* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



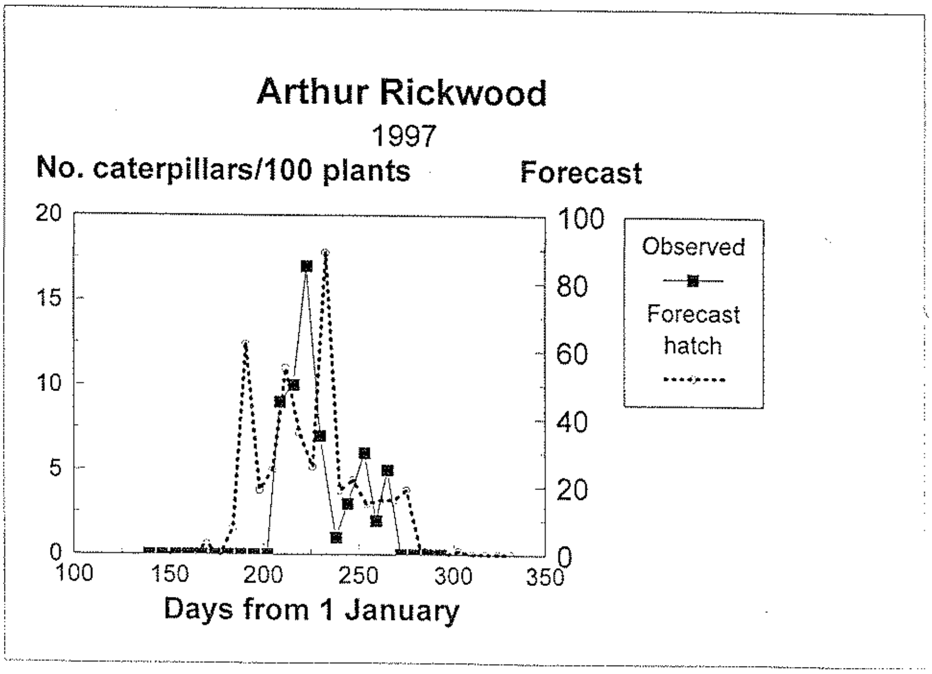
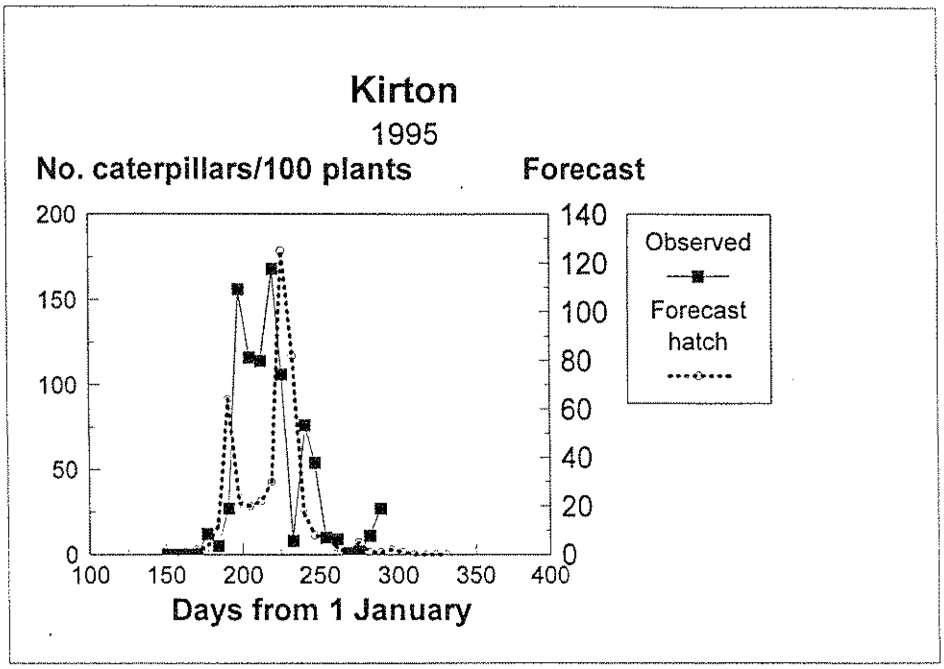


Figure 3k *P. xylostella* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



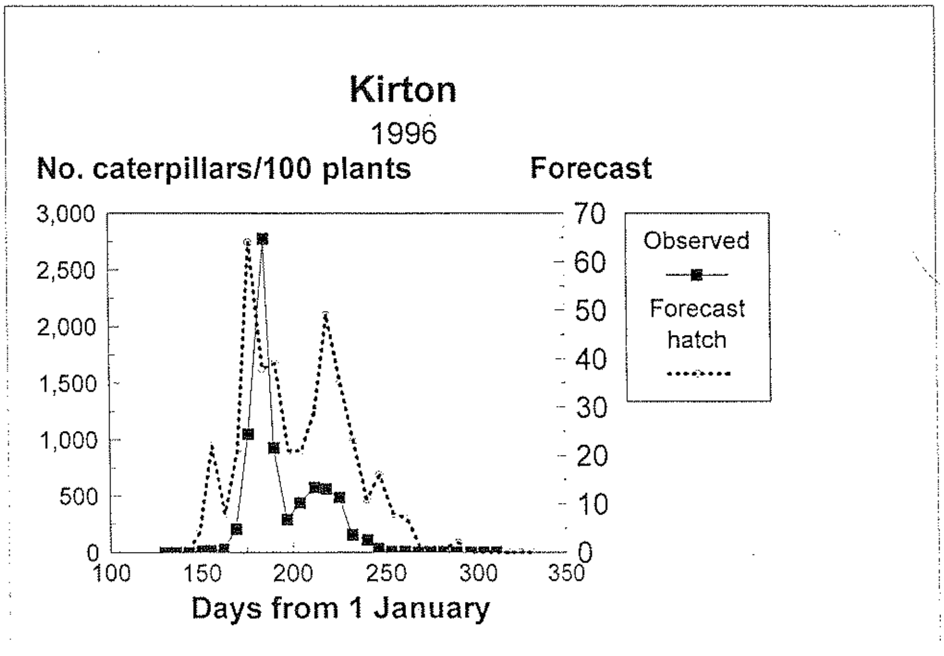
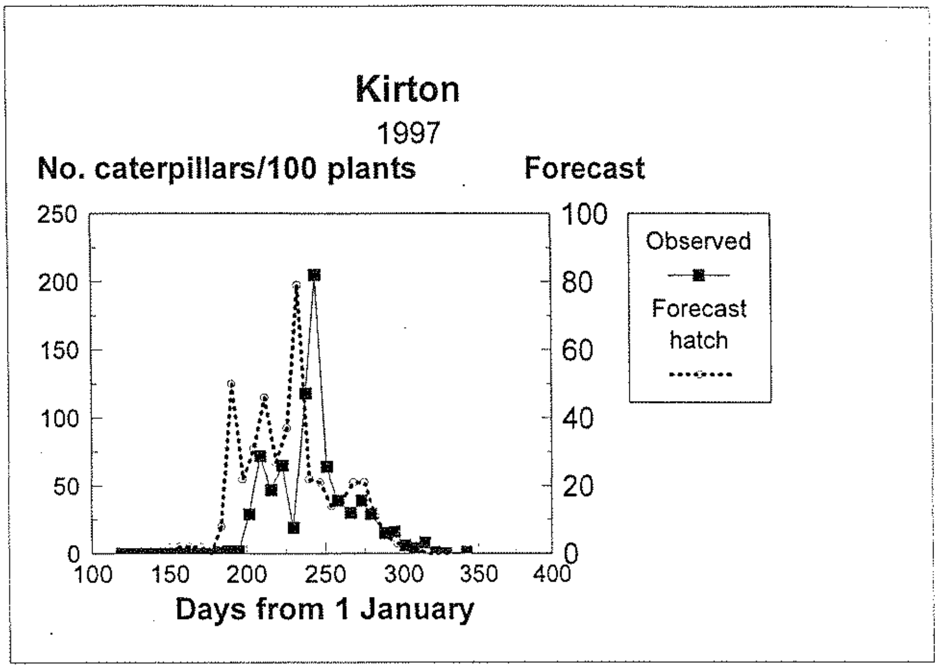


Figure 3k *P. xylostella* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



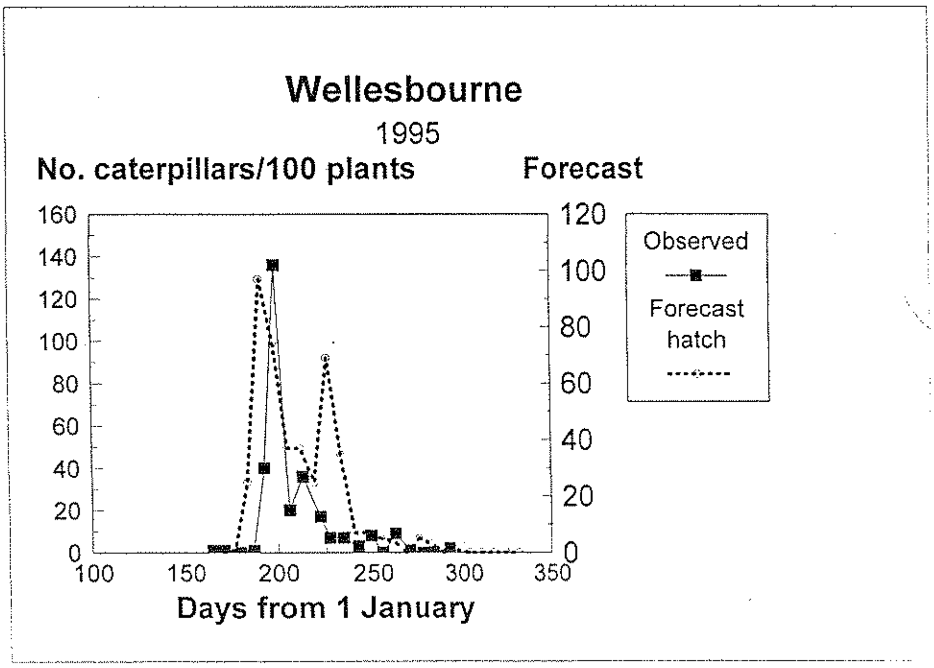
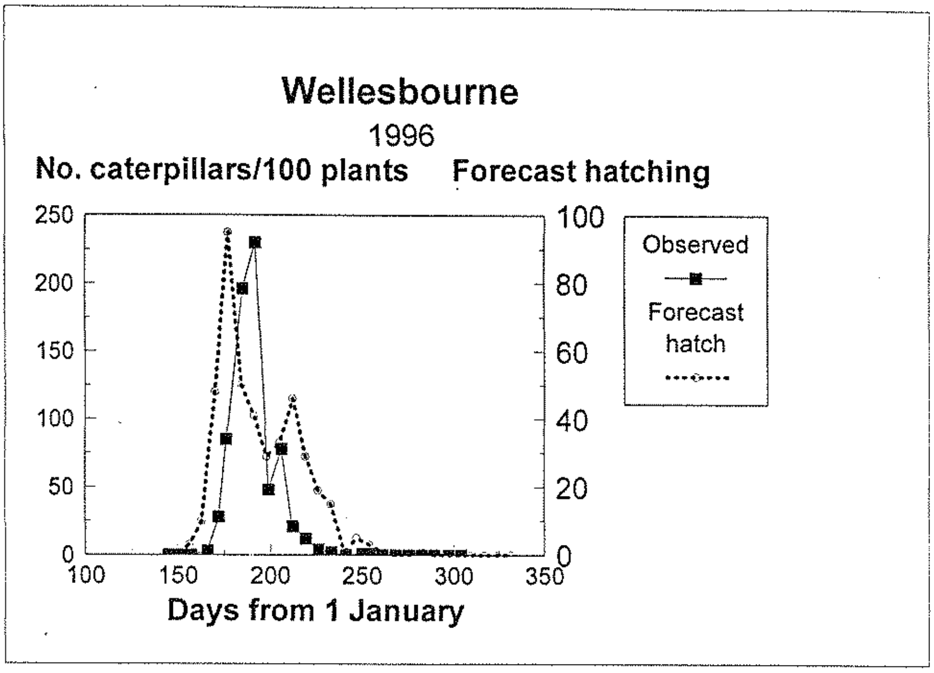


Figure 3k *P. xylostella* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



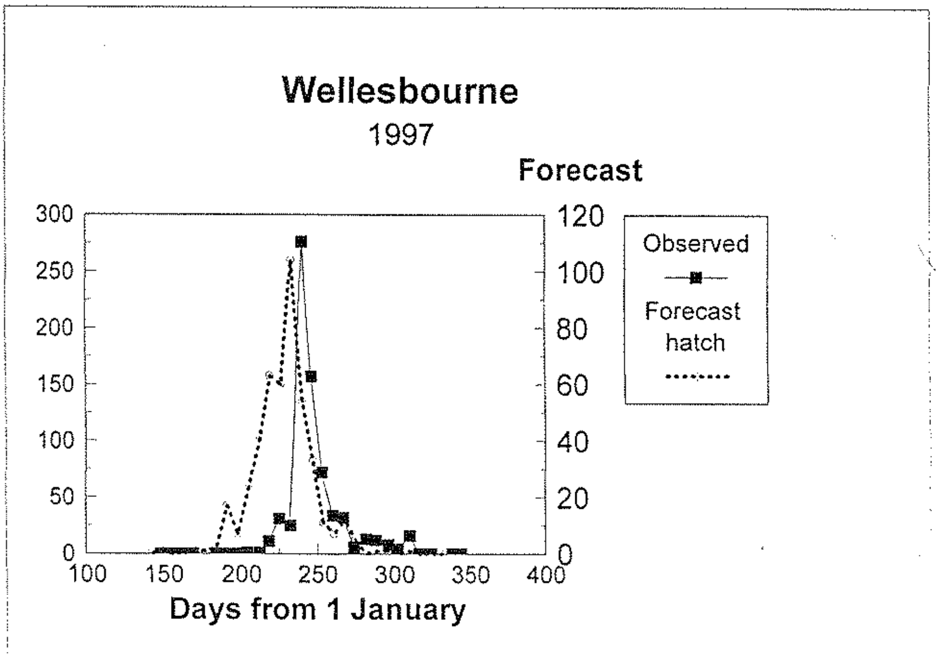
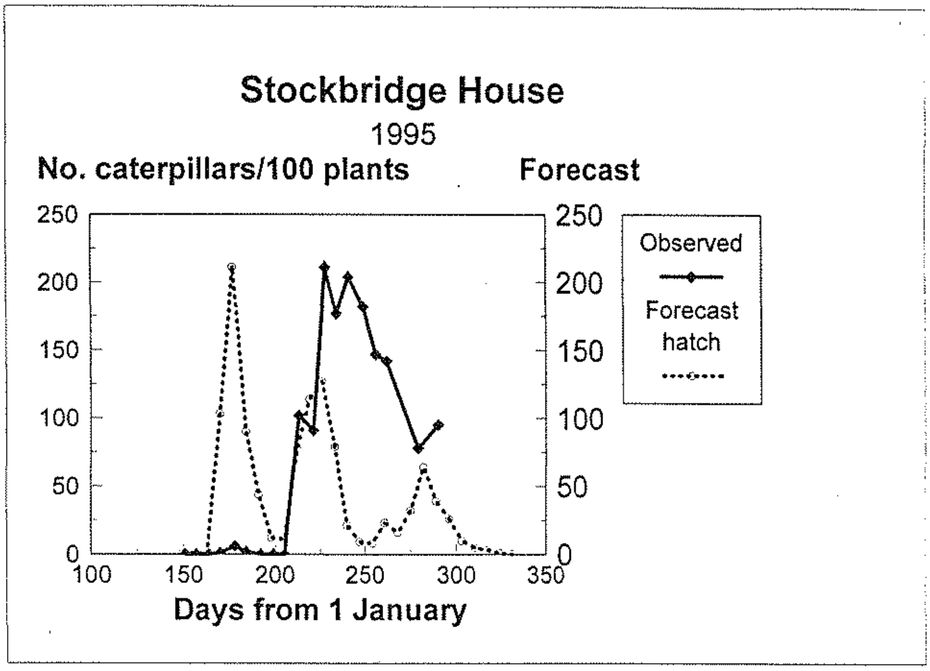


