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FINAL REPORT

Carrot fly and cabbage root fly: improved systems for forecasting attacks

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GROWERS' SECTION

APPLICATION

The objective of the project was to develop improved systems, based on weather data, for forecasting the timing of carrot fly and cabbage root fly attacks, so that insecticide sprays applied to control these pests could be targetted more accurately. The two major aims of the project were to make the most effective use of the insecticides available for controlling these pests and to use forecasts to minimize environmental hazards, by spraying only when the pests were present in relatively high numbers. As a result of this project weekly carrot fly and cabbage root fly forecasts were available free, on request, to HDC levy payers during 1992 and 1993.

SUMMARY

Growers are now well aware that the use of insecticides for crop protection is being challenged by environmentalists and that certain supermarket chains demand their vegetables to be produced with the minimum of insecticide, and in some cases without insecticide at all. In an attempt to use insecticides effectively and possibly reduce the amounts applied during vegetable production, the HDC commissioned a project to develop systems for accurately forecasting the times of carrot fly and cabbage root fly attacks, so that insecticides could be applied at times when they would have most effect. In particular, the forecasts were intended for the timing of mid-season sprays against carrot fly on, for example, carrots/parsnips and cabbage root fly on, for example, culinary swedes. They were made available to HDC levy payers during 1992 and 1993.

Pest forecasts are based on the fact that the rate of insect development is directly related to temperature. Therefore, the hotter it is in a particular season, the faster an insect will pass from one generation to the next. This means that there are invariably more insect generations in the south of the British Isles than in the north. It also means that in any locality, if there are only two generations of a particular pest insect in a cool season, there may be three generations in the same locality in a warm season. Both carrot fly and cabbage root fly generations are earlier during warm years and in very warm years there may be a partial third generation of carrot flies and a large third generation of cabbage root flies. For reasons of this kind, there is not much point in applying insecticide treatments on routine calendar dates each year. Growers may be near to the best date in a few years, but in most years they will apply the insecticide either too early or too late since the timing of carrot fly and cabbage root fly generations can vary by as much as 3-5 weeks from one year to the next. Such applications waste chemical and time, kill beneficial insects and contaminate the environment and the vegetable produce.

Growers regularly talk about early and late seasons. What the forecasts do is to indicate how early or how late the season will be, so that an appropriate insecticide

treatment can be applied at the time it is likely to kill maximum numbers of pest insects. The forecasts assume that the grower will apply an insecticide and indicate the best time to apply it. They cannot be used at the time a pest attack is predicted to indicate whether or not an insecticide should be applied. The severity of both carrot fly and cabbage root fly attacks in individual crops cannot be forecast because this depends on the size of the local fly population. However, the forecasts do highlight the "insect-free" periods, when it is pointless to apply insecticide.

The forecasts have been field-tested using data collected generally from most regions of the United Kingdom and intensively from the major vegetable growing areas. Much of this information has been collected by ADAS colleagues, particularly by entomologists working at Cambridge and Leeds. The forecasts for most areas coincide almost exactly with the activity of the flies in the field since they generally estimate the times of 10% and 50% fly activity to within one week of observed activity. There are some difficulties with forecasting cabbage root fly attacks in south-west England, south Wales and south-west Lancashire because some of the overwintering flies emerge later in the spring than in most regions. However, provided the district is pinpointed accurately, adequate forecasts can be produced even for these localities. Similarly, there is a problem at present with forecasting carrot fly activity in certain parts of Lancashire. With the help of Lancashire growers and ADAS colleagues from Wolverhampton, this difficulty should be resolved. In addition, the time of peak second generation carrot fly activity can be delayed by late drilling. Forecasts can be produced to account for the effect of drilling date, if this is provided.

All that the forecasts require are daily records of the maximum and minimum air temperatures and the temperature of the soil at a depth of 6 cm (2.5 inches), the depth at which the fly maggots spend most of their life-cycle. As temperatures at 6 cm deep are not recorded at meteorological stations, they have to be estimated from the 10 cm deep soil temperature recorded daily at 0900 h. With just 21 temperatures a week, which can be obtained from meteorological stations near to the main brassica/carrot growing areas, regional forecasts can be produced for both pests.

Forecasts can also be produced for individual fields provided growers can provide the appropriate weather data on a weekly basis. They can then be provided with an individual forecast and a general forecast for their region. They could then decide for themselves whether the individual forecast was worth the extra effort. Any individual forecast can only be as good as the weather data on which it is based. If growers are already collecting weather data as a routine procedure to help in other cultural decisions, then there should be no problems. If not, then they should seek advice, as collecting weather data on a routine basis tends to be time-consuming. For those growers wishing to obtain a forecast specific to their particular fields, weather data must be available from 1 February.

SCIENCE SECTION

PART 1. FORECASTING CARROT FLY ATTACKS

INTRODUCTION

The carrot fly (*Psila rosae* F.) is a serious pest of umbelliferous crops in northern Europe and North America and most carrot crops in the UK are vulnerable to attack by carrot fly larvae. In the UK, the carrot fly completes two generations each year and in warm years there may sometimes be a small third generation. Depending on climate, first generation fly activity occurs during May/June and second generation fly activity during July-October.

Most early-sown carrot crops can be protected against attack by the first generation of carrot fly by applying insecticides either directly to the seed or to the soil at drilling. Such treatments are generally all that are needed to protect carrot crops harvested before September. However, crops that are harvested later, and thus exposed to attack by the later-instar larvae of the second generation of carrot fly, usually require supplementary mid-season sprays of insecticide if crop damage is to be kept to a minimum. Accurate timing therefore is essential if such treatments are to be effective.

The timing of peak activity by the first and second generations of carrot fly may vary by several weeks from year-to-year and from region-to-region. Therefore 'calendar spraying' frequently fails to protect crops adequately. A project was started in 1987 to develop a system, based on weather data, for forecasting accurately the timing of carrot fly activity throughout the UK. The two major aims of the project were to make the most effective use of the insecticides available for controlling the carrot fly and to use the forecast to minimize environmental hazards by spraying only when the pest was present in relatively high numbers.

EXPERIMENTAL

The experimental studies were divided into the three following sections:-

1. **MONITORING CARROT FLY POPULATIONS -**
   Experiments were carried out to determine the trap most suitable for monitoring changes in carrot fly populations. Traps of the preferred type were then used to:-
   a) record the pattern of fly activity from region-to-region
   b) record the pattern of fly activity from year-to-year
   c) collect data to validate the carrot fly forecasts.