Figure 31 *P. rapae* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



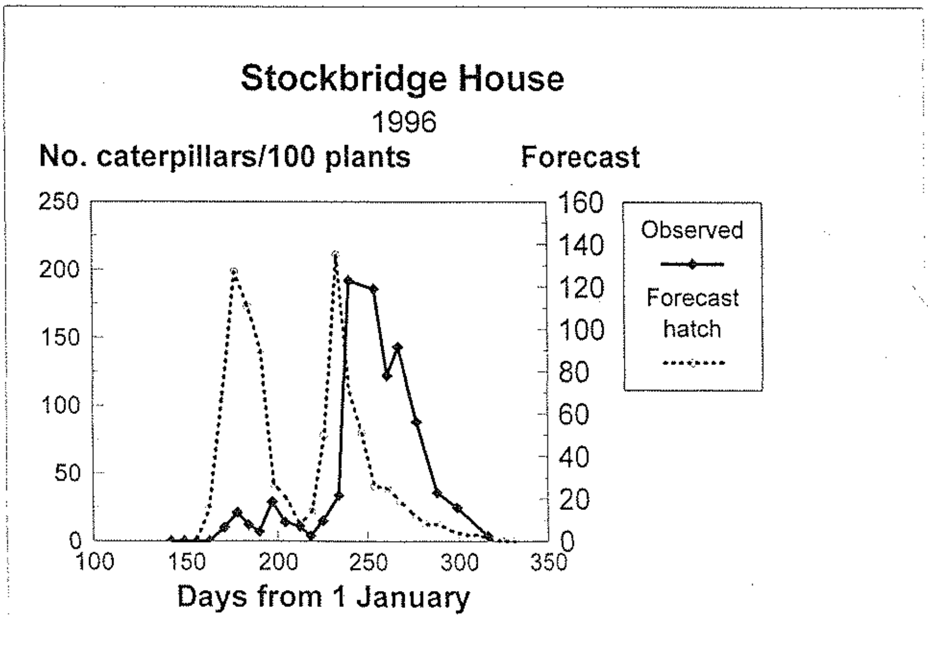
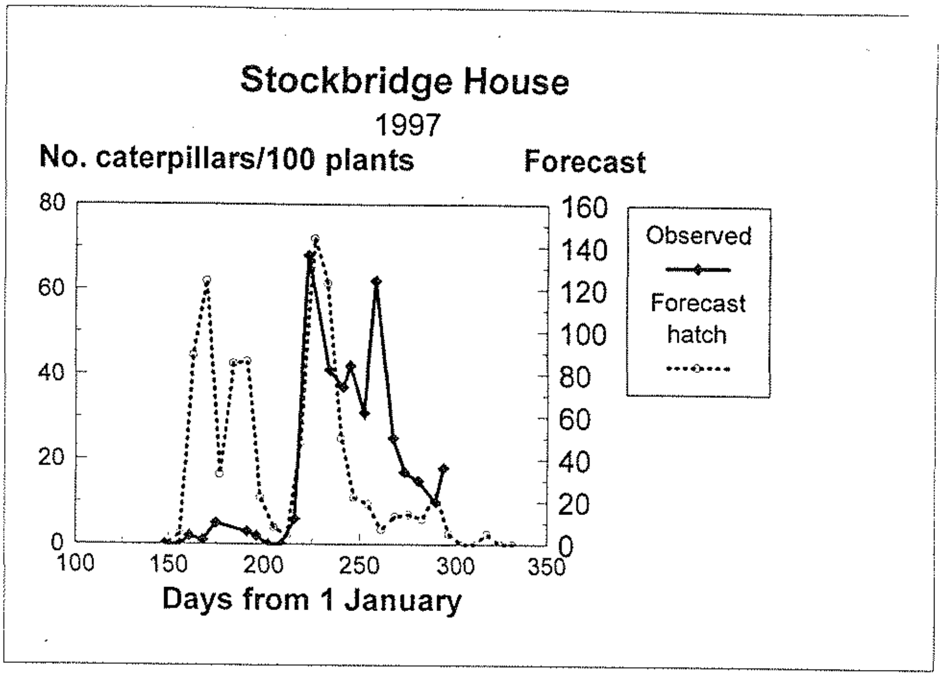
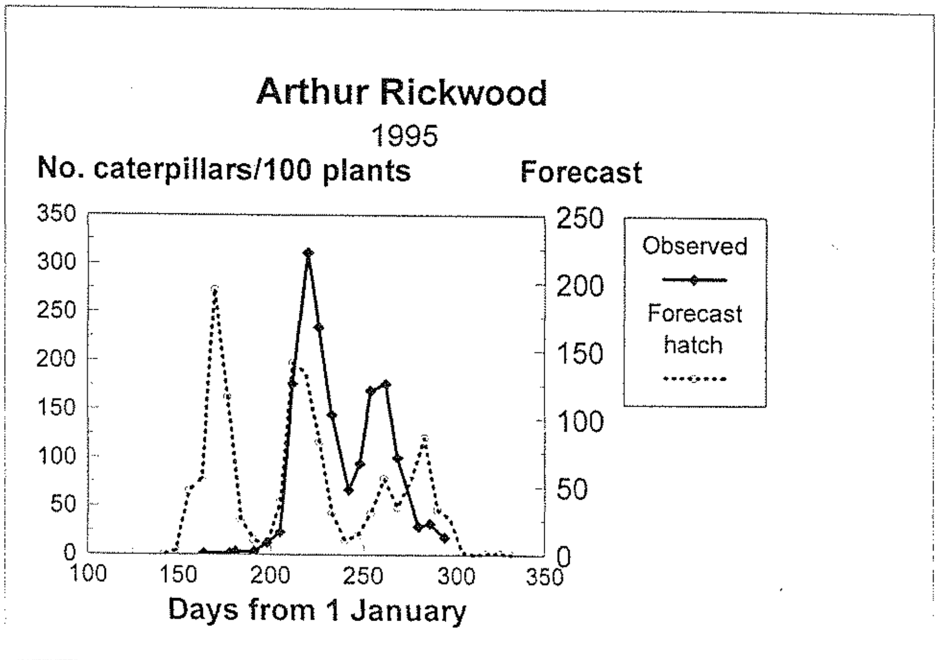


Figure 31 *P. rapae* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.





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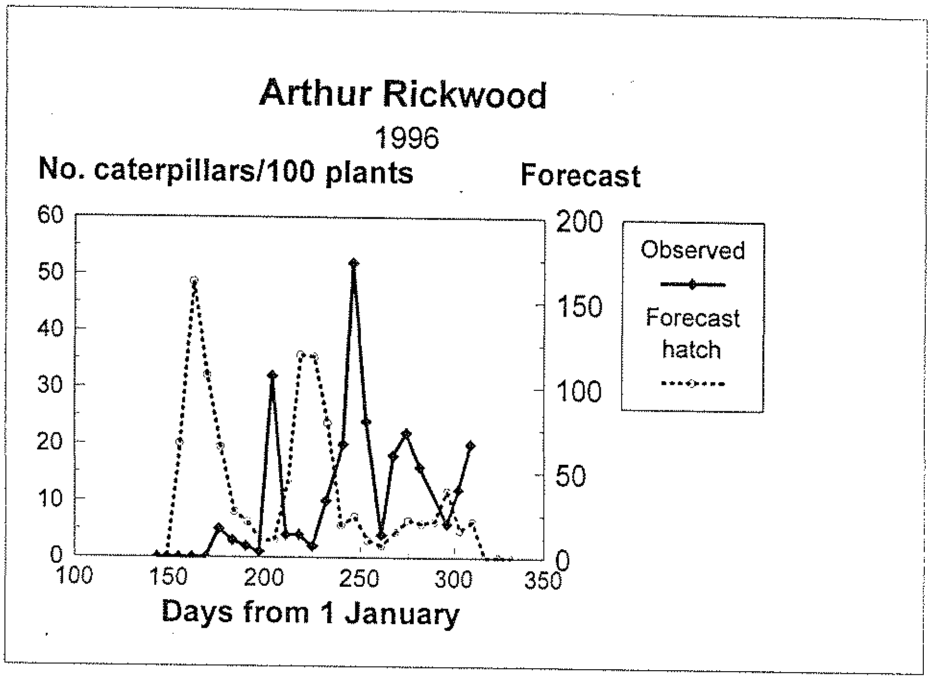

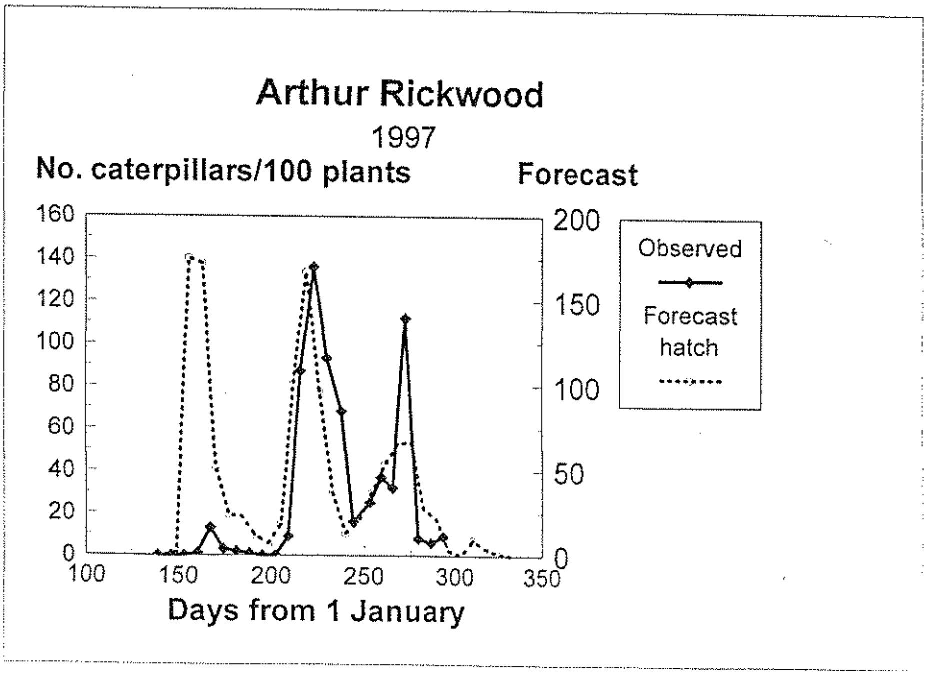

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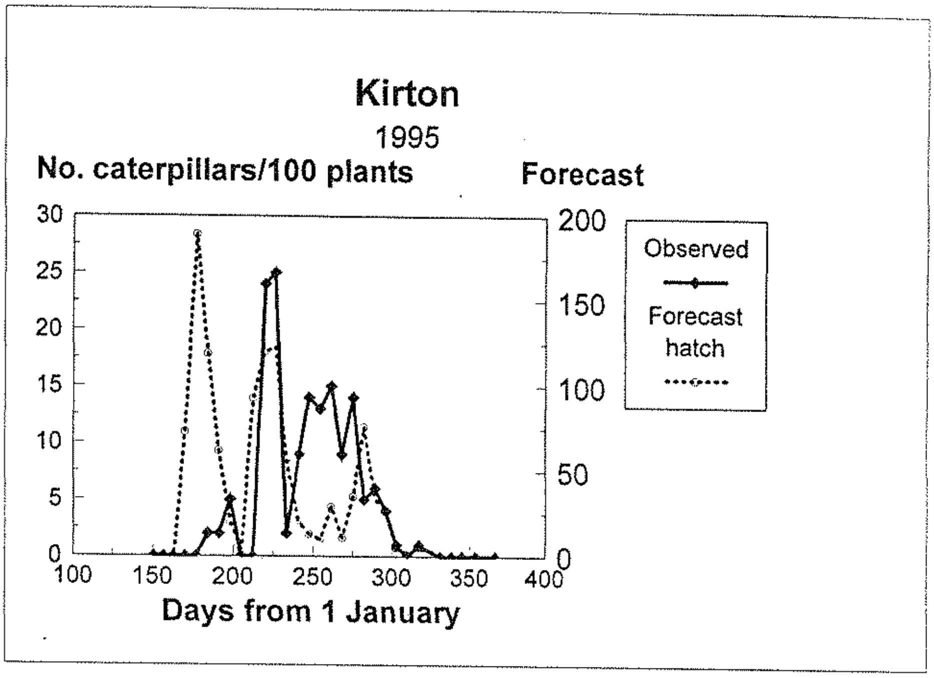


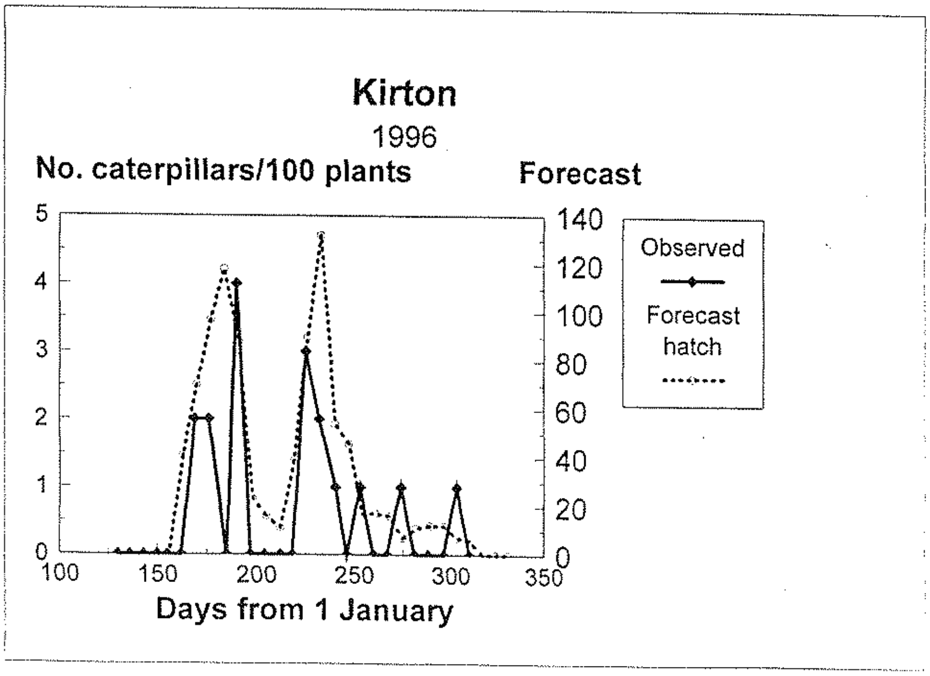
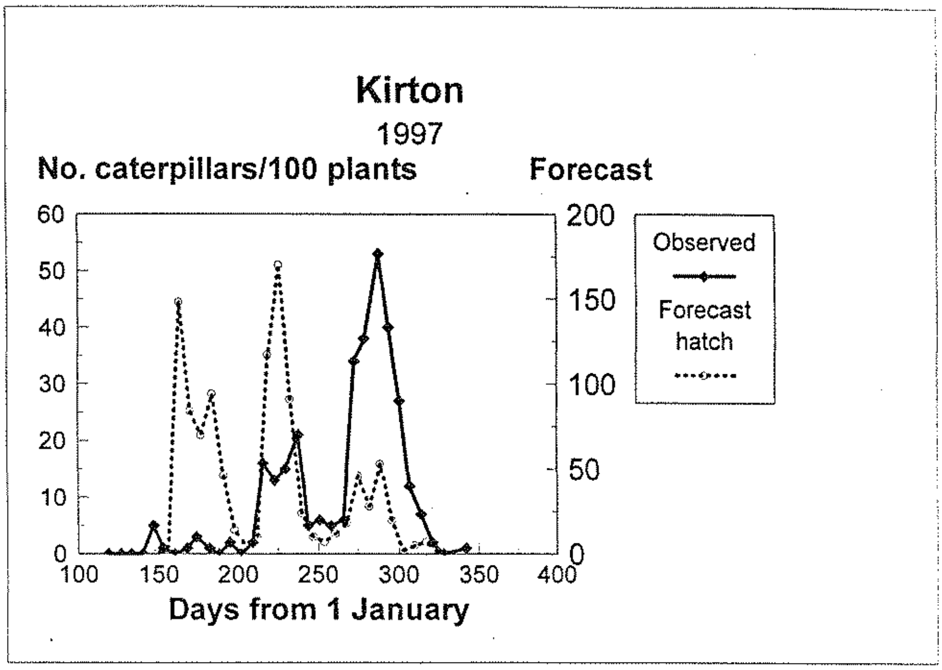


Figure 31 *P. rapae* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



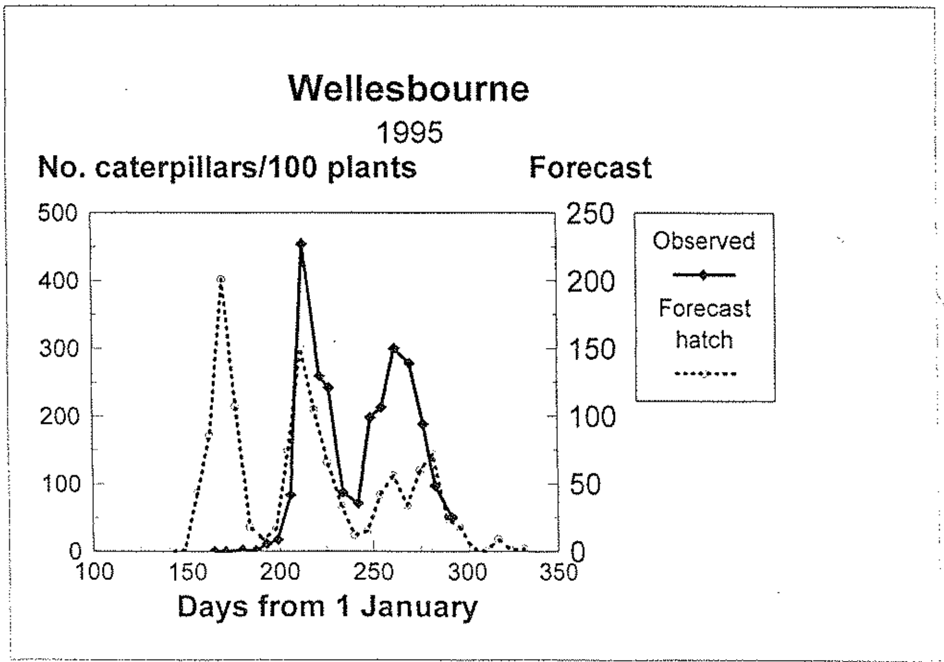
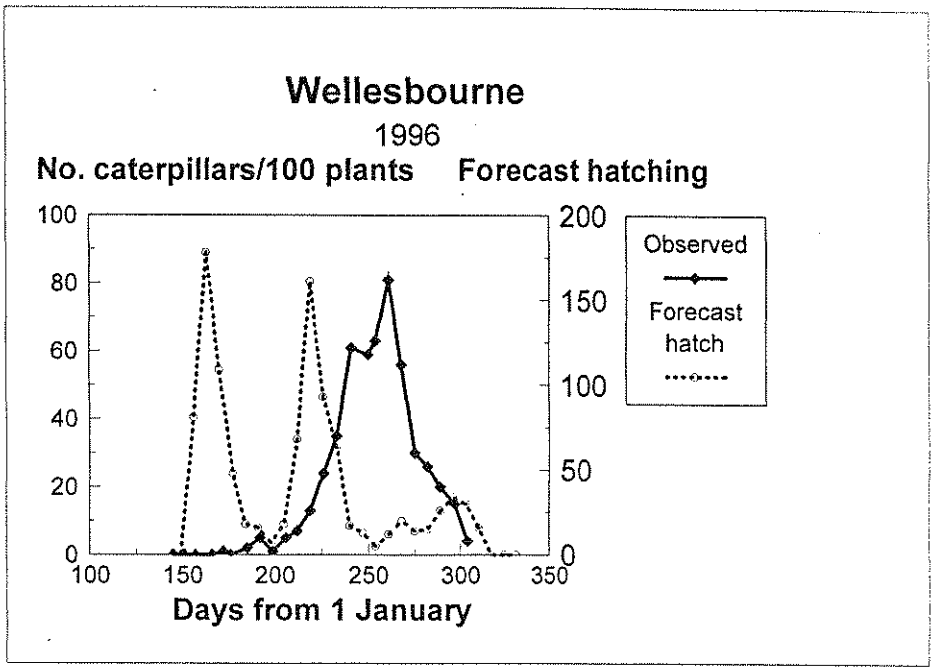