2. **DEVELOPMENTAL BIOLOGY -**
   Studies were made on carrot fly populations under both field and laboratory conditions to determine the relationships between the rate of the various stages of fly development and temperature. Such relationships form the basis of the current

forecasting model.

3. **DEVELOPMENT AND VALIDATION OF THE FORECAST -**
A computer model, based on the rates of insect development, was produced that enabled the timing of carrot fly attacks to be forecasted. Field monitoring data on insect activity were then used to validate the accuracy of the computer-generated forecasts.

1. MONITORING CARROT FLY POPULATIONS

Comparison of carrot fly traps

To obtain a good estimate of the pattern of carrot fly activity at a particular site, a relatively large sample of insects must be collected from that site. Thus the traps used to monitor carrot fly populations should be as effective as possible.

Several traps are used currently in Europe and North America for monitoring populations of the carrot fly. Sticky board traps are used in the USA, Canada, Denmark and Switzerland, water traps in France and the UK, cylindrical sticky traps in the UK and windmill sticky traps in the Netherlands. The relative effectiveness of the various traps was assessed in nine field experiments, three in south-west Lancashire, four in the Fens (Suffolk, Norfolk, Cambridgeshire), one in East Suffolk and one at Wellesbourne, Warwickshire. Traps were compared during the first and second generation of carrot fly in 1988. The numbers of carrot flies caught were recorded weekly by ten operators and the traps were replaced. Operators also recorded the time required to renew each trap and to count the carrot flies.

Regression analysis of the numbers of flies caught on each type of trap against the numbers caught on the standard Rebell^R trap (manufactured in Switzerland) indicated that each trap sampled a constant proportion of the fly population relative to the other traps. Therefore, provided the fly population was sufficiently large for insects to be caught on the least effective traps, any of the traps would monitor adequately fluctuations in carrot fly populations. However, the Rebell trap caught 4-17 times as many flies per trap and 5-7 times as many flies per unit area of trap as any of the other traps tested (Table 1). Operators considered the Rebell trap to be the easiest to use. However, it was more expensive than any of the other traps tested.

Effect of trap colour

Attempts to produce a cheap sticky board trap that was as effective as the Rebell^R trap were unsuccessful. Irrespective of the colour it was painted or the translucent plastic it was made from, no trap was more effective than the Rebell^R trap (Table 2).

Studies showed that the relative attractiveness of coloured sticky board traps to the carrot fly could be described by a model in which fly catch was related positively to the amount of light reflected from the trap in the green-yellow (550-570 nm) band of the spectrum and negatively to the amount of light reflected in the violet-green (390-550 nm) band. The model allows the performance of new commercial coloured traps to be predicted solely from spectral reflectivity measurements.

Effect of trap size and trap height

The effects of trap size and trap height were also examined. Similar numbers of flies were caught per unit area on sticky board traps varying in size from 150 cm^2 to 4800 cm^2. Most flies were caught on traps resting on the ground and the number of flies caught was reduced by 0.84% for each cm the trap was raised above 10 cm from the ground.

Trap selectivity

Insect traps used in pest monitoring schemes should be sufficiently selective to enable the pest species to be separated easily from the other insects caught on the trap. Sticky traps can be made selective for carrot fly by enclosing the traps in cylinders of green Netlon^R (1.2cm^2 mesh) or by inclining the actual traps at 45° to the vertical.

At Wellesbourne, covering the traps with Netlon^R had no significant effect on the numbers of carrot flies trapped but reduced the numbers of larger Diptera and pollen beetles caught by 52% and 90% respectively. The hoods had no effect on the numbers of smaller Diptera trapped.

One-sided sticky traps angled at 45° to the vertical with the sticky surface facing downwards doubled the numbers of carrot flies caught per unit trapping area and reduced by 90% the numbers of non-target insect species caught. Hence, the traps were much more selective for carrot fly and therefore the catch was much easier to count.

2. DEVELOPMENTAL BIOLOGY

Spring emergence

Carrot flies overwinter in the soil either as diapausing pupae or as larvae. Diapause is induced in the pre-pupal stage during late summer/autumn in response to low temperatures. Diapause pupae form from 6-60% of the overwintering population.

Later-developing insects remain as larvae throughout the winter. Hence crop damage gradually increases during the winter as these insects continue to feed. Flies generally emerge earlier in the spring from insects that overwinter as larvae and pupate in the spring, than from insects that overwinter as diapausing pupae. Studies were undertaken in both the laboratory and the field to determine the temperature requirements for spring emergence, both from diapause pupae and from insects which overwintered as larvae.

Carrot fly populations were sampled at Wellesbourne during the winters of 1987-88, 1988-89, 1989-90 and 1990-91. Between 20-55% of the individuals overwintered as diapausing pupae whereas the remainder continued larval development and formed nondiapausing pupae in the early spring. In May, flies emerged earlier and over a shorter period of time from insects which had overwintered as larvae than from those which had overwintered as pupae.

Diapause was most intense during late December and early January. In the laboratory, diapause was completed gradually at temperatures of 5°C and above but not at 0°C. When the overwintering stages were sampled in early February, and maintained at constant temperatures in the laboratory, overwintering pupae required from 114 days at 9°C to 44 days at 21.5°C to give rise to flies. In contrast, overwintering larvae required only 91 days (9°C) and 27 days (21.5°C) respectively.

Populations of overwintering carrot fly collected from Wellesbourne and Norfolk had similar requirements for spring emergence but diapause pupae collected in Lancashire emerged over a longer period of time than those collected at Wellesbourne. Comparisons with published data indicated that North American and European pupae had different requirements for the completion of diapause.

Spring and summer development

Newly-emerged carrot flies require a few days to mature their eggs. The eggs, when laid, then require several days incubation prior to hatching. Larval development proceeds through three instars and is followed by pupation and pupal development, which culminate in emergence of the next generation of flies. There is evidence that the durations of most stages in the life-cycle of the carrot fly are temperature-dependent.

In laboratory experiments, carrot flies were reared in Gallenkamp cooling incubators at a range of constant temperatures to determine the relationship between the duration of each development stage and temperature. Adults, eggs, larvae and pupae of the carrot fly were reared at a series of constant temperatures between 9-24°C. Female carrot flies generally laid batches of 20-40 eggs, the pre-oviposition period lasting from 28 days at 9° to 4 days at 24°. When supplied with both protein and carbohydrate, females laid several batches of eggs and subsequent batches were laid after an average of 7 days at 11.5° to 3 days at 24°. Egg development required from 25 days at 9° to 5 days at 24°, larval development from 145 days at 9° to 31 days at 21.5° and pupal development from 84 days at 9° to 24 days at 21.5°. Full development from egg to newly-emerged fly required from 254 days at 9° to 60 days at 24°.

In the 'field' experiments similar tests were conducted under fluctuating daily temperatures. In most cases, however, the experimental insects were partially screened to protect them from the extreme effects of direct sunlight and heavy rainfall. Temperature integrators were used to record the accumulated day-degrees (D°) required to complete development. Base temperatures of 2° and 4°C were used; each being appropriate for part of the carrot fly life-cycle. Under field conditions, during May-July, eggs were laid after 55 D° above 4°C or 66 D° above 2°C. Egg to adult development (eggs laid between mid-May and early September) lasted 91 days and required a mean of 1033 D° above 4°C or

1254 D° above 2°C. Fewest D°, above either base, were required when development was most rapid.

Aestivation

High temperatures may cause carrot fly pupae pupae to enter aestivation, the summer resting phase. Newly-formed carrot fly pupae were kept at 16.5°C and exposed to temperatures of 22-30°C for various 5-10 day periods during pupal development. Exposure to temperatures of 24 and 26°C caused some of the pupae to delay development, whereas exposure to 28 and 30°C caused all of the pupae to delay development. The insects were only sensitive to high temperature 4-10 days after pupation.

3. DEVELOPMENT AND VALIDATION OF THE FORECAST

The data on carrot fly development described in the previous section provided the basis for the carrot fly forecasting model. Further information on the life-cycle and additional data on development times were obtained from published studies.

The relationships between the rate of insect development and temperature were established for each phase (e.g. spring emergence from diapause pupa, spring emergence from overwintered larva, egg maturation, egg, larval and pupal development) in the life-cycle of the insect by plotting the mean rate of development (100/time to completion of the stage) against temperature.

For those stages where rates of development were proportional to temperature, linear and non-linear (Gompertz) rate equations were fitted to the data to describe the relationship between rate of development and temperature. The most appropriate equation to describe each stage of development was selected by maximum likelihood analysis and inspection of residuals.

Carrot fly development was summarised using seven equations, which were for:

1. Larval and pupal development in the spring
2. Diapause development and post-diapause development
3. Pre-oviposition period - maturation of first batch of eggs
4. Maturation of second batch of eggs (by specified proportion of population)
5. Egg stage
6. Larval stage
7. Pupal development

These equations formed the basis of the simulation model and were linked together in a FORTRAN program. Lower development thresholds were estimated by interpolation from linear equations or from other biological data. Upper development thresholds were set at 30°C, this being close to the extreme of temperature normally experienced in the field.

The variation in the rate of insect development was estimated for each stage in the life-cycle using coefficients of variation (CV). These were derived from the laboratory experiments by calculating the mean and variance of the rate of development at each constant temperature. CVs were approximately constant. This variation was included in the model by simulating the development of cohorts of 10-500 individual insects. At the start of each new phase of the life-cycle, each of the individuals was randomly allocated a personal development rate in such a way that at each temperature the resulting frequency distribution of rates was compatible with a normal distribution with the required mean and variance.

The forecast was started from 1 February, as this is normally the coldest time of the year. The percentage of insects overwintering as larvae was specified at the start of the model. The model was started with the diapause and post-diapause development phase of overwintering pupae and with the pupation and pupal development phase of overwintering larvae. The percentage development of each individual insect was accumulated using the appropriate rate equations and hourly soil temperatures, until each stage was completed (100% development). The individual, now a newly-emerged adult, was then placed into the next phase of development, the pre-oviposition period. The simulation was run on this phase using the appropriate development equation and hourly air temperatures. Progress continued through each phase in the insects' life-cycle.

The model was used to predict 1) the times of 10% and 50% fly emergence and egg-laying activity for each generation, 2) the number of weeks when fly activity was high and 3) the likely occurrence of a third generation of flies.

Meteorological data used in the forecast

The carrot fly forecast used maximum and minimum soil temperatures at a depth of 6 cm to model the development of egg, larval and pupal stages. Maximum and minimum air temperatures were required to model the period from when the flies emerged from the soil to when they started to lay.

Of the standard data recorded at Agro-met stations, only the daily maximum and minimum air temperatures and a reading of the 10 cm soil temperature taken at 9.00 h are appropriate for the carrot fly model. The maximum and minimum soil temperatures at a depth of 6 cm therefore have to be derived from the Agro-met temperature data using empirical equations developed from field studies.

Size of the simulated population

The model was run with from 10 to 500 individuals, to determine the population size required to obtain repeatable simulations. A different random number seed was used to run each simulation. The times to 10% and 50% activity were estimated for the Wellesbourne carrot fly population in 1991 and the mean and spread of 10% and 50%

second generation activity times, over 10 simulations, are shown in Table 3.

With a population of only 10 insects the dates of 10% and 50% activity were extremely variable and simulations were not repeatable (range 9 and 16 days for first generation, 19 and 28 days for second generation). With a population of 500 insects the repeatability of the simulation was greatly improved (range 2 days for first generation, 3 days for second generation). Populations of more than 100 individuals were required to reduce the range to less than one week. Populations of 500 individuals were used to produce regional carrot fly forecasts.

Numbers of flies trapped in the field

The simulated population also indicated the number of insects that would have to be trapped per generation to validate the forecast reliably. Similar evidence was obtained by comparing separately the patterns of carrot fly activity from three individual traps placed at a single monitoring site. Figure 1 shows the pattern of second generation carrot fly activity at a site in the Fens in 1988 from each of three traps. At the time of the second generation, a total of 92 flies were trapped. Estimated times of 10% and 50% activity were 24 August, 19 August, 19 August and 7 September, 30 August, 28 August for the three traps respectively; ranges of 5 and 10 days. Thus three traps, each catching an average of 30 flies, gave estimates of the time of activity that varied by 5-10 days. These estimates did not differ greatly from the ranges estimated from the 10 repeated forecast simulations on populations of 50 insects.