Figure 31 *P. rapae* - comparisons of forecast egg hatch with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



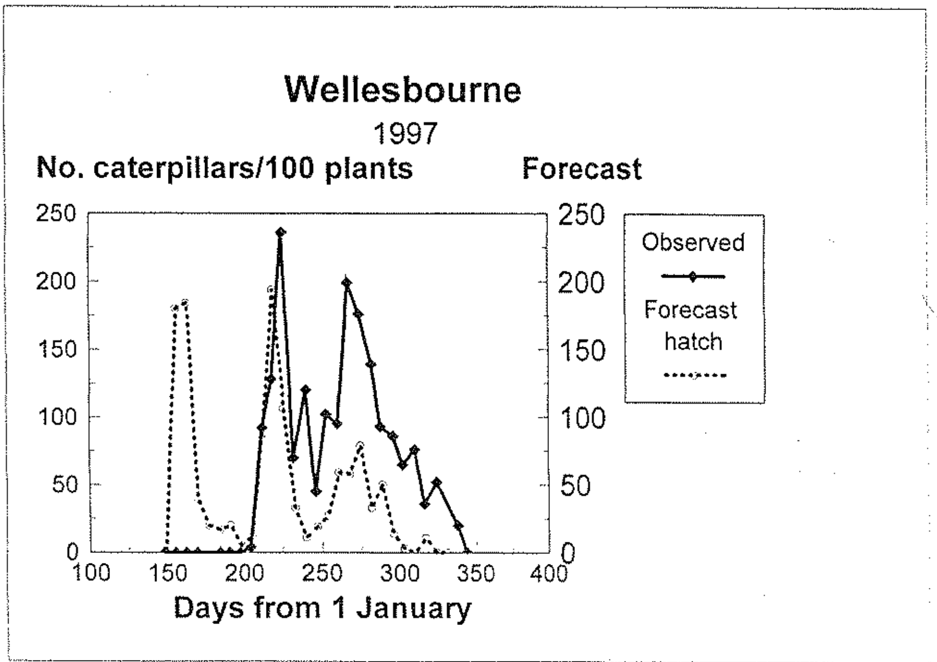
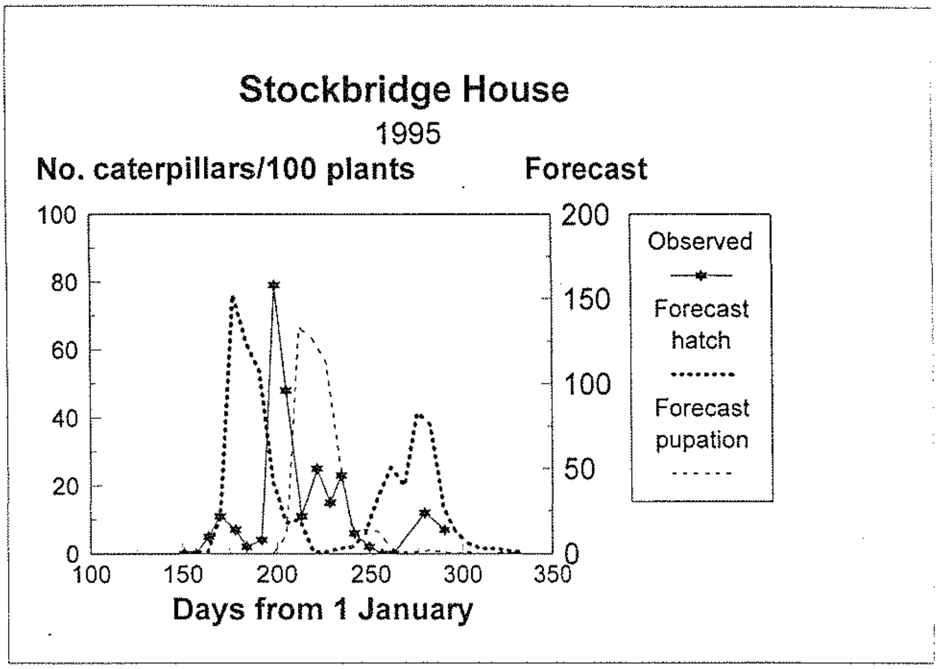


Figure 3m *M. brassicae* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



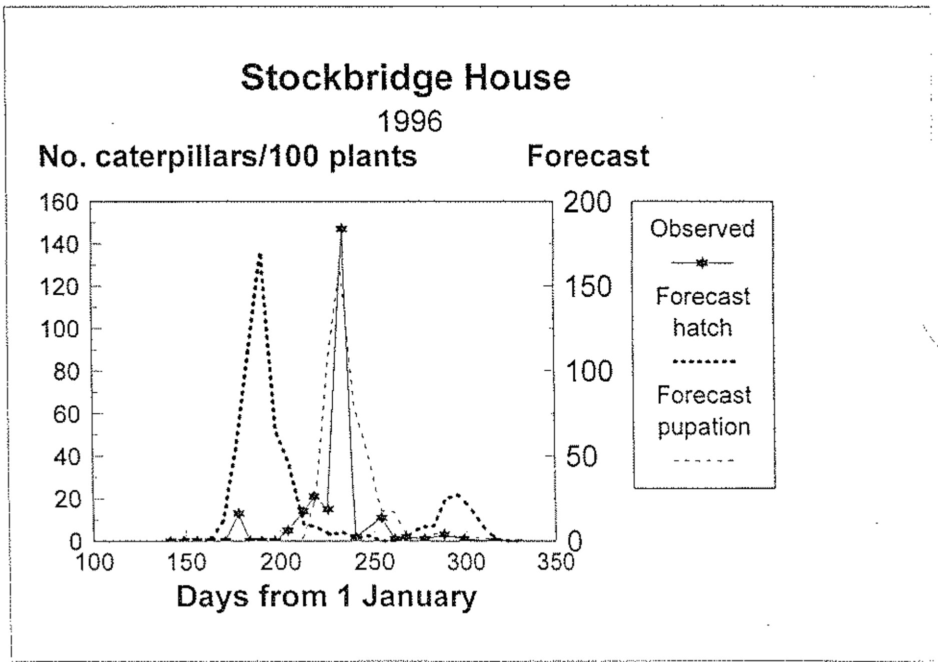
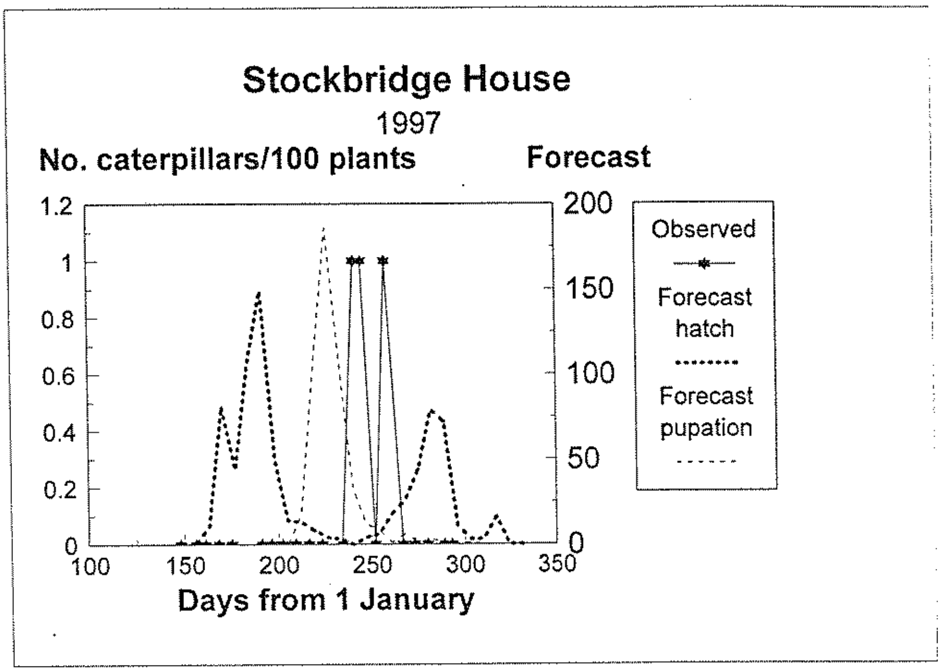
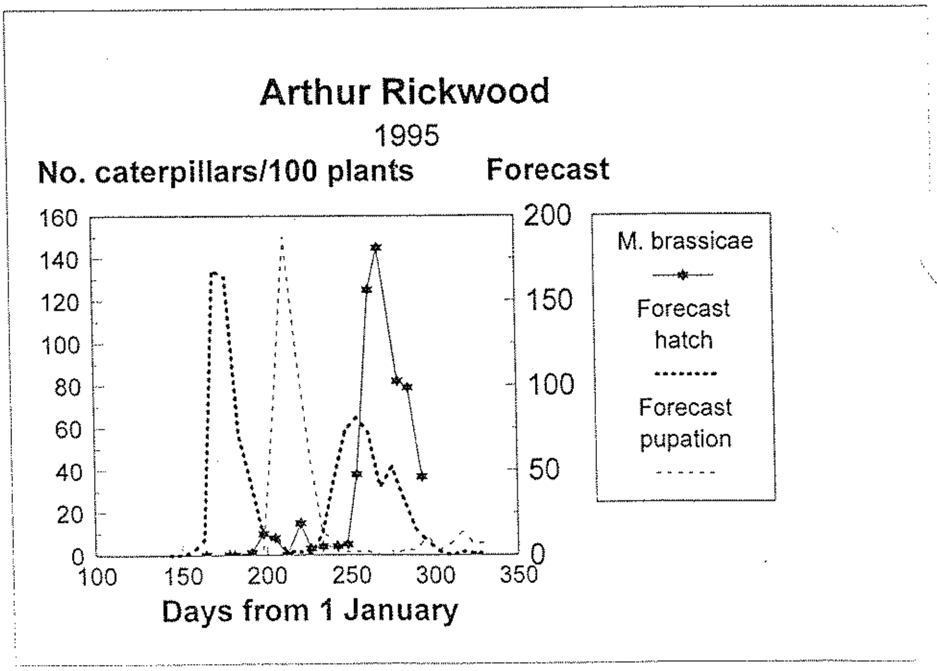


Figure 3m *M. brassicae* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.





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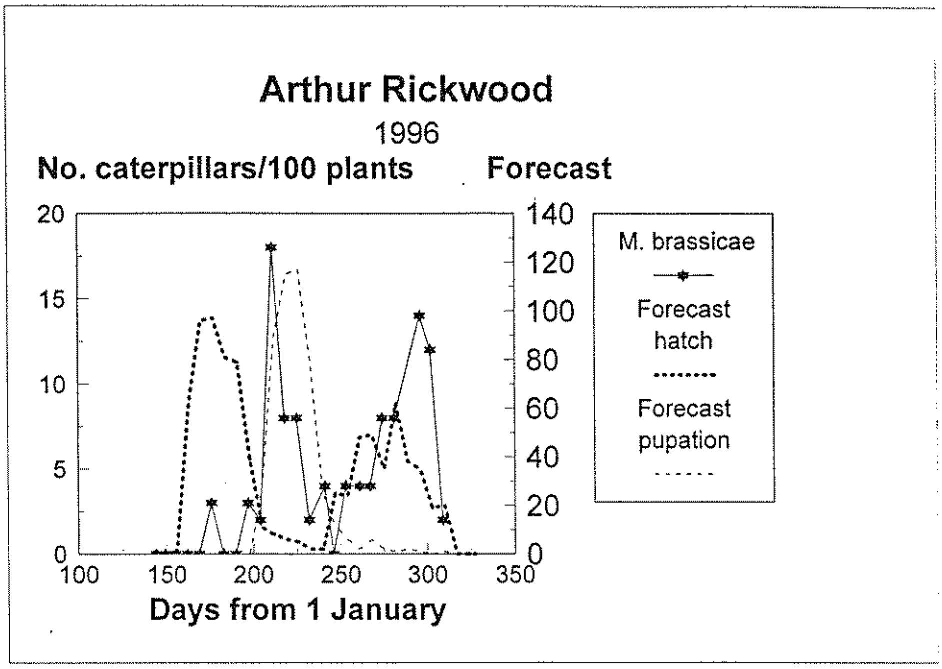


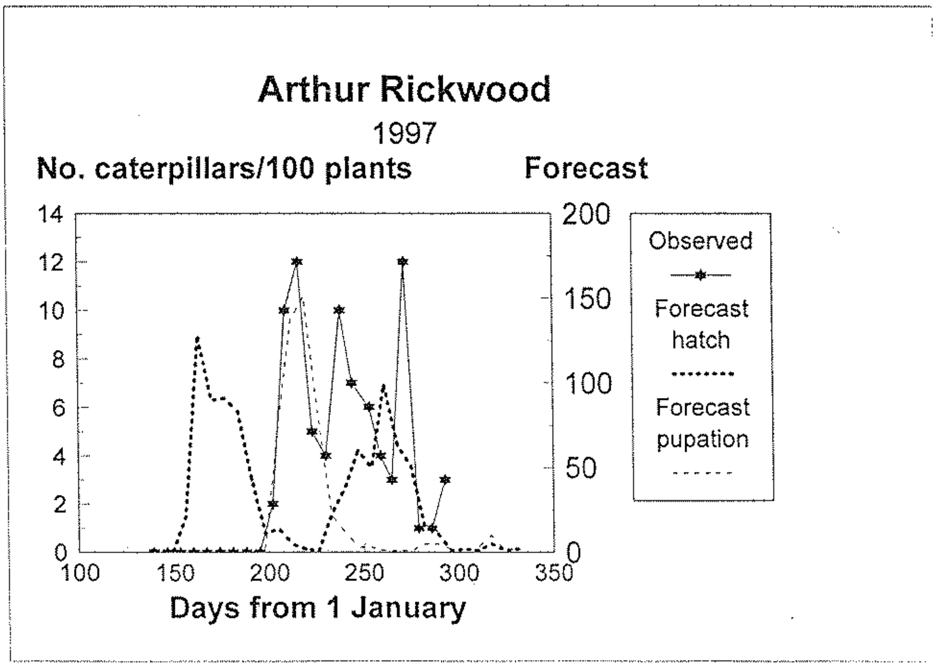
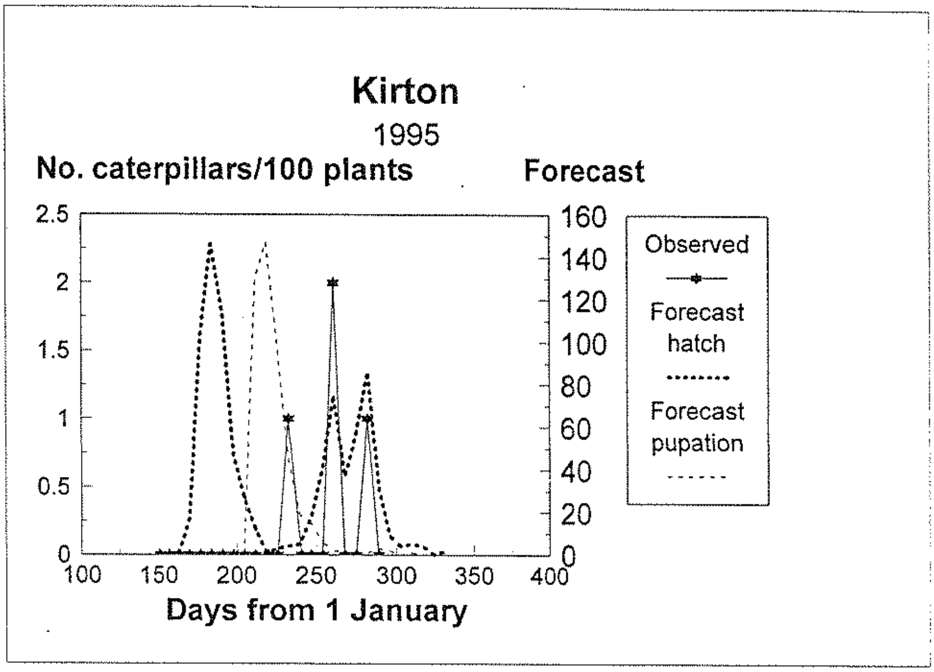


Figure 3m *M. brassicae* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



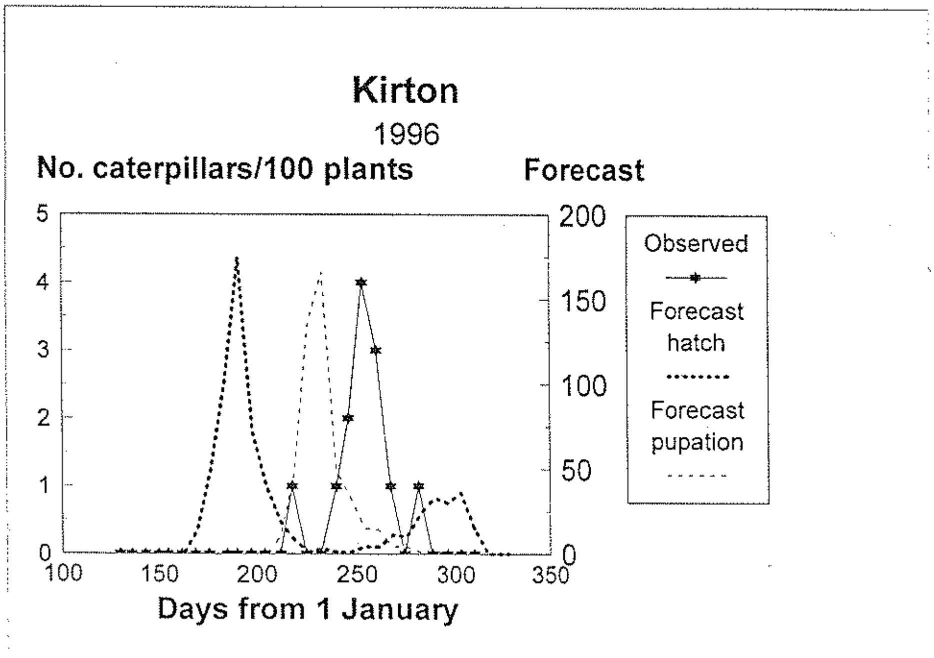
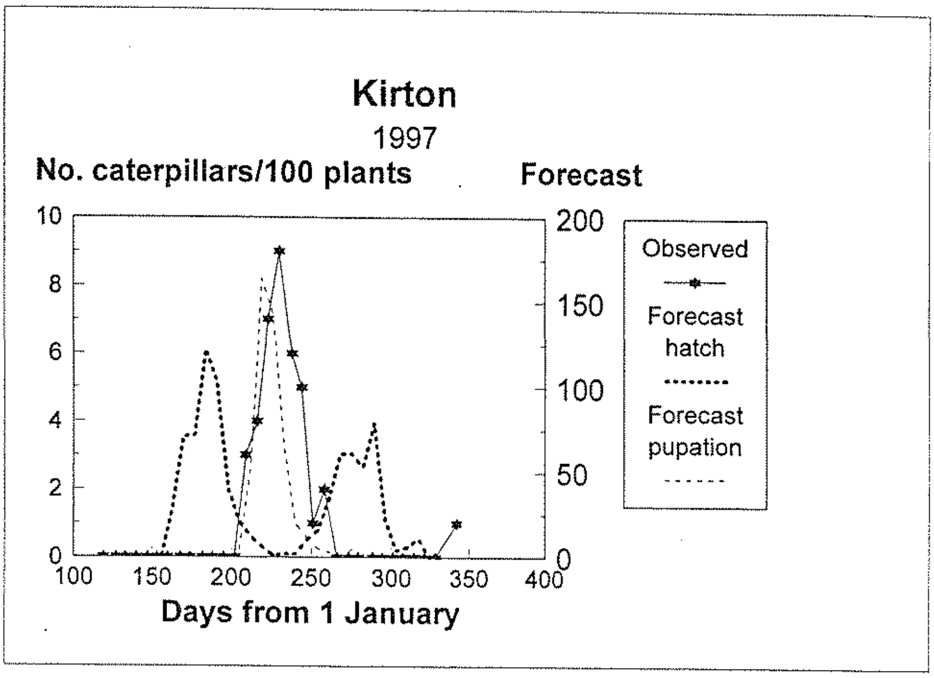


Figure 3m *M. brassicae* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



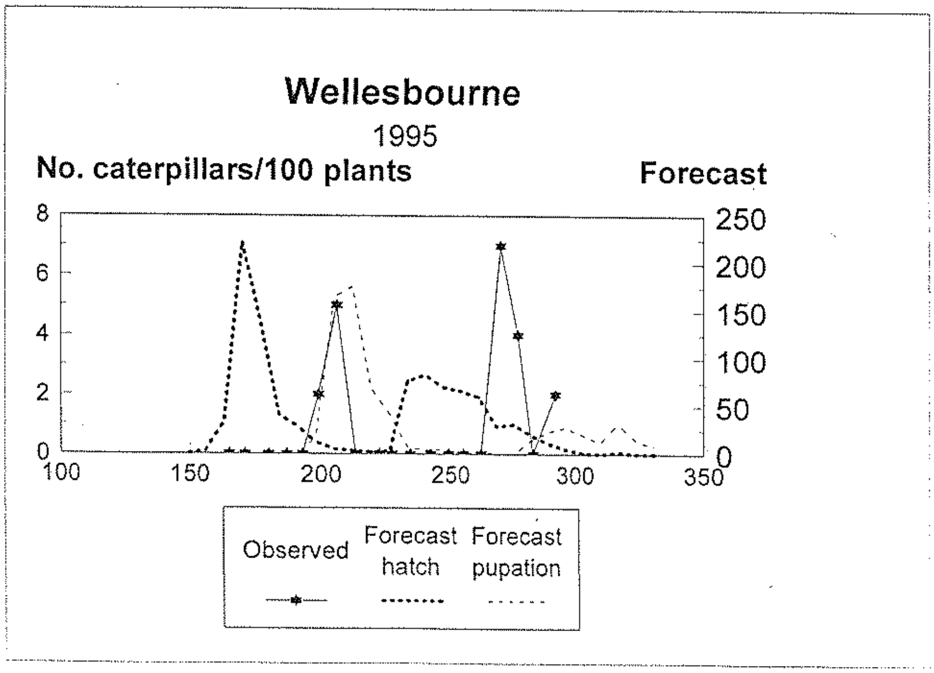
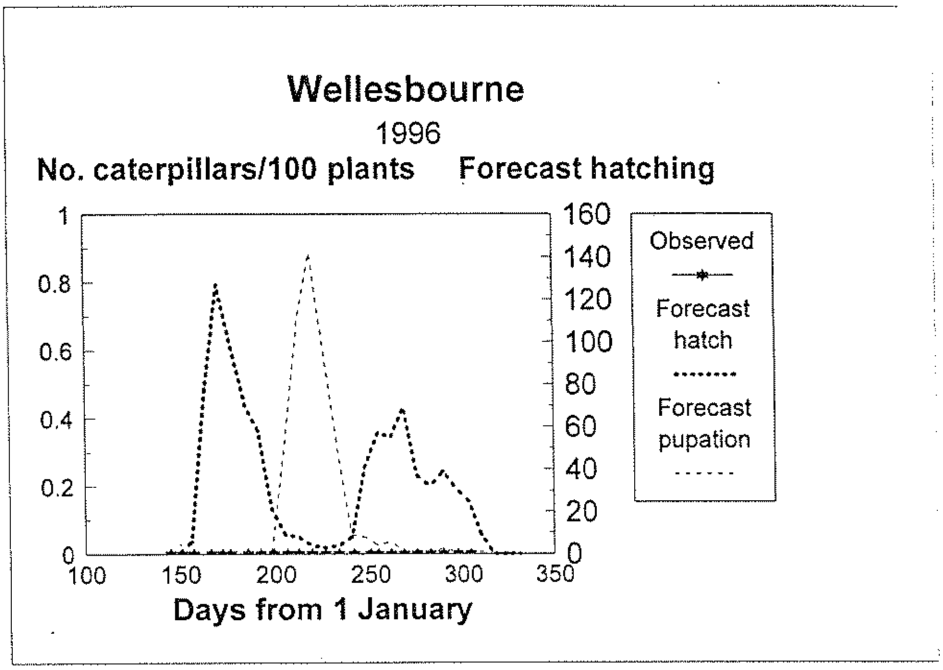


Figure 3m *M. brassicae* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



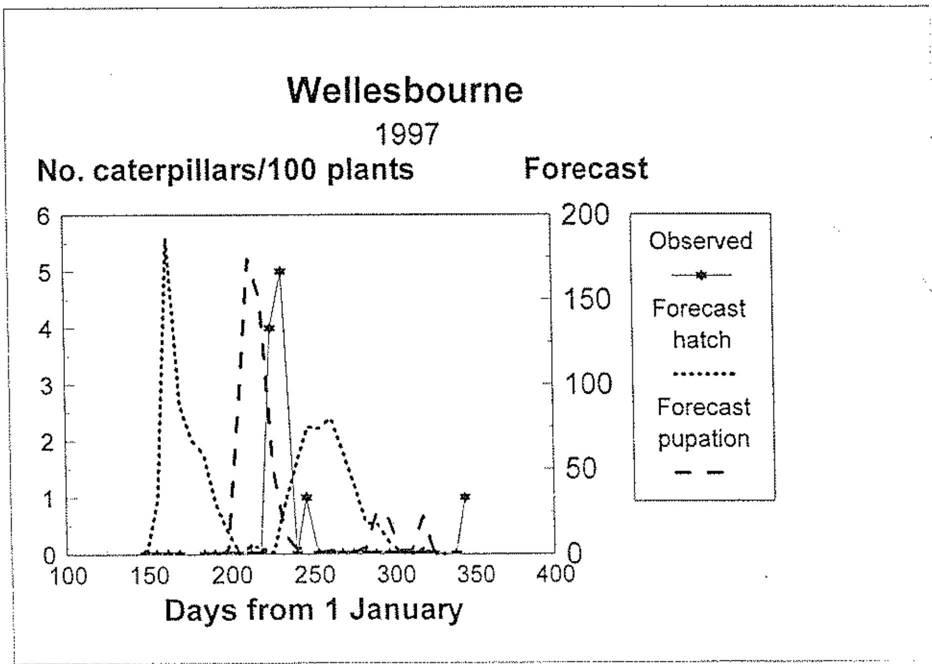
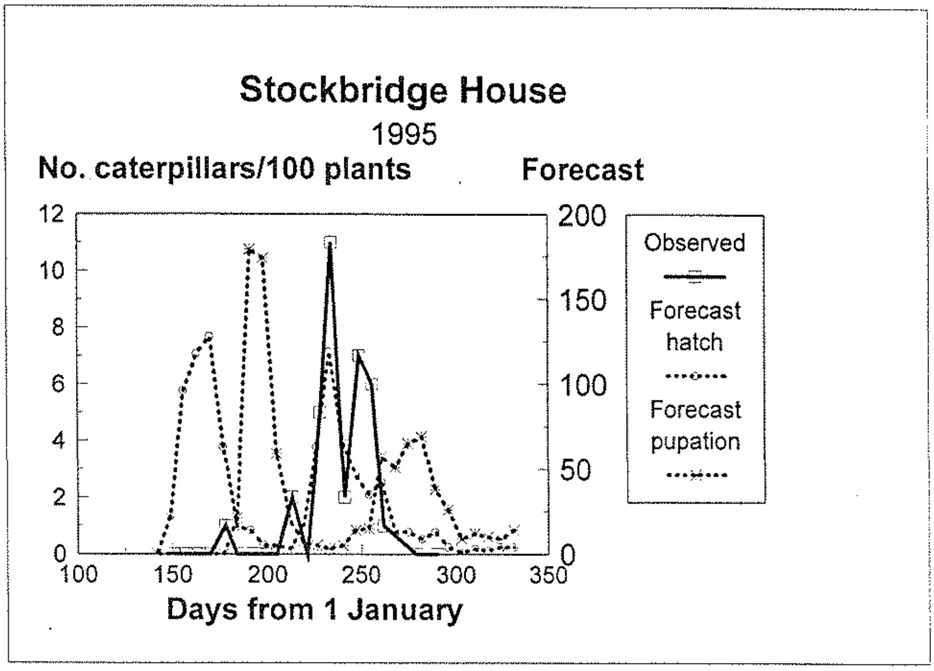


Figure 3n *E. forficalis* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



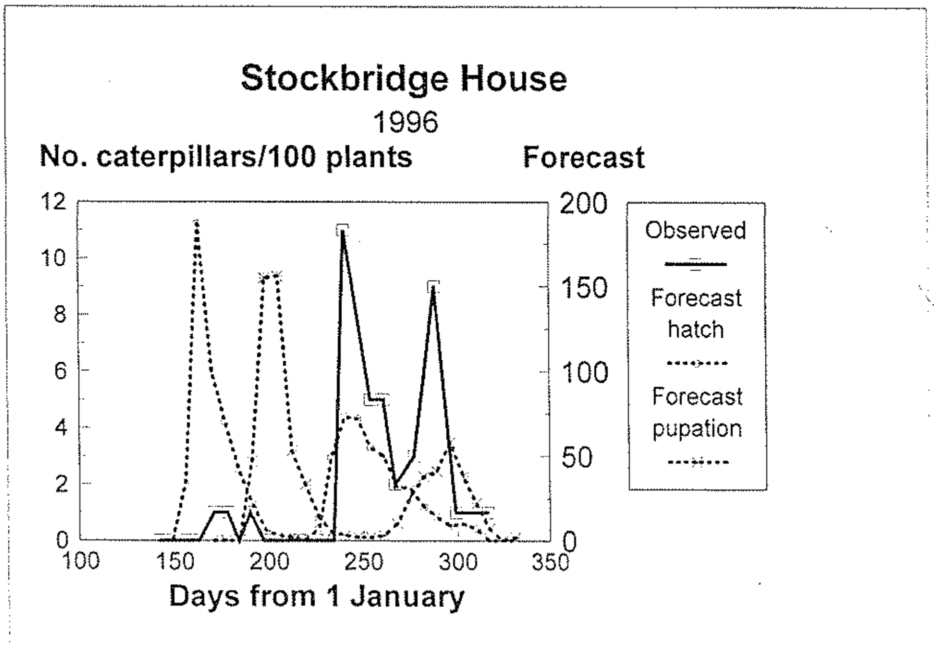
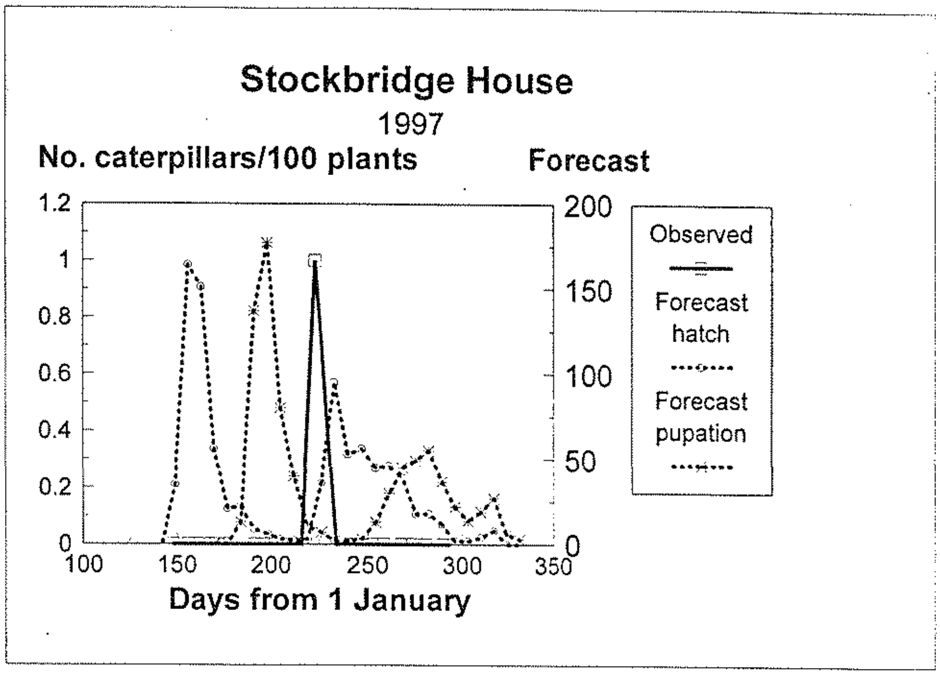


Figure 3n *E. forficalis* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



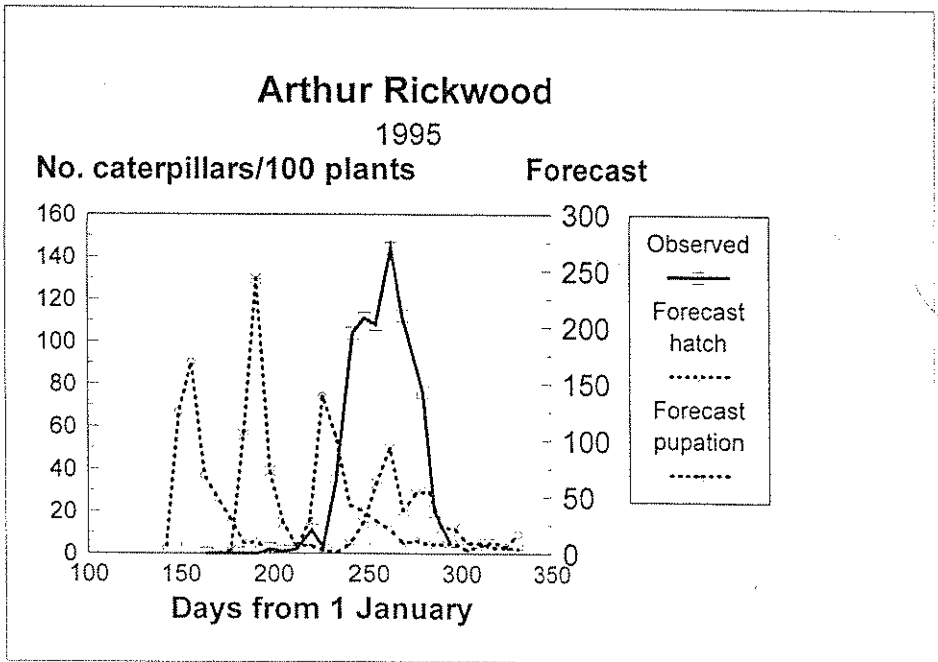
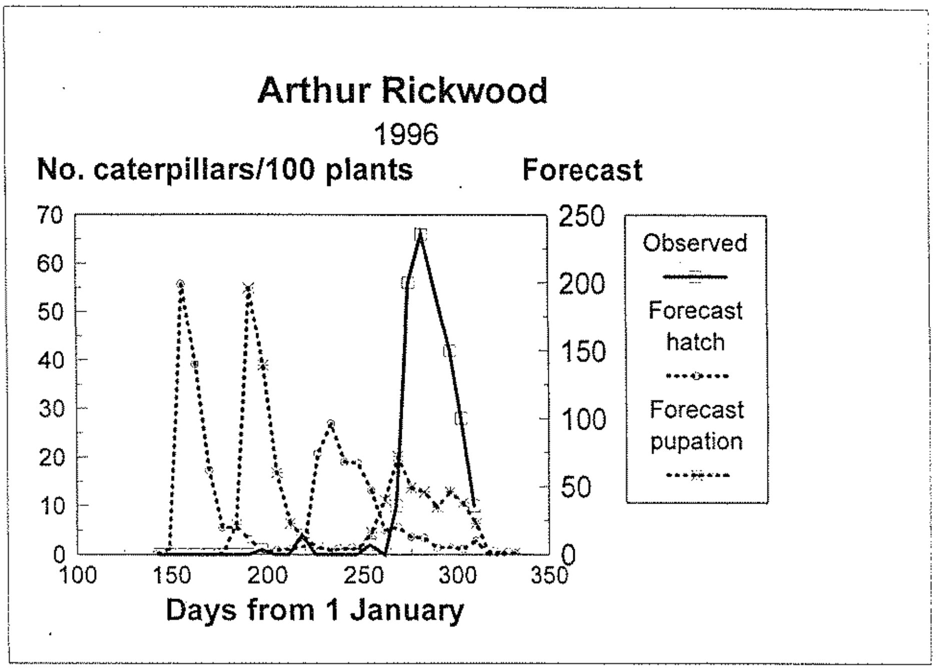