Validation of the carrot fly forecast

Differences between years in fly activity at Wellesbourne

Carrot flies were monitored at Wellesbourne during 1981-1983 and 1986-1992 inclusive, during a total of ten seasons. Carrot fly traps were located within plots of carrots grown in an area of the Research Station at Wellesbourne where the carrot fly population had been encouraged with minimal applications of pesticides and continuous cultivations of carrots. Carrot flies were trapped with yellow/orange water or sticky traps which were serviced each week or more frequently.

The earliest first generation fly activity (50%) was recorded on 7 May in 1982 and 1990, and the latest on day 27 May in 1986. Earliest second generation activity was recorded on 21 July in 1989 and 1990 and the latest on 26 August in 1986. Second generation activity curves for a cold year (1986) and for a warm year (1990) are shown in Figure 2. Forecasts were based on fixed populations of 500 insects per generation. There was also a partial third generation at Wellesbourne in 1990. Therefore, at Wellesbourne, there was a three week and a five week difference in the times of attack of the first and second generations during the nine seasons.

The fit of the model was assessed by comparing simulated insect activity with actual insect activity monitored in the field. Figure 3 shows typical sets of monitoring/simulated data for Wellesbourne in 1989 and 1991. The two sets of data are plotted on separate scales, the monitoring data showing the actual numbers of flies trapped in the field and the simulations being based on a fixed population of 500 insects per generation. The two or sometimes three broad peaks of insect activity that occurred annually were separated into generations to enable the data to be expressed as percentage insect activity during each generation. This enabled similar curves of insect activity to be produced for each generation and made the forecast independent of the large changes in insect numbers that can occur from one generation to the next in certain years and/or localities. The data could then be compared on a cumulative percentage scale to enable comparison of observed and forecast times of activity; particularly the start of activity (10%) and the mid-point (50%). Figure 4 shows data for Wellesbourne in 1986 and 1990 compared in this way.

Over the nine years at Wellesbourne the mean absolute differences between times of observed and predicted carrot fly activity were 2.5 and 6.6 days for 10% and 50% first generation activity and 4.3 and 8.3 days for 10% and 50% second generation activity. Figure 5 shows the dates of forecast 10% activity plotted against the dates of observed activity at Wellesbourne. Straight lines were fitted to both sets of data ($P=0.01$).

Regional monitoring 1989

To validate the carrot fly forecast at a range of different sites, fly activity was monitored throughout the UK in 1989. This work was funded by MAFF. At many sites low numbers of carrot fly were trapped and of the 34 sites monitored, only approximately 30% produced sufficient flies (i.e. 100 or more flies per generation captured on three Rebell traps) to enable reliable comparisons to be made between the forecast and the fly monitoring data.

Unlike Wellesbourne where carrots were available for oviposition throughout the year, the drilling dates of commercial crops varied according to growers' requirements and so carrots were not necessarily available at all times.

The majority of late carrot crops were sprayed against carrot fly attack during the second generation. This may have reduced the numbers of flies trapped and as a consequence influenced the estimated times of 10% and 50% fly activity.

Few flies were trapped in Berkshire, Deeside, Nottinghamshire, Yorkshire and Lincolnshire. Higher numbers were trapped in Norfolk, Suffolk, Cambridgeshire, the West Midlands and south-west Lancashire. The carrot fly forecast validations are summarised in Table 4. The mean absolute difference between observed and predicted first generation activity (50%) was 4.6 days, but the difference was more than 7 days at one site and more than two weeks at another. The difference between observed and predicted second generation activity (50%) averaged 7.8 days. However, at two sites the difference exceeded 7 days and at two sites it exceeded 14 days.

Working in Denmark, Esbjerg and colleagues have set guidelines for the numbers of carrot flies trapped on Rebell traps. They consider that below a threshold catch of 3.5 flies per trap per week (0.5 per trap per day) there is normally no need to apply sprays for carrot fly control except under special conditions. During the 1989 survey, at some sites, this threshold was exceeded during as many as seven weeks of the first generation and eight weeks of the second generation.

The forecast was used to predict those weeks when high numbers of carrot flies were expected. In the first generation, of the 68 weeks when > 3.5 flies per trap were captured per week, only three of the weeks were not predicted by the forecast. In the second generation, of the 40 weeks when > 3.5 flies were trapped, once again, only three were not predicted by the forecast.

Further forecast validation

The forecast has been tested against every available set of monitoring data using weather data from the nearest Agro-met station. Figures 6a & 6b show comparisons of the observed and simulated second generation carrot fly activity for a number of sites in the Fens during 1987-1991. Forecasts were based on fixed populations of 500 insects per generation. Figures 7a & 7b show comparable data from sites in other regions. These sets of data were selected because the traps caught relatively large numbers of flies or, in some cases, because the traps were in a location different from the major carrot growing areas.

Sites where errors between forecast and observed activity are large

Large differences in the forecasted and observed carrot fly activity were recorded from a number of sites in south-west Lancashire and Holme Fen in Cambridgeshire. These sites were generally those where the growers consistently drilled their main crop carrots relatively late in the season.

It is believed that the majority of carrot flies move only short distances between crops (possibly less than 500 m) and that the insects present in a particular crop during the first generation largely govern what occurs in the second generation. In areas where no early carrots are grown, first generation carrot fly that emerge early have no large areas of crop in which to lay their eggs. With crops drilled during May, for example, only the later-emerging insects will be able to establish and this will influence the timing of peak emergence of the subsequent (second) generation of insects. This can be simulated using the forecast program by assuming that the progeny of carrot flies that emerge before the crop has emerged do not lay on that crop and that only the progeny of later-emerging insects survive. The results of such simulations are shown in Figure 8. They are compared with monitoring data collected at sites in south-west Lancashire where both carrot drilling and emergence dates were available.

Carrot fly populations in Lancashire

Because of the differences between observed and forecast carrot fly activity in south-west Lancashire, a large sample of overwintering carrot fly larvae/pupae was collected from a heavily-infested site in 1992. The post-winter emergence of this population was compared with that of the Wellesbourne population under standard field and laboratory conditions at Wellesbourne.

In the laboratory, at a constant temperature of 16.5°C, the patterns of emergence of flies from insects which had overwintered as larvae were identical (Figure 9a). However, the emergence of flies from overwintering pupae was more extended in the Lancashire population and insects continued to emerge for approximately two weeks longer (Figure 9b). In the spring, flies from both overwintering populations began to emerge at the same time into field cages at Wellesbourne, but once again, emergence of a small proportion of the Lancashire population was prolonged (Figure 9c). Such discrepancies in the pattern of emergence can be incorporated readily into the forecast program.