Figure 3n *E. forficalis* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



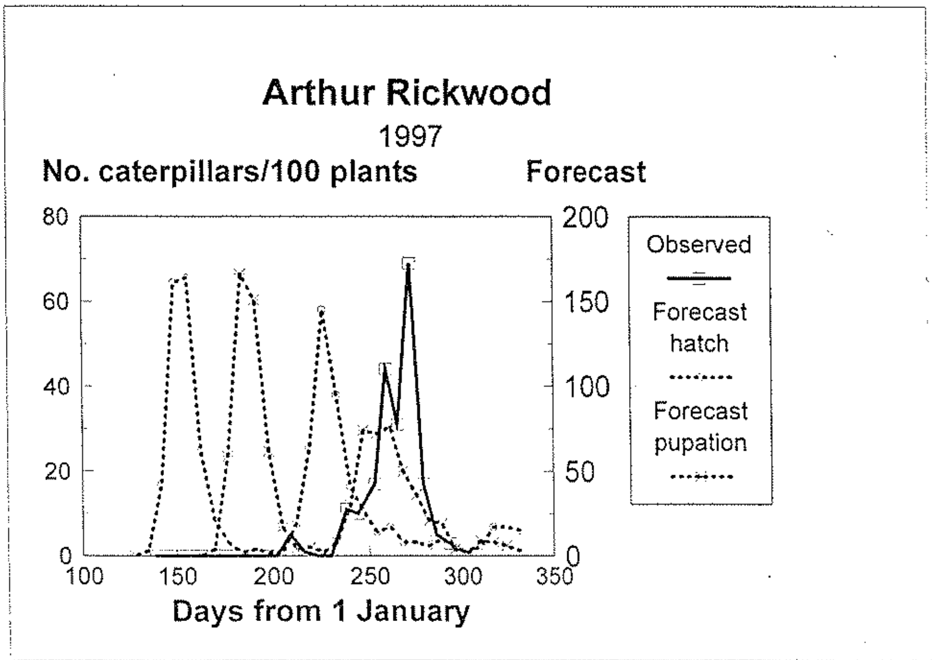
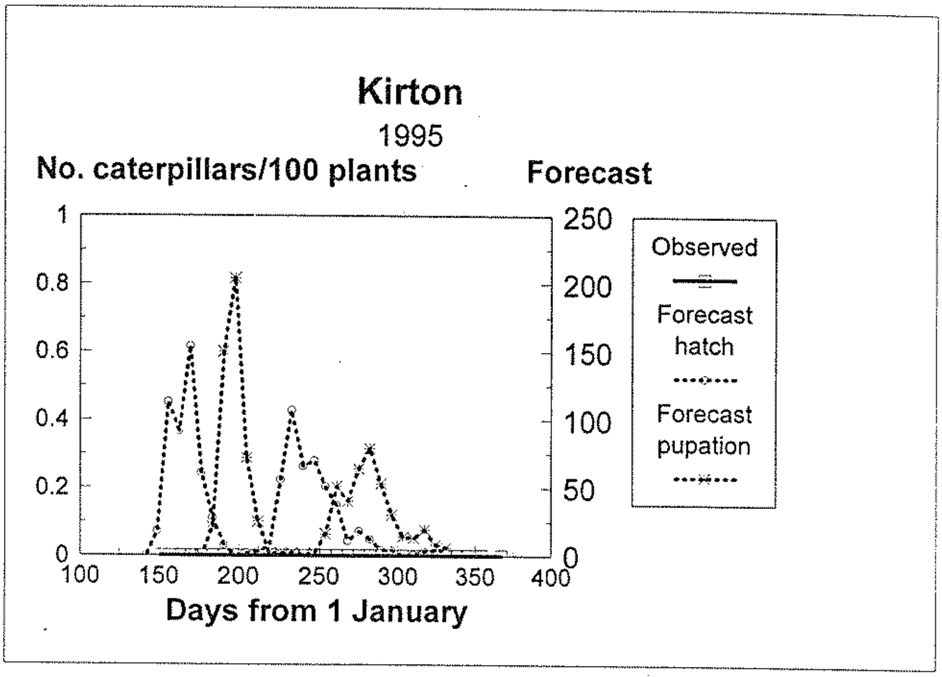


Figure 3n *E. forficalis* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.



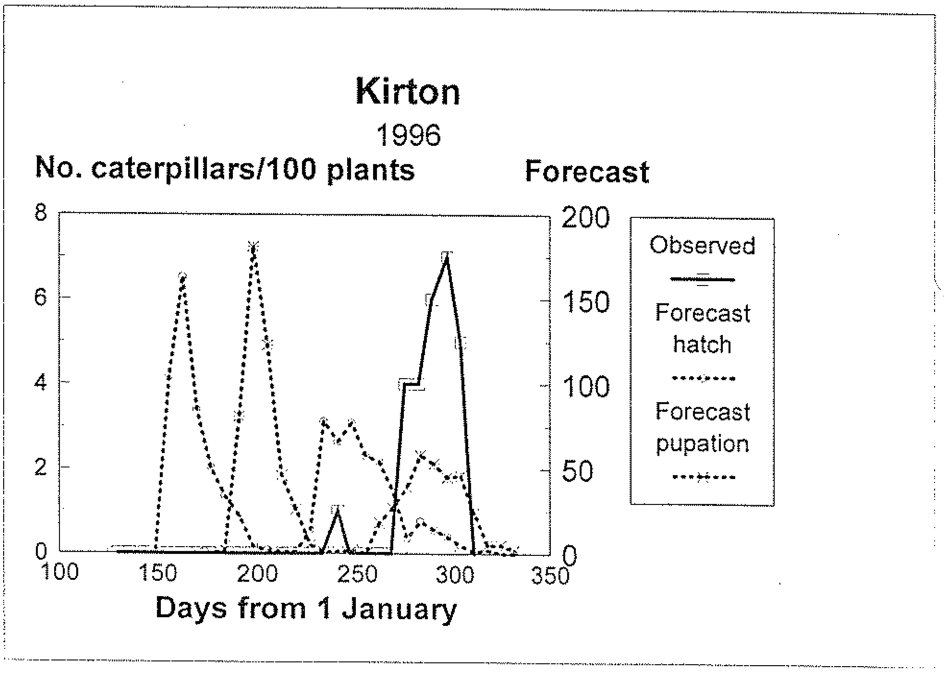
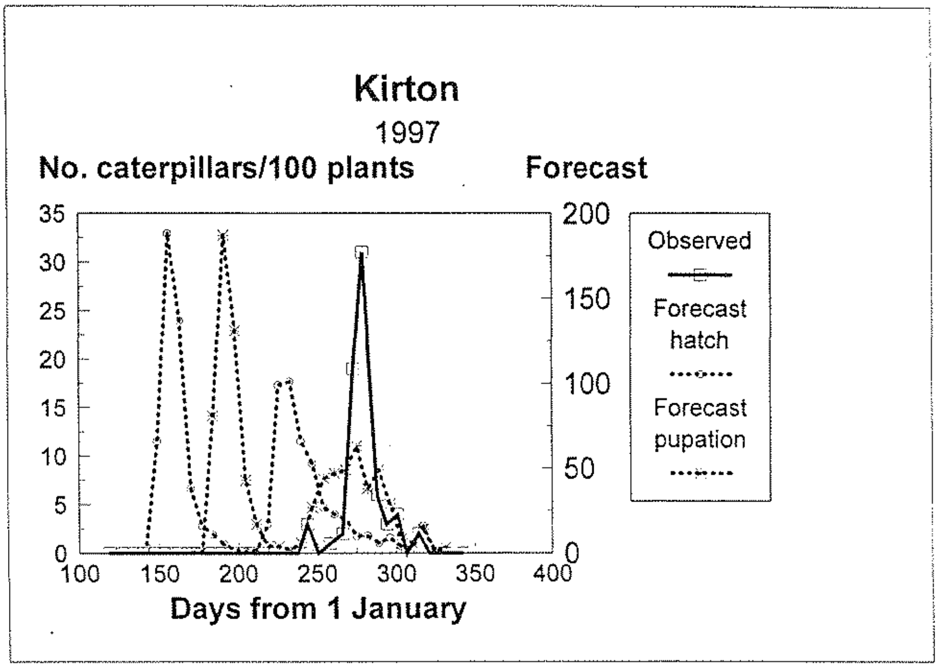
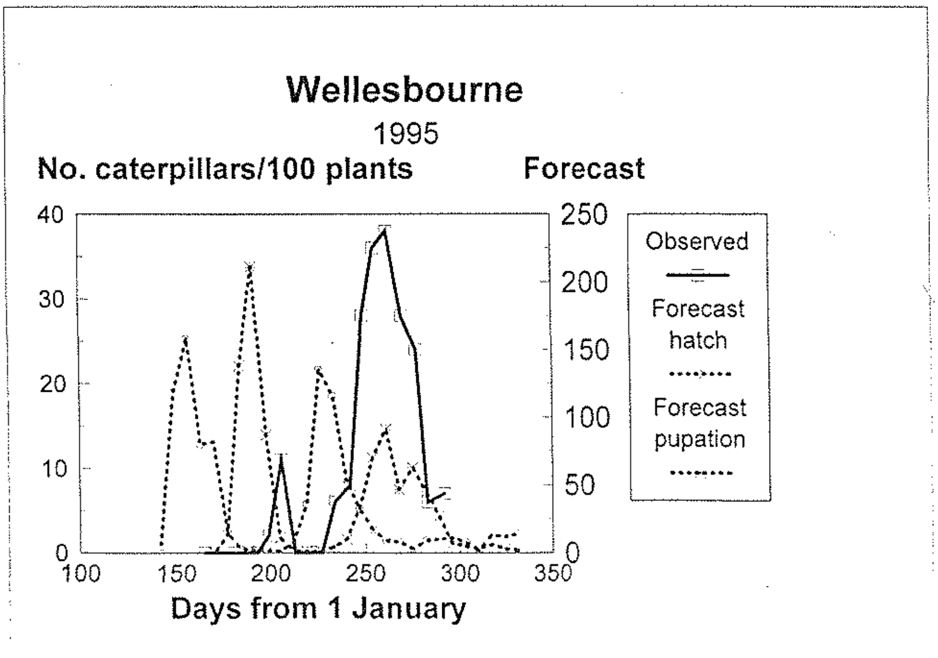


Figure 3n *E. forficalis* - comparisons of forecast egg hatch and pupation with the numbers of caterpillars found on 100 untreated Brussels sprout plants at HRI Kirton, HRI Wellesbourne, HRI Stockbridge House and ADAS Arthur Rickwood in 1995-97.





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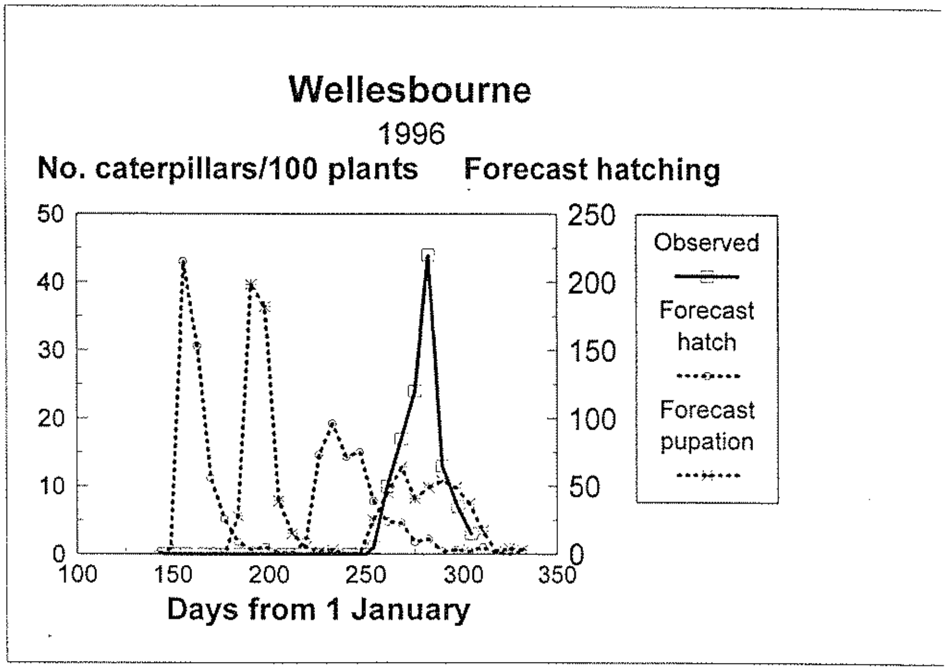


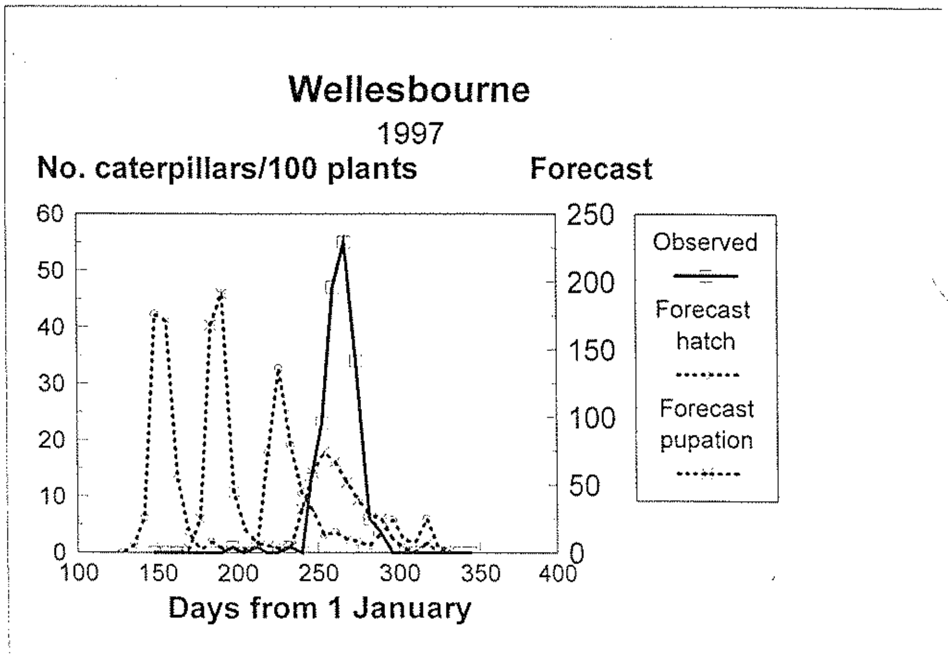
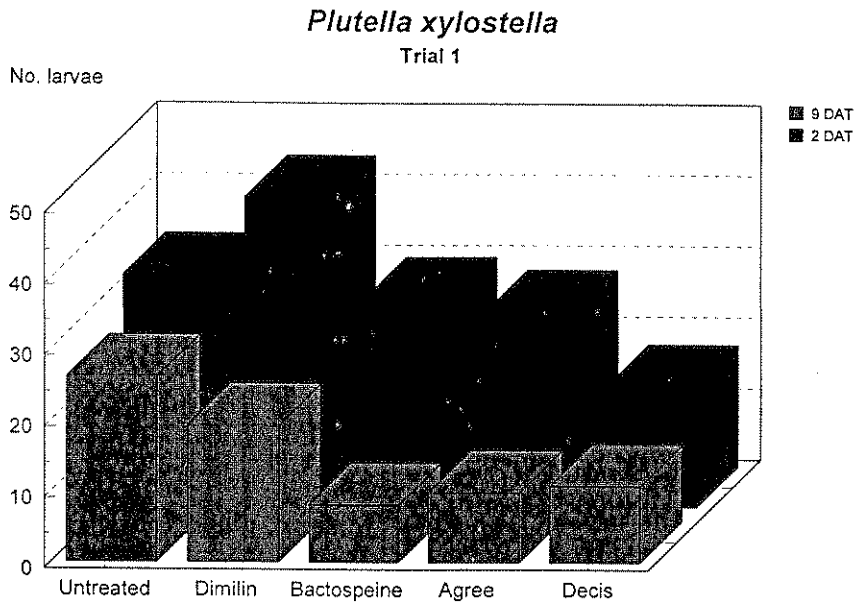


Figure 5a The numbers of insects remaining in plots of Brussels sprouts at ADAS Arthur Rickwood following treatment with insecticide sprays. Plots were assessed 2-3 and 7-10 days after treatment.