CONCLUSIONS

1. At present, the Rebell trap is the most effective for monitoring carrot fly.

2. Sticky traps can be made more selective for carrot fly by angling the trap at 45° to the vertical with the sticky surface facing downwards. This also makes Rebell traps more economical to use, as the upper surface can be covered with clear polythene for use in the following week.

3. The timing of carrot fly generations can vary by as much as 3-5 weeks from one year to the next.

4. Carrot flies are active earlier during warm years and in very warm years there can be a partial third generation.

5. The time of peak flight by the second generation of carrot fly can be delayed by drilling late.

6. Carrot fly traps can be used to indicate periods of peak carrot fly activity. The accuracy of the information obtained, however, is influenced considerably by sample size.

7. Very low numbers (less than 30 flies per trap per generation) of carrot flies are frequently captured in commercial carrot crops, particularly in regions where

carrots are not grown extensively. The start and peak of fly activity cannot be estimated accurately from such small samples.

8. Where insect numbers are being monitored, it is essential that every effort is made to obtain as large a sample of flies as possible. This can generally be achieved by increasing either trap number or trap size.

9. The timing of carrot fly activity can be forecast using daily records of air and soil temperatures starting from 1 February each year.

10. The severity of carrot fly attacks in individual crops cannot be forecast as this depends on the size of the local fly population.

11. The program can produce forecasts to account for the effect of drilling date on the timing of second generation activity.

12. The forecasts generally estimate the times of 10% and 50% fly activity to within approximately one week of the observed activity.

SUMMARY

A range of carrot fly traps were compared under field conditions to find the most effective trap for monitoring field populations of the carrot fly. The Rebell trap from Switzerland caught most flies. Angling Rebell traps at 45° to the vertical with the sticky surface facing downwards increased considerably their selectivity without reducing the total numbers of carrot flies caught. Carrot fly populations were monitored during 1987-92 to measure variations in the pattern of fly activity from region-to-region and from year-to-year and to provide data to validate further the carrot fly forecasts.

Carrot fly development was studied in the field and laboratory. In general, carrot flies developed more rapidly as temperatures were increased. However, at very high temperatures, development was delayed (aestivation). For each stage of development (egg, larva, pupa, adult), the relationship between the rate of development and temperature was described by a mathematical equation.

The equations relating the rate of carrot fly development to temperature were incorporated in a computer program used to forecast the timing of carrot fly attacks under field conditions. The program used local air and soil temperatures to simulate carrot fly activity in a given locality. The accuracy of the forecasts was tested using sets of monitoring data collected from both experimental and commercial carrot crops.

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Table 1. Relative efficiencies of three types of carrot fly trap compared with the Rebell trap

Trap type	Percentage efficiency compared with Rebell trap	Percentage efficiency /unit area compared with Rebell trap
Cylinder	25	15
Windmill	7	18
Water	6	19

Table 2. The effect of trap colour and trap type on the numbers of carrot flies captured on sticky board traps.

Trap colour	Trap type	Mean number of flies trapped
Yellow/orange	Rebell	36
Yellow	Correx	24
Orange/red	Correx	13
Yellow/orange	Painted	11
Orange	Painted	13
Yellow	Painted	12
Green	Painted	3
Red	Painted	3

Table 3. Range of simulated times to a) 10% and b) 50% egg-laying by second generation carrot flies at Wellesbourne in 1991. Each simulation was run 10 times

a) **10% egg-laying**

Population size	Range	Days	Mean
10	25 Jul - 13 Aug	19	31 Jul
50	29 Jul - 6 Aug	8	2 Aug
100	31 Jul - 6 Aug	6	3 Aug
250	2 Aug - 6 Aug	4	3 Aug
500	2 Aug - 5 Aug	3	3 Aug

b) **50% egg-laying**

Population size	Range	Days	Mean
10	6 Aug - 3 Sep	28	16 Aug
50	14 Aug - 28 Aug	14	20 Aug
100	16 Aug - 28 Aug	12	21 Aug
250	17 Aug - 25 Aug	8	21 Aug
500	19 Aug - 22 Aug	3	21 Aug

Table 4. Results obtained from the monitoring data used to validate the carrot fly forecast during 1989

	First generation	Second generation
Number of sites	15	22
Mean difference in 10% activity (days)	6.7	7.9
No. sites with error > 1 wk	3	4
No. sites with error > 2 wk	0	0
Mean difference in 50% activity (days)	4.6	7.8
No. sites with error > 1 wk	1	2
No. sites with error > 2 wk	1	2

Figure 1. Numbers of second generation carrot flies trapped by three traps in a carrot crop in the Fens during 1988.

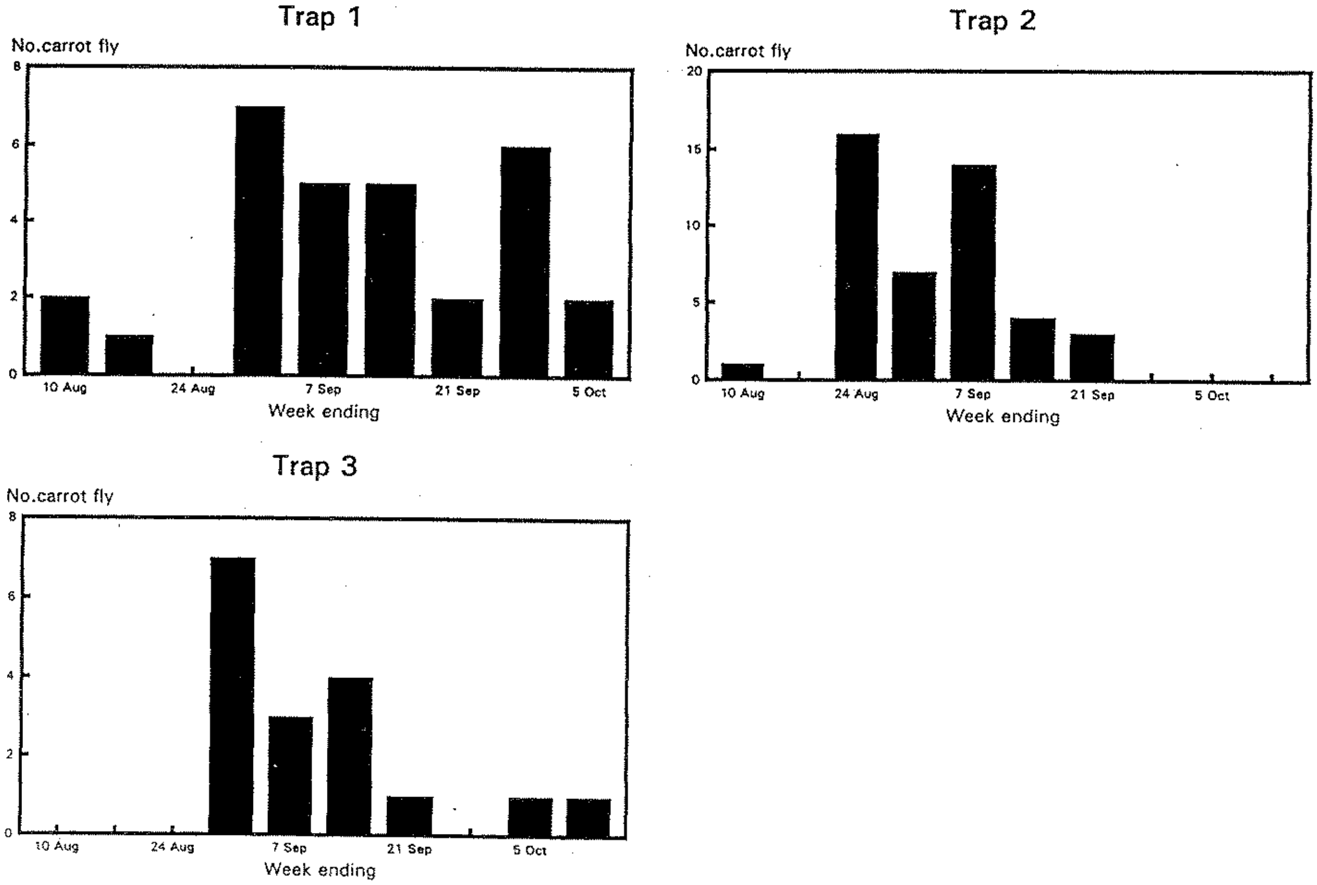
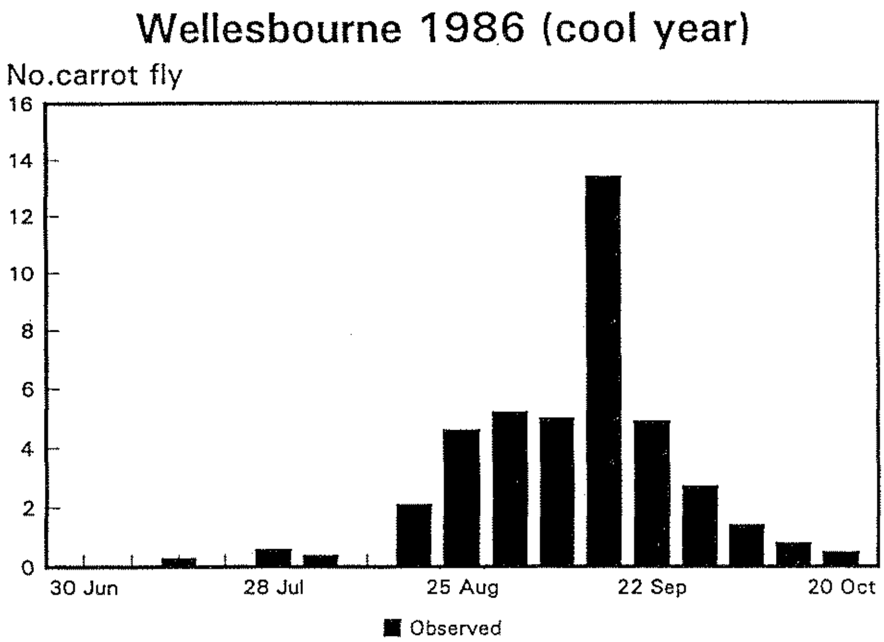


Figure 2. Second and third generation carrot fly activity at Wellesbourne in cool (1986) and warm (1990) years.



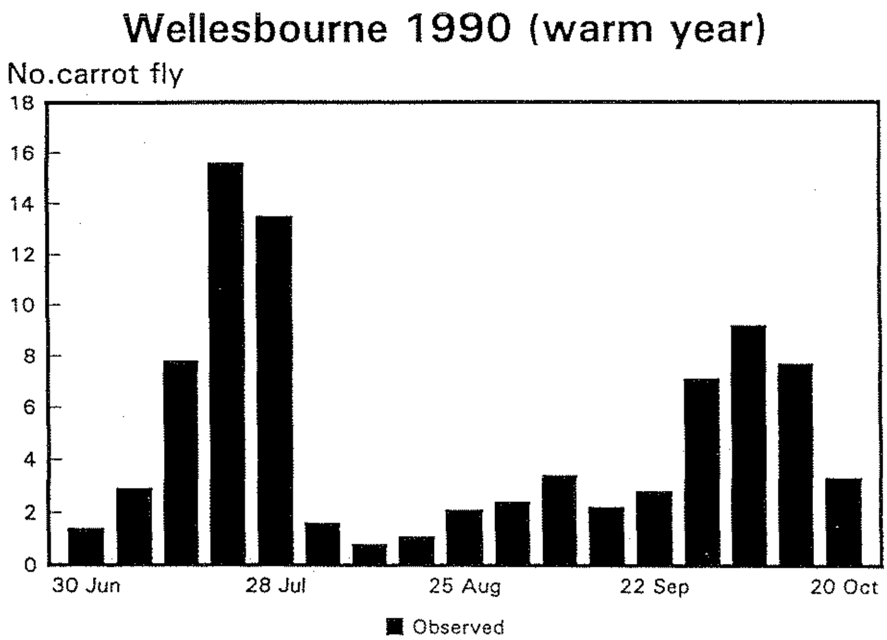


Figure 3. Observed and forecast first and second generation carrot fly activity at Wellesbourne in 1989 and 1991.