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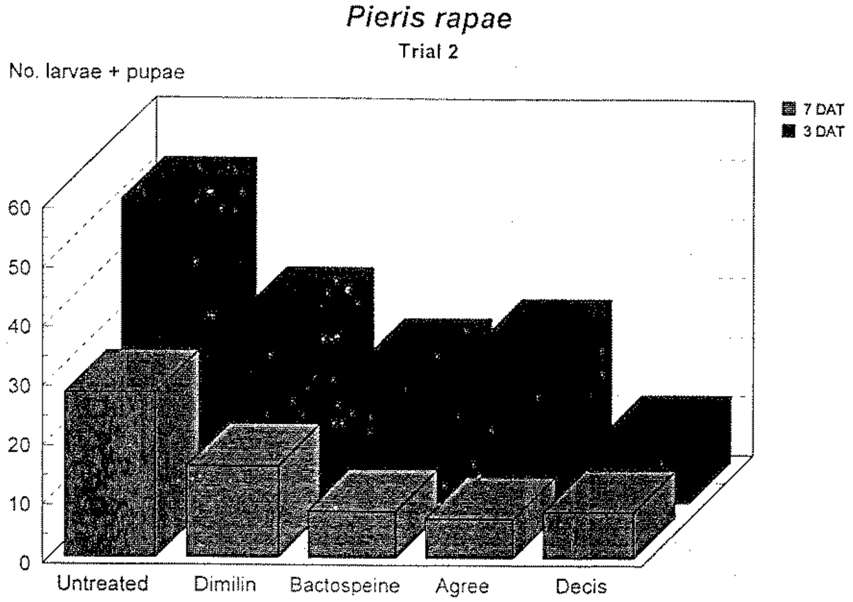

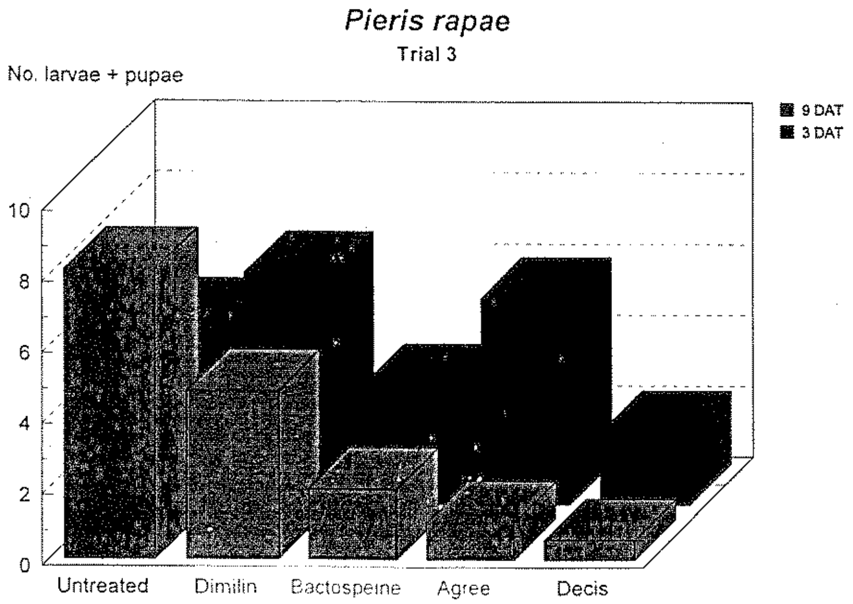

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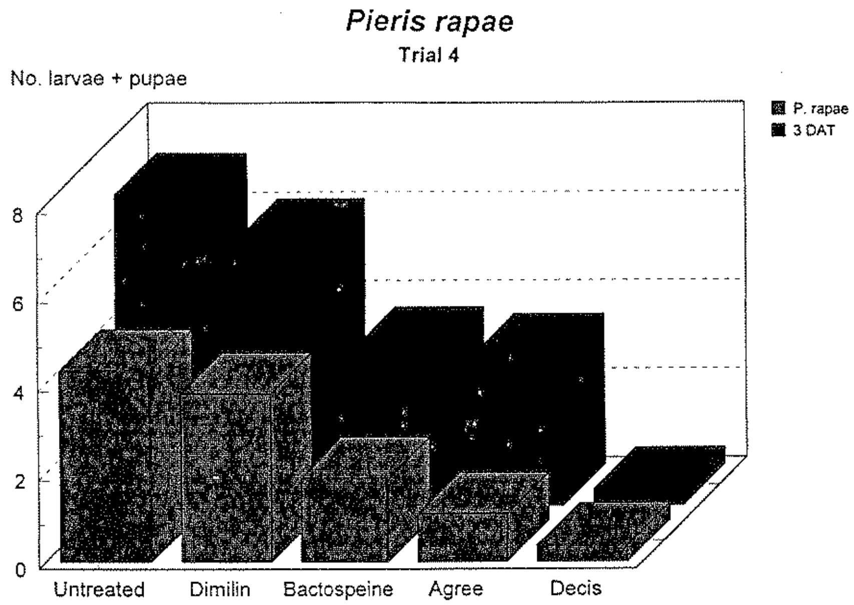

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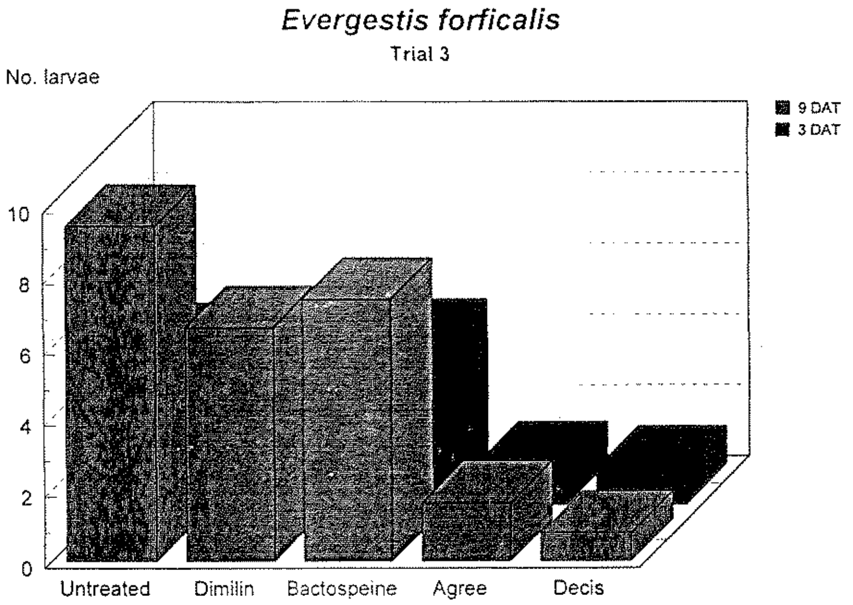


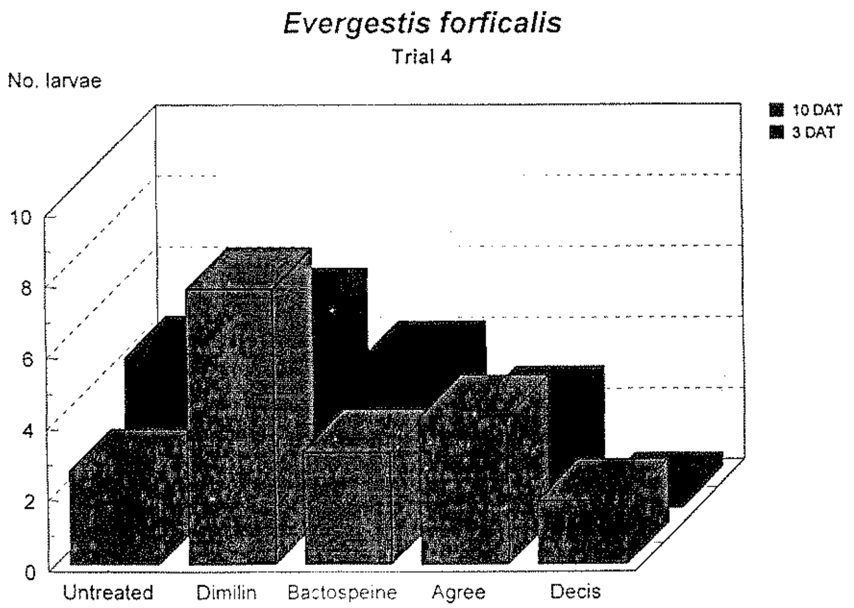
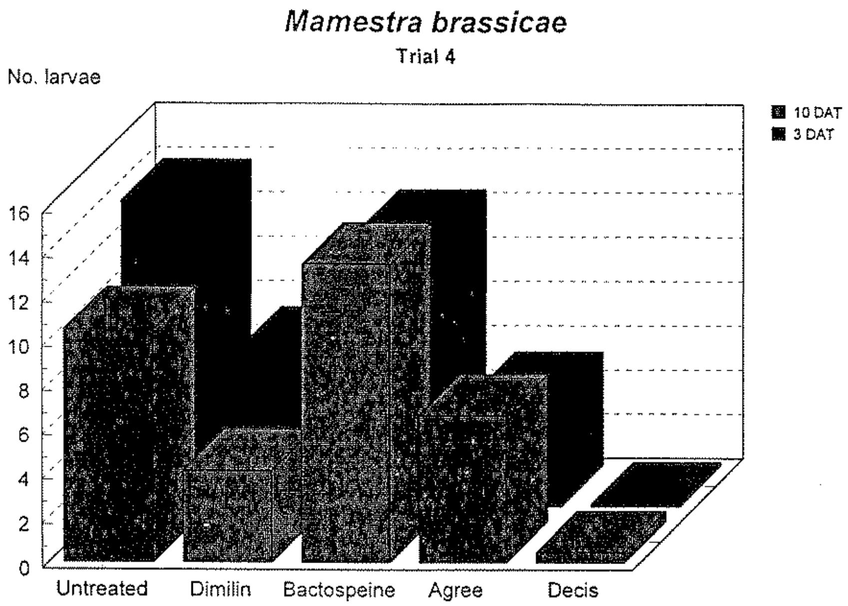


Figure 5a The numbers of insects remaining in plots of Brussels sprouts at ADAS Arthur Rickwood following treatment with insecticide sprays. Plots were assessed 2-3 and 7-10 days after treatment.

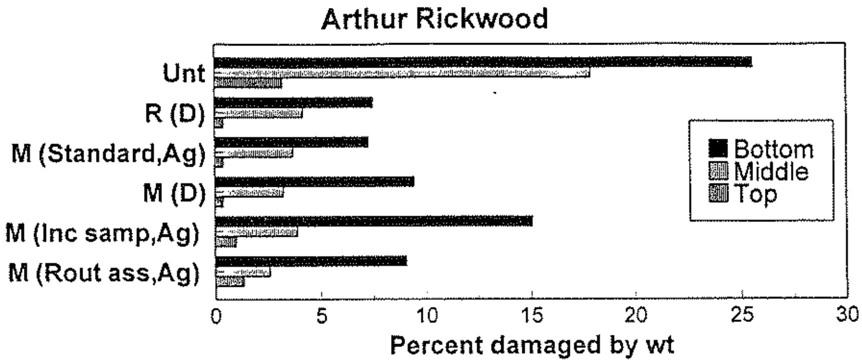


KEY TO GRAPHS FOR CATERPILLAR CONTROL TRIALS 1996

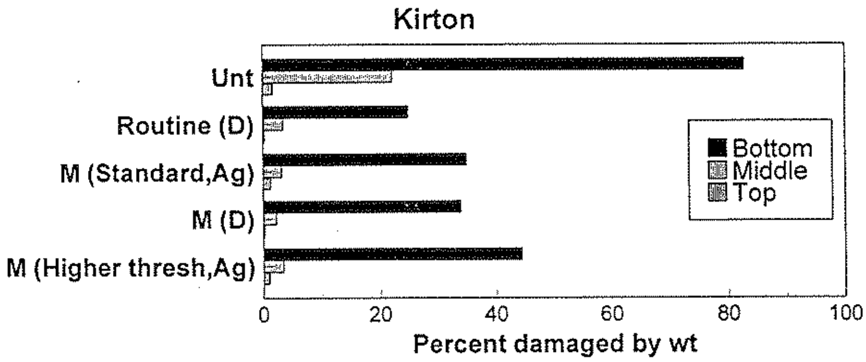
Treatments

Unt	Untreated
R	Routine sprays of deltamethrin (Decis) every two weeks
M (standard,Ag)	Standard managed treatment using *Bt* (Agree)
M (D)	Managed treatment using deltamethrin
M (Inc samp,Ag)	Managed treatment with increased sample size (Agree)
M (Rout ass,Ag)	Managed treatment with routine assessments
M (Higher thresh,Ag)	Managed treatment with higher tolerance levels

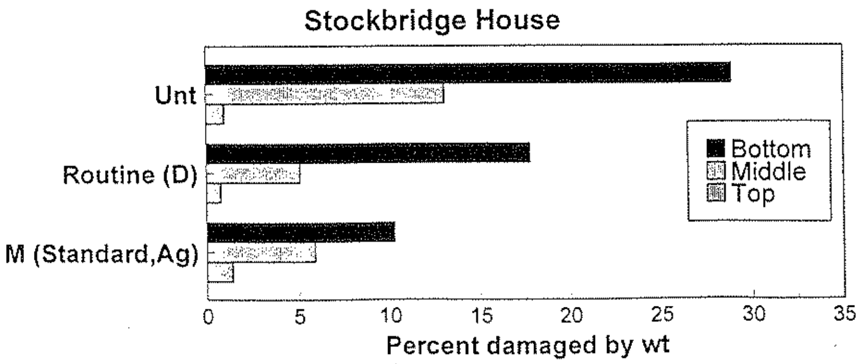
7a. Caterpillar control trials 1996 – percentage of buttons damaged by caterpillars (by weight) at harvest. Buttons taken from top, middle and bottom thirds of stem.



SED (between treatments within zone) 3.0
SED (between zones within treatment) 2.2

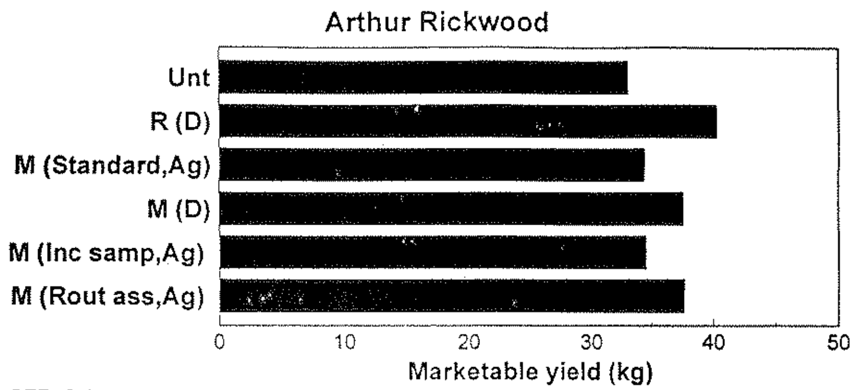


SED (between treatments within zone) 4.1
SED (between zones within treatment) 3.3

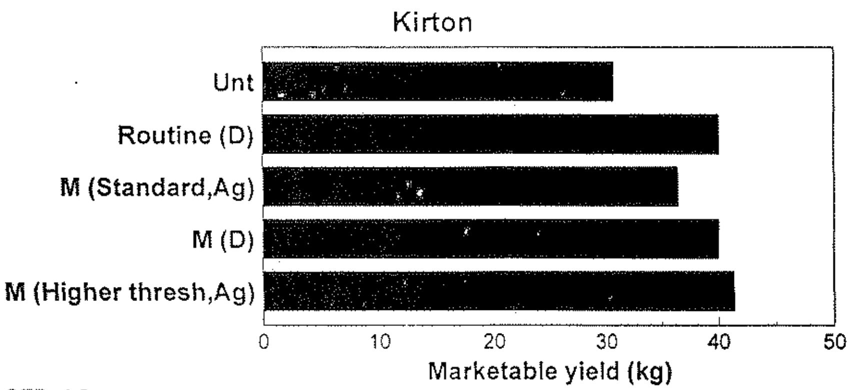


SED (between treatments within zone) 8.6
SED (between zones within treatment) 10.3

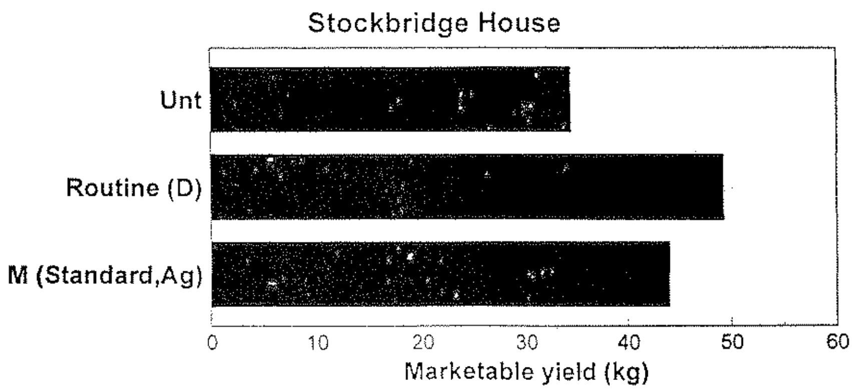
7b. Caterpillar control trials 1996 - marketable yield (kg).