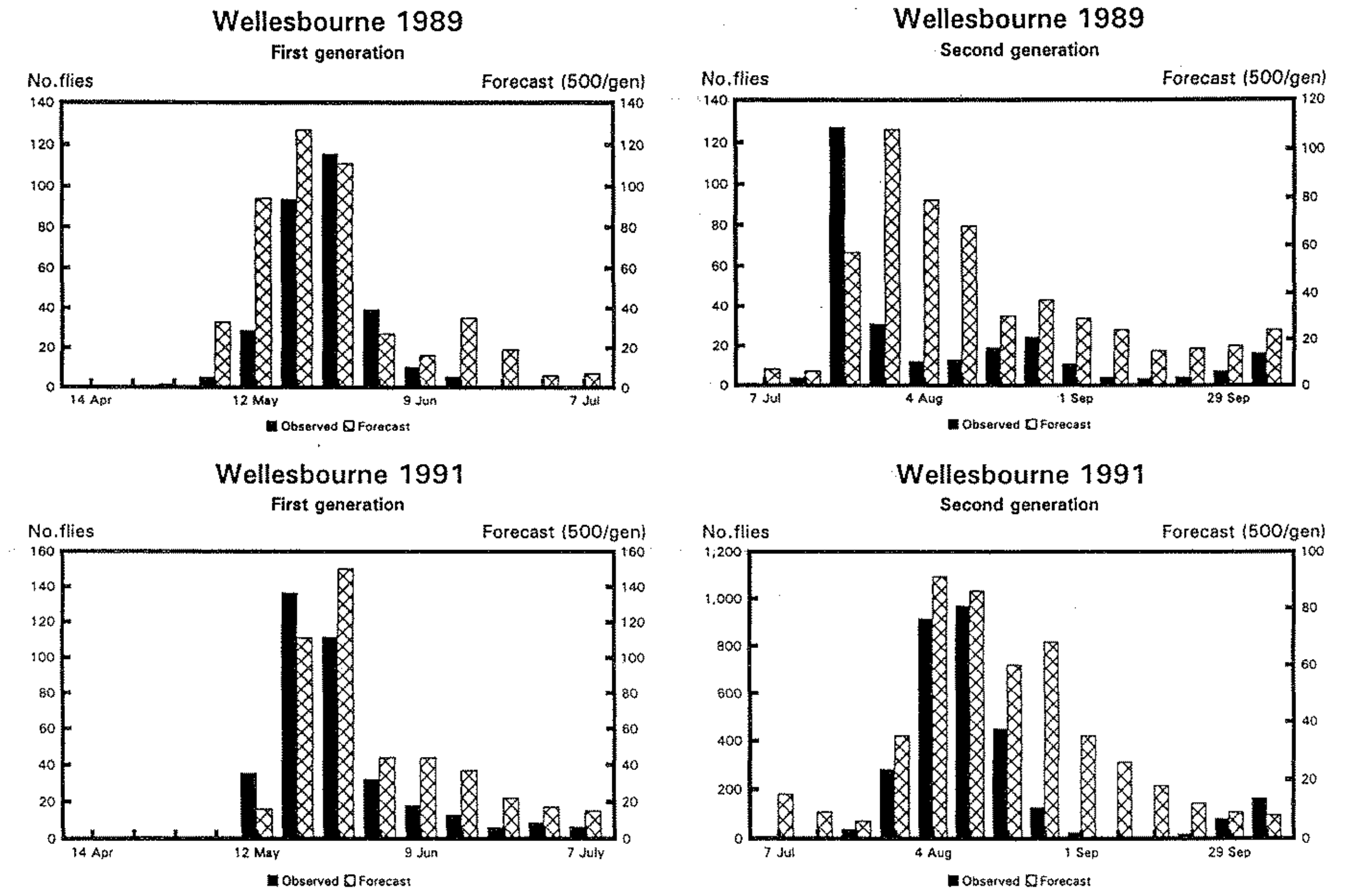
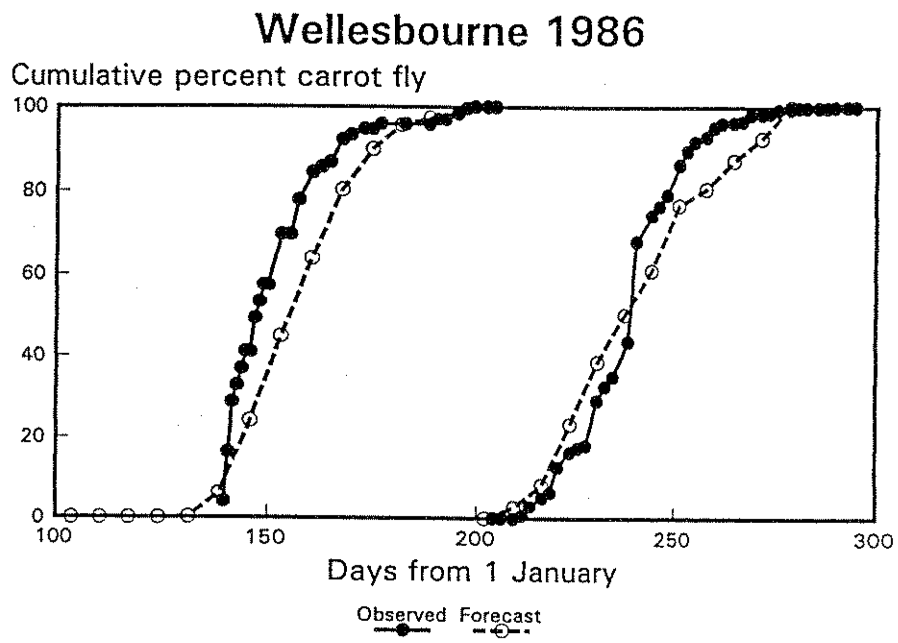


Figure 4. Observed and forecast first, second and third generation carrot fly activity at Wellesbourne in 1986 and 1990. Values plotted on a cumulative percentage scale.



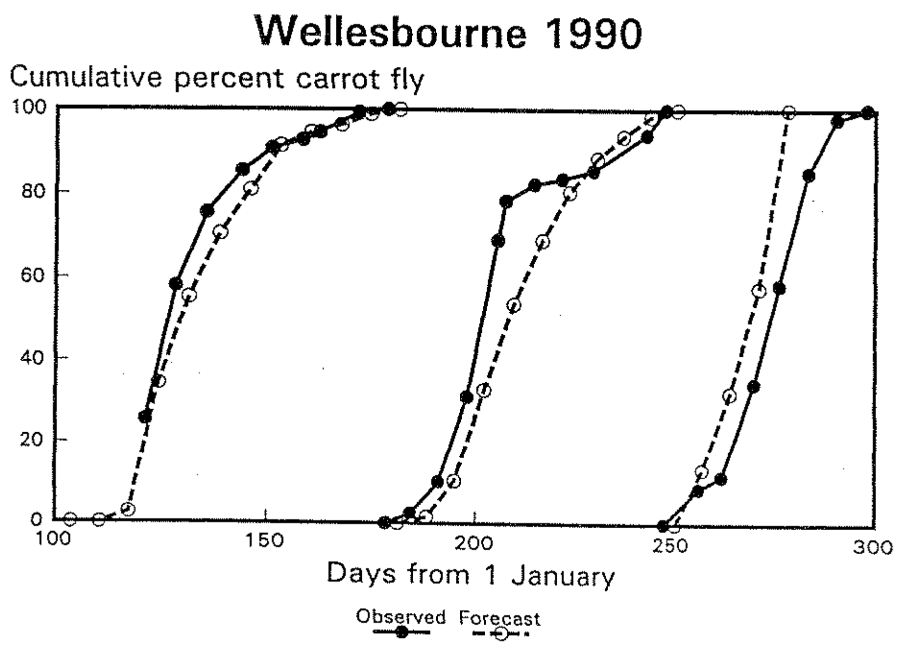


Figure 5. Observed and forecast times of 10% first and second-generation carrot fly activity at Wellesbourne (1981-83 & 1986-92 inclusive).

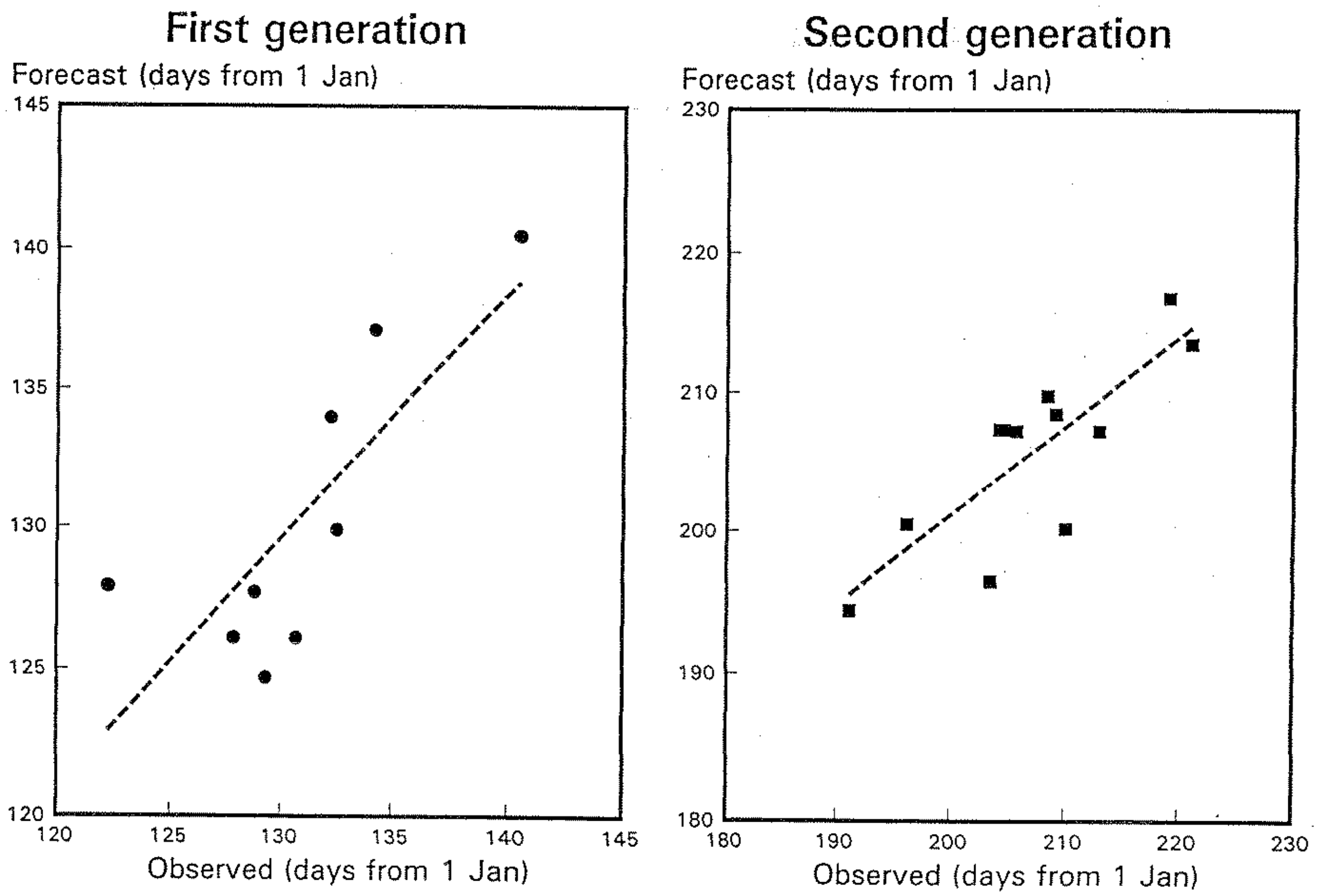
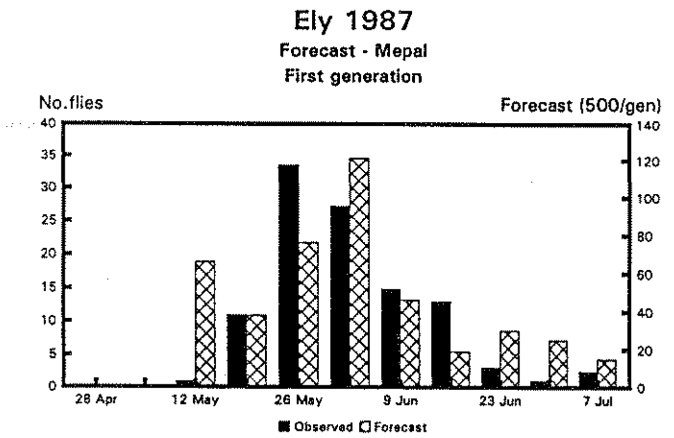