SED 2.1

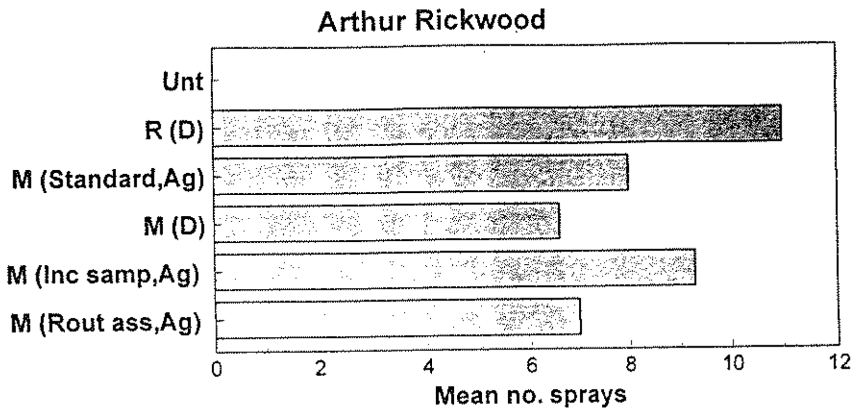


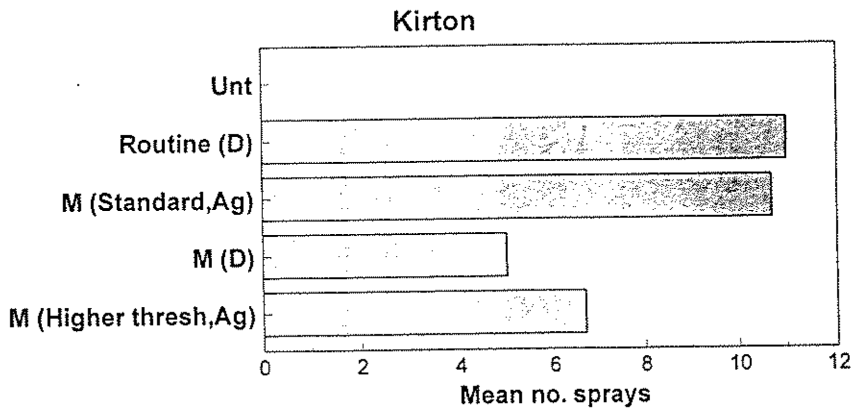
SED 1.3

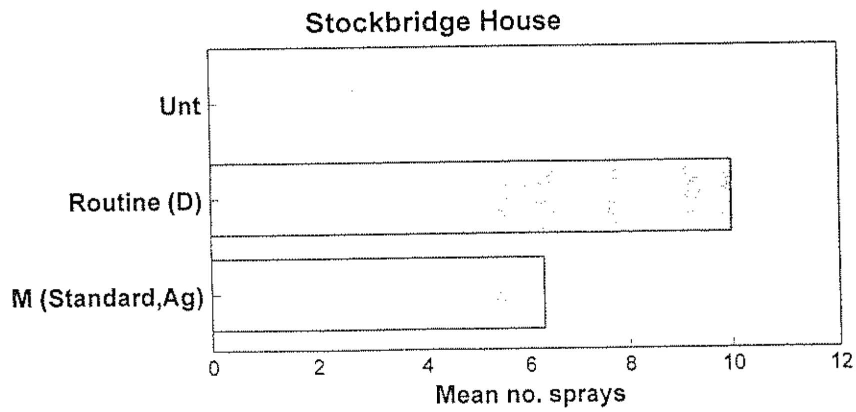


SED 4.7

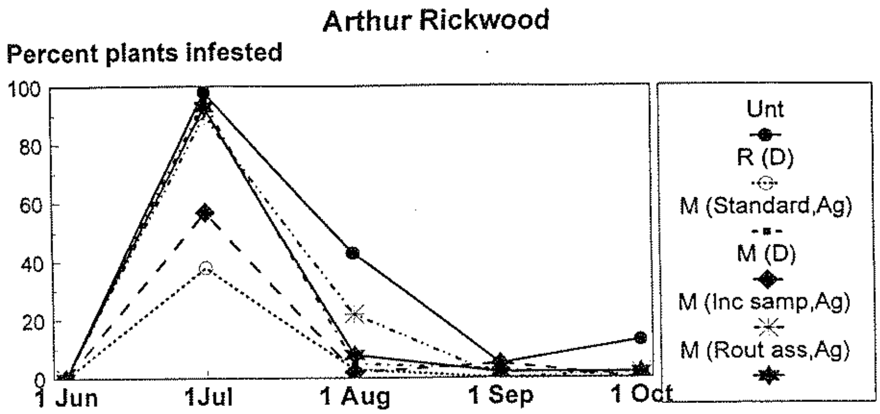
7c. Caterpillar control trials 1996 - mean number of sprays.

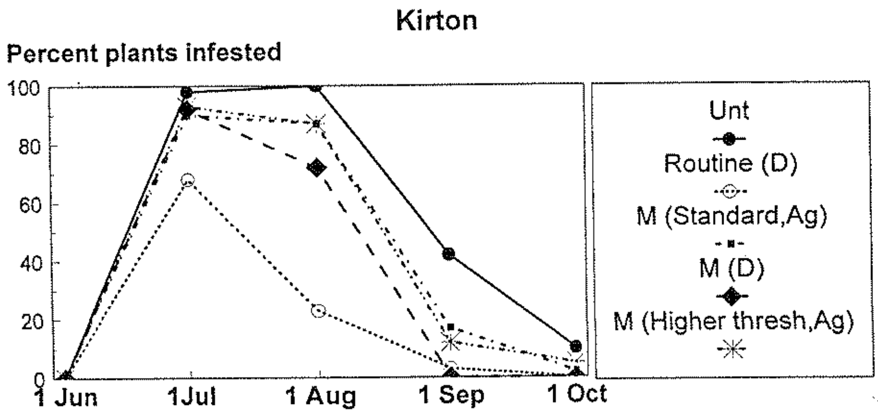


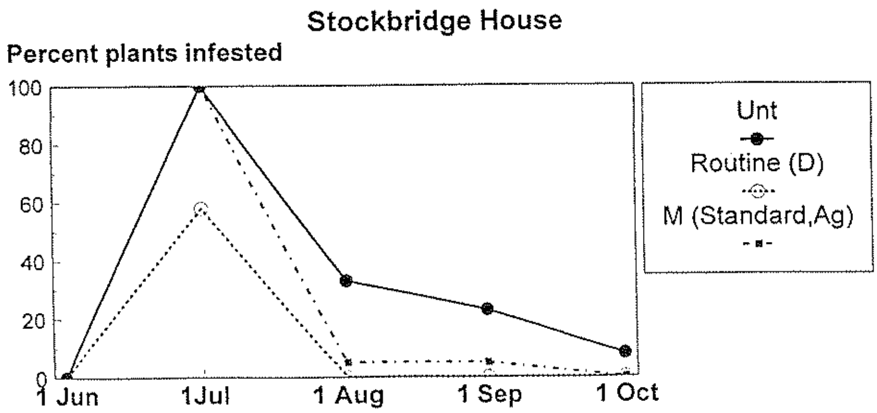




7d. Caterpillar control trials 1996 - monthly assessments to determine the percentage of plants infested with caterpillars.





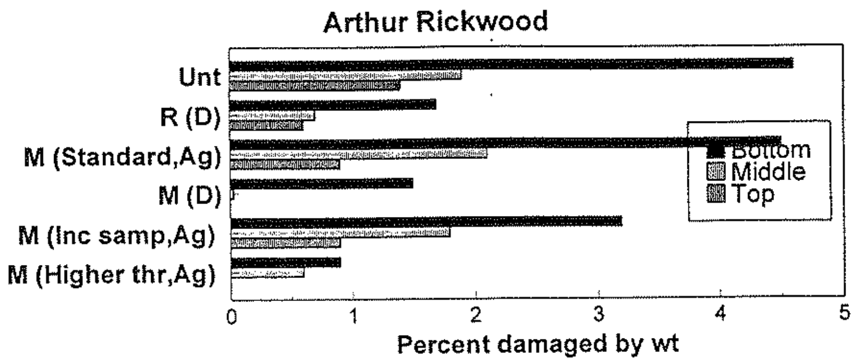


KEY TO GRAPHS FOR CATERPILLAR CONTROL TRIALS 1997

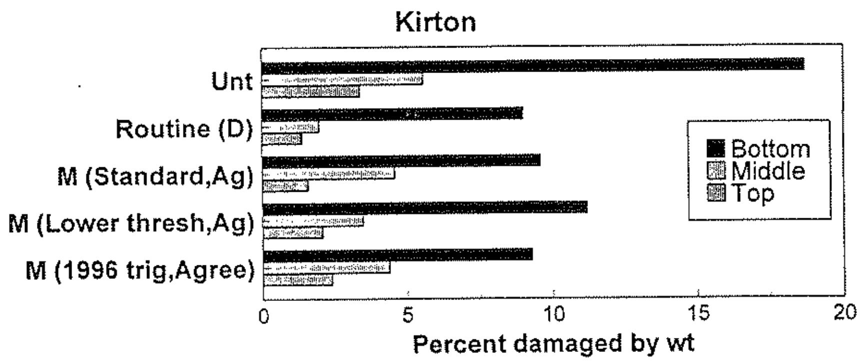
Treatments

Unt	Untreated
R	Routine deltamethrin
M (standard,Ag)	Standard managed
M (D)	Standard managed with deltamethrin
M (Inc samp,Ag)	Increased sample size
M (Lower thresh,Ag)	Lower tolerance level at start for *P. xylostella*
1996 trig	Same triggers as in 1996
M (Higher thresh,Ag)	Higher tolerance level at end

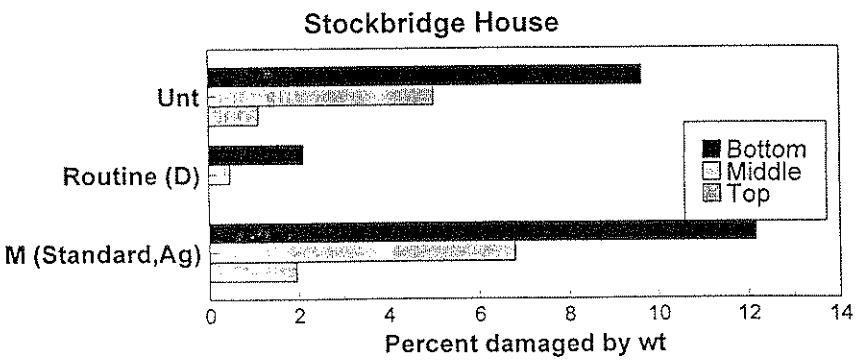
7e. Caterpillar control trials 1997 – percentage of buttons damaged by caterpillars (by weight) at harvest. Buttons taken from top, middle and bottom thirds of stem.



SED (between treatments within zone) 1.0
SED (between zones within treatment) 1.2

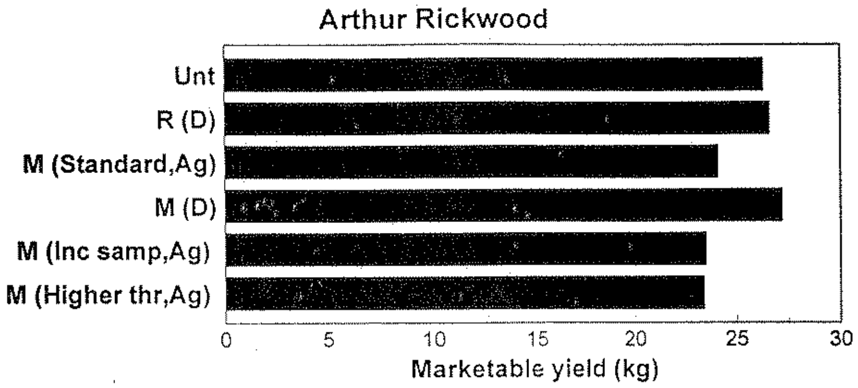


SED (between treatments within zone) 2.6
SED (between zones within treatment) 2.6

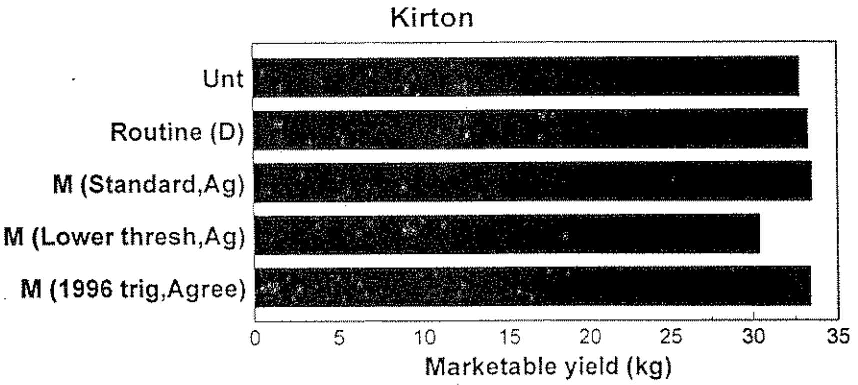


SED (between treatments within zone) 1.1
SED (between zones within treatment) 2.2

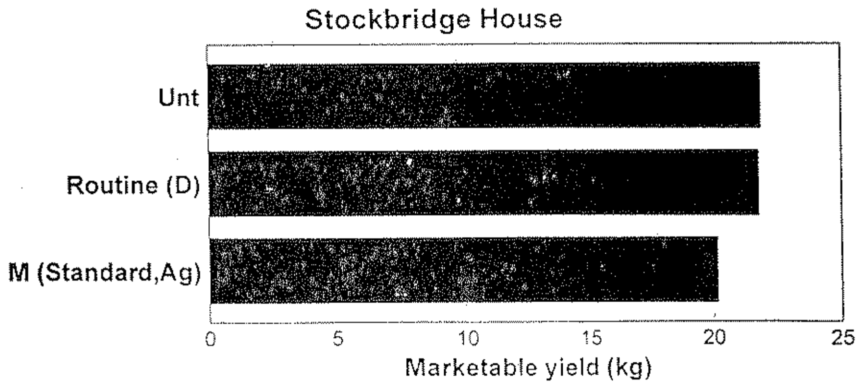
7f. Caterpillar control trials 1997 - marketable yield (kg).



SED 1.7

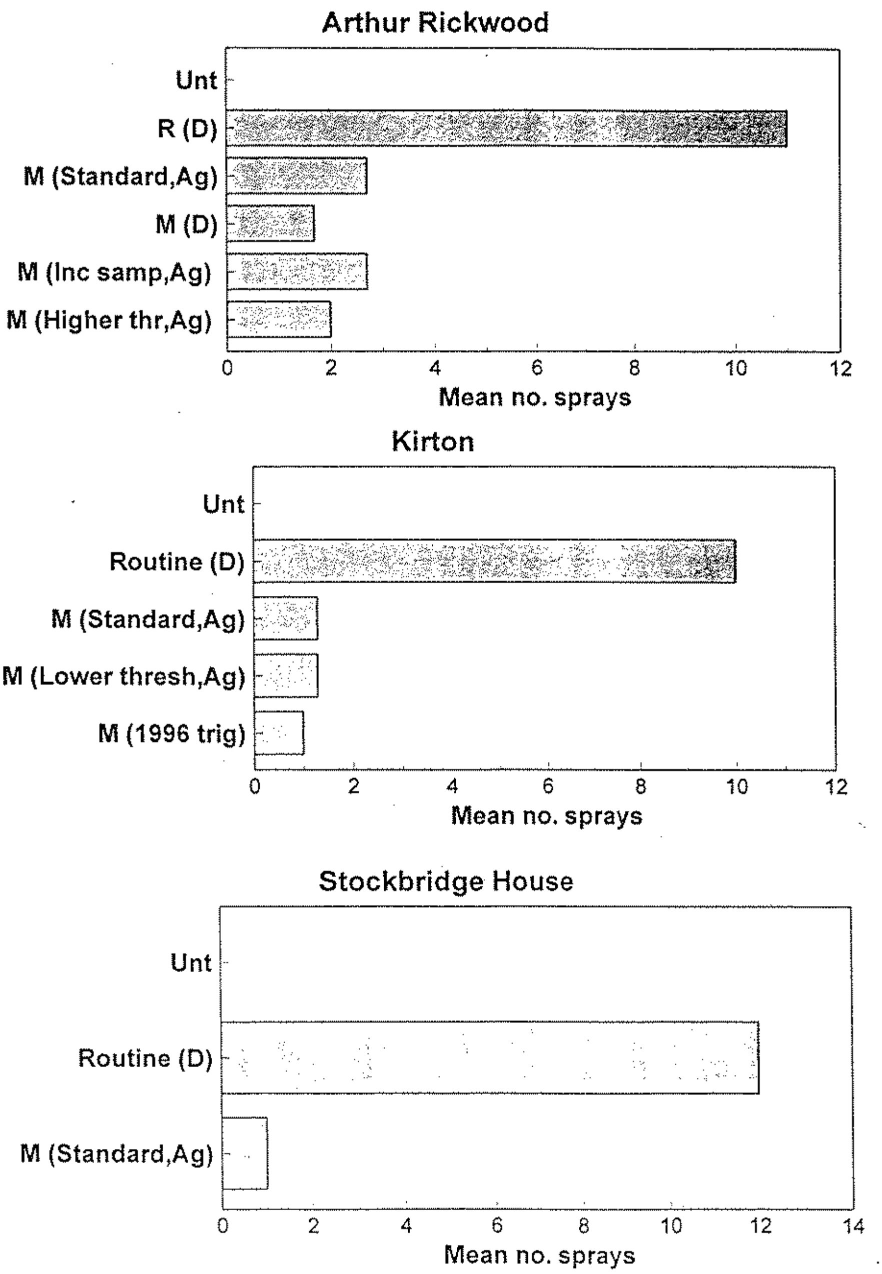


SED 1.2



SED 1.4

7g. Caterpillar control trials 1997 - mean number of sprays.



APPENDIX 1

Table 1 Summary of crops used for caterpillar sampling during 1996 showing percentage of plants infested overall.

Field No.	Crop	Sampling date	Percent plants infested
1	Brussels sprouts	11/07/96	9.1
2	Calabrese	18/07/96	3.7
3	Brussels sprouts	23/07/96	14.5
4	Calabrese	26/07/96	12.2
5	Brussels sprouts	31/07/96	54.3
6	Cauliflower/Calabrese	09/08/96	65.4
7	Cauliflower	13/08/96	10.5
8	Cauliflower	16/08/96	40.8
9	Calabrese	20/08/96	11.5
10	Calabrese	23/08/96	29.6
11	Cauliflower/Calabrese	30/08/96	1.3
12	Cauliflower	04/09/96	0.6
13	Cauliflower	06/09/96	1.7
14	Cauliflower	10/09/96	17.1
15	Cauliflower	17/09/96	5.2
16	Cauliflower	20/09/96	2.5
17	Cauliflower/Calabrese	02/10/96	10.4
18	Cauliflower/Calabrese	09/10/96	18.1
19	Calabrese	15/10/96	1.1
20	Cauliflower	16/10/96	3.5
21	Cauliflower	23/10/96	7
Mean			**15.2**

Table 2 The percentage of plants infested with caterpillars in the different areas of the each crop sampled in 1996.

Field	All areas	All corners	All edges	Middle
1	9.1	10.5	12.5	2.7
2	3.7	5.2	1.5	4.7
3	14.5	17.7	9.7	16.7
4	12.2	11.2	13.5	11.3
5	54.3	61	73.1	20.7
6	65.4	75.4	69.5	46.7
7	10.5	13.5	15	0.7
8	40.8	45.2	42.4	32.7
9	11.5	10.5	10.7	14.1
10	29.6	29	27.3	33.3
11	1.3	1	2	0.7
12	0.6	1.1	0.5	0
13	1.7	1	2	2
14	17.1	15.7	17.2	18.8
15	5.2	4.5	5.7	5.3
16	2.5	1	4	0
17	10.4	11.6	11.5	7.3
18	18.1	12	24.5	17.6
19	1.1	1	1.7	10.7
20	3.5	3.5	4.5	2
21	7	12.1	6	1.4
Mean	**15.2**	**16.4**	**16.9**	**11.4**

Table 3 The percentage of plants infested with caterpillars on each edge of the crops sampled in 1996.

Field	Edge 1	Edge 2	Edge 3	Edge 4	Mean
1	16	18	10	6	**12.5**
2	2	0	2	2	**1.5**
3	8	6.2	10	14.9	**9.7**
4	14	5.7	18	14.3	**13.5**
5	70	74	70	78.7	**73.1**
6	56	58	68	96	**69.5**
7	36	0	2	22	**15**
8	16.7	56	48	48	**42.4**
9	10.9	8	10	16.1	**10.7**
10	38	15.9	20	34.9	**27.3**
11	0	6.2	0	2	**2**
12	0	0	2	0	**0.5**
13	4.1	2	0	2	**2**
14	14.3	20	20.4	16.3	**17.2**
15	12	8.5	2.2	0	**5.7**
16	2	12.2	0	2	**4**
17	10	10	18	8	**11.5**
18	10	38	16	34	**24.5**
19	0	2	2	2	**1.7**
20	0	6	12	0	**4.5**
21	10	2	8	4	**6**

Table 4 The percentage of plants infested with caterpillars on each corner of the crops sampled in 1996.

Field	Corner 1	Corner 2	Corner 3	Corner 4	Mean
1	14	6	10	12	**10.5**
2	4.2	4.1	12.8	0	**5.2**
3	13	19.1	26.1	12.8	**17.7**
4	12	4	4.3	24	**11.2**
5	44	58	62	80	**61**
6	86	77.6	70	68	**75.4**
7	30	2	2	20	**13.5**
8	42.9	34	58	46	**45.2**
9	11.1	20.4	4	6.4	**10.5**
10	58	24	10	24	**29**
11	2	2	0	0	**1**
12	0	2.3	0	2	**1.1**
13	0	2.1	2.2	0	**1**
14	19.1	4	22	18	**15.7**
15	0	10	4	4	**4.5**
16	4.1	0	0	0	**1**
17	18	6.1	22	0	**11.6**
18	10	16	14	8	**12**
19	0	2	0	2	**1**
20	0	12	0	2	**3.5**
21	4	4	18	22.9	**12.1**

Table 5 Summary of crops used for caterpillar sampling during 1997 showing the percentage of plants infested overall.

Field No.	Crop	Sampling date	Percent plants infested with *P. xylostella*	Percent plants infested with *P. rapae*
1	Calab/cauli	1 Aug	7.7	5.3
2	Cauli	6 Aug	2	1
3	Calab	6 Aug	14.7	3.7
4	B. sprouts	8 Aug	3.3	4
5	Cauli	15 Aug	3	3
6	Cauli	15 Aug	10.3	5
7	Cauli	19 Aug	42.6	12.6
8	Cauli	20 Aug	69	8.7
9	Calab	20 Aug	69	6
10	Cauli	22 Aug	69	3.7
11	Cauli	27 Aug	16.9	31.2
12	Calab	8 Sep	65.3	7.3
13	Cauli	16 Sep	24.8	6.6
14	Cauli	22 Oct	9.4	1.3
15	Calab/cauli	22 Oct	25.3	3
16	Calab/cauli	29 Oct	13.1	2.4
17	Cauli	29 Oct	49	1.3
Mean			**29.1**	**6.3**

Table 6 The percentage of plants infested with diamond-back moth in the different areas of each crop sampled in 1997.

Field No.	PERCENT PLANTS INFESTED			
	All areas	**All edges**	**Worst edge**	**Middle**
1	7.7	5	14	13
2	2	2.5	8	1
3	14.7	12.5	16	19
4	3.3	4.5	8	1
5	3	3.5	6	2
6	10.3	8.5	10	14
7	42.6	47.6	70	38
8	69	70.5	90	66
9	69	57.5	84	91
10	69	63.5	86	81
11	16.9	16.7	24	12
12	65.3	60.5	96	75
13	24.8	27.4	38	20
14	9.4	10.5	22	7
15	25.3	23.5	68	29
16	13.1	14.5	48	11
17	49	52.5	90	42
Mean	**29.1**	**28.3**	**45.8**	**30.7**

Table 7 The percentage of plants infested with *P. xylostella* on each edge of the crops sampled in 1997.

Field No.	Edge 1	Edge 2	Edge 3	Edge 4
1	2	0	14	4
2	2	0	0	8
3	16	8	10	16
4	2	8	2	6
5	2	6	2	4
6	12	10	8	4
7	70	40	50	30
8	90	68	62	62
9	84	42	64	40
10	86	54	74	40
11	16	19	8	24
12	16	58	72	96
13	38	28	6	38
14	4	22	14	2
15	68	4	2	20
16	48	6	2	2
17	90	28	46	46

Table 8 The percentage of plants infested with *P. rapae* in the different areas of the each crop sampled in 1997.

	PERCENT PLANTS INFESTED			
Field No.	**All areas**	**All edges**	**Worst edge**	**Middle**
1	5	7	16	3
2	1	2	6	0
3	4	5	8	2
4	4	5	12	2
5	3	4	8	2
6	5	4	12	9
7	13	14	28	1
8	9	13	26	1
9	6	5	10	8
10	4	6	20	0
11	31	24	48	4
12	7	10	30	3
13	7	8	24	4
14	1	2	4	0
15	3	4	10	2
16	2	2	4	4
17	1	2	4	0
Mean	**6.3**	**6.6**	**13.8**	**2.7**

Table 9 The percentage of plants infested with *P. rapae* on each edge of the crops sampled in 1997.

Field No.	Edge 1	Edge 2	Edge 3	Edge 4
1	16	0	4	6
2	6	0	0	0
3	4	0	8	6
4	2	4	12	2
5	4	8	0	2
6	12	0	2	0
7	28	16	10	0
8	26	4	2	18
9	6	10	2	2
10	20	0	0	2
11	0	48	42	8
12	0	6	2	30
13	24	3	0	4
14	0	4	4	0
15	4	0	0	10
16	4	2	0	0
17	4	4	0	0

APPENDIX 2

Simulation of sampling strategy

```
Sampling Strategy Simulationss
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For the Supervised Control of Brassica Pests
---------------------------------------------

Simulations are based on real data collected in 1996

A number of fields were sampled on various dates

Press RETURN to continue

Selected field details are:

    Cauliflower, sampled 13/8/96, Edges - Verge, Trees, Dyke


Information is available about the presence and absence
of aphids, aphid colonies, all caterpillars, and a range
of caterpillar species

Press RETURN to continue

Selected pest is : Diamond Back Moth

Summary of infestation levels in field areas
---------------------------------------------
```

Area	Number Infested	Total Number	Percentage Infested
Edge 1	17	50	34.0
Edge 2	0	50	0.0
Edge 3	1	50	2.0
Edge 4	8	50	16.0
All Edges	26	200	13.0
Corner 1	12	50	24.0
Corner 2	1	50	2.0
Corner 3	1	50	2.0
Corner 4	10	50	20.0
All Corners	24	200	12.0
Edges & Corners	50	400	12.5
Middle	0	150	0.0
All Areas	50	550	9.1

```
Do you want to continue the simulations with this pest? (Y/N - default Y):

To illustrate the importance of the choice of sample
size and location, we are now going to design a sampling
```

strategy for this field.

In designing a sampling strategy, a number of decisions need to be made:
 (1) the locations within the field from which the samples will be taken (edges / corners / middle)
 (2) the total sample size, and how it will be divided between these locations
 (3) the method by which plants will be sampled within each location (at random / in clumps / along transects)

Firstly, select the location(s) within the field from which you want to sample

Press RETURN to continue

Now choose your sample size.

For the locations you have chosen the limits are:
 Maximum sample size: 25
 Minimum sample size: 10

Sample size? 10

Finally you must choose the method of sampling within each field area. Within each field area the plants on which information is available are from a grid of reasonably widely spaced plants. You can choose to re-sample these plants in one of three ways :
 (1) completely at random
 (2) along randomly chosen transects
 (3) from randomly chosen clumps - clump size chosen by the program

Press RETURN to continue

Simulation 1

Your chosen Sampling Strategy is:

Field : Cauliflower, sampled 13/8/96, Edges - Verge, Trees, Dyke

Pest : Diamond Back Moth

Sampling from : Edges only
 using 1 edge(s)

Total sample size : 10

Within each area plants will be chosen along transects

Number of replications (default 100)?

Summary of results for simulation 1

Field : Cauliflower, sampled 13/8/96, Edges - Verge, Trees, Dyke

Pest : Diamond Back Moth

Sampling from : Edges only

Number of replicates = 100
Sample size = 10

Mean number of infested plants = 1.4 (14.1 percent)
Standard deviation of number of infested plants = 1.63

CV of number of infested plants = 115.42

Maximum number of infested plants = 5 (50.0 percent)
Upper quartile number of infested plants = 3 (30.0 percent)
Median number of infested plants = 1 (10.0 percent)
Lower quartile number of infested plants = 0 (0.0 percent)
Minimum number of infested plants = 0 (0.0 percent)

Interquartile range of number of infested plants = [illegible]

APPENDIX 3

Managed treatments in 1996

The seven treatments (A-G) are listed below. All plots were treated routinely for caterpillars.

A. Untreated

No treatments for caterpillars.

B. Routine treatment

Fortnightly sprays of Decis.

C. 'Standard' managed treatment using *Bt*

Tolerances (see below)	40, 5, 0.5
Sampling determined by	Forecasts/monitoring
Number of plants assessed	25
Insecticide	Agree 1.125kg product in 1000 l water/ha. Double rate when no. plants infested with *M. brassicae, E. forficalis, A. gamma* exceed tolerance levels on their own.
Action after reaching 'no decision'	Re-sample later, interval determined by pest development

D. Managed with deltamethrin

NB. Variable that has been changed vs 'Standard' is in **bold**.

Tolerances	40, 5, 0.5
Sampling determined by	Forecasts
Number of plants assessed	25
Insecticide	**Decis**
Action after reaching 'no decision'	Re-sample later, interval determined by pests development

E. Managed with increased sample size

Tolerances	40, 5, 0.5
Sampling determined by	Forecasts/monitoring
Number of plants assessed	25
Insecticide	Agree (as in treatment C)
Action after reaching 'no decision'	**Immediately increase sample size to 60 plants in total**

F. Managed with routine assessments

Tolerances	40, 5, 0.5
Sampling determined by	**Every 2 weeks, re-sample after a week**
Number of plants assessed	25
Insecticide	Agree (as in treatment C)
Action after reaching 'no decision'	**Re-sample after a week**

G. Managed with higher tolerance levels

Tolerances	**40, 10, 5**
Sampling determined by	Forecasts/monitoring
Number of plants assessed	25
Insecticide	Agree (as in treatment C)
Action after reaching 'no decision'	Re-sample later, interval determined by pest development

Location of treatments

ADAS Arthur Rickwood	A, B, C, D, E, F
HRI Kirton	A, B, C, D, G
HRI Stockbridge House	A, B, C

APPENDIX 4

Managed treatments in 1997

A. Untreated

No treatments for caterpillars, fortnightly sprays of DSM or Heptenophos for aphids.

B. Routine treatment

Fortnightly sprays of Decis. 150 ml product in 600 l water/ha.

C. 'Standard' managed treatment using *Bt*

Tolerances (see below)	40, 10, 5
Sampling determined by	Forecasts/monitoring. If a positive decision is made ('spray' or 'no spray') then plots re-sampled after 1 week (if risk of *Plutella*) or 2 weeks (other species).
Number of plants assessed	25
Insecticide	Agree 1.125kg product in 1000 l water/ha with Agral wetter (0.5 l Agral/1000 l water). Double rate when no. plants infested with *M. brassicae*, *E. forficalis*, *A. gamma* exceed tolerance levels on their own.
Action after reaching 'no decision'	Re-sample later, interval determined by pest species. If risk of *Plutella* sample after 1 week (or 3 days if mean temperature > 22° C). Sample after 1 week for other species.

D. Standard managed with deltamethrin

NB. Variable that has been changed vs 'Standard' is in **bold**.

Tolerances	40, 10, 5
Sampling determined by	Forecasts/monitoring. If a positive decision is made ('spray' or 'no spray') then plots re-sampled after 1 week (if risk of *Plutella*) or 2 weeks (other species).
Number of plants assessed	25
Insecticide	**Decis**
Action after reaching 'no decision'	Re-sample later, interval determined by pest species. If risk of *Plutella* sample after 1 week (or 3 days if mean temperature > 22° C). Sample after 1 week for other species.

E. Increased sample size

Tolerances	40, 10, 5
Sampling determined by	Forecasts/monitoring. If a positive decision is made ('spray' or 'no spray') then plots re-sampled after 1 week (if risk of *Plutella*) or 2 weeks (other species).
Number of plants assessed	25
Insecticide	Agree 1.125kg product in 1000 l water/ha with Agral wetter (0.5 l Agral/1000 l water). Double rate when no. plants infested with *M. brassicae*, *E. forficalis*, *A. gamma* exceed tolerance levels on their own.
Action after reaching 'no decision'	**Immediately increase sample size to 60 plants in total**. If still 'no decision', re-sample later, interval determined by pest species. If risk of *Plutella* sample after 1 week (or 3 days if mean temperature > 22° C). Sample after 1 week for other species.

F. Lower tolerance at start for diamond-back moth

Tolerances	**10, 10, 5**
Sampling determined by	Forecasts/monitoring. If a positive decision is made ('spray' or 'no spray') then plots re-sampled after 1 week (if risk of *Plutella*) or 2 weeks (other species).
Number of plants assessed	25
Insecticide	Agree 1.125kg product in 1000 l water/ha with Agral wetter (0.5 l Agral/1000 l water). Double rate when no. plants infested with *M. brassicae*, *E. forficalis*, *A. gamma* exceed tolerance levels on their own.
Action after reaching 'no decision'	Re-sample later, interval determined by pest species. If risk of *Plutella* sample after 1 week (or 3 days if mean temperature > 22° C). Sample after 1 week for other species.

G. Same triggers as in 1996

Tolerances	**40, 10, 5**
Sampling determined by	**Forecasts/monitoring. Triggered by trapping any species or finding cabbage moth eggs. Following positive 'spray' or 'no spray' decision, plots sampled every week. Sampling stopped when no pests trapped or CM eggs found for two weeks.**
Number of plants assessed	25
Insecticide	Agree 1.125kg product in 1000 l water/ha with Agral wetter (0.5 l Agral/1000 l water). Double rate when no. plants infested with *M. brassicae*, *E. forficalis*, *A. gamma* exceed tolerance levels on their own.
Action after reaching 'no decision'	**Re-sample after 1 week (or 3 days if mean temperature > 22°C)**

H. Higher tolerance level at end

Tolerances	**40, 10, 10**
Sampling determined by	Forecasts/monitoring. If a positive decision is made ('spray' or 'no spray') then plots re-sampled after 1 week (if risk of *Plutella*) or 2 weeks (other species).
Number of plants assessed	25
Insecticide	Agree 1.125kg product in 1000 l water/ha with Agral wetter (0.5 l Agral/1000 l water). Double rate when no. plants infested with *M. brassicae*, *E. forficalis*, *A. gamma* exceed tolerance levels on their own.
Action after reaching 'no decision'	Re-sample later, interval determined by pest species. If risk of *Plutella* sample after 1 week (or 3 days if mean temperature > 22° C). Sample after 1 week for other species.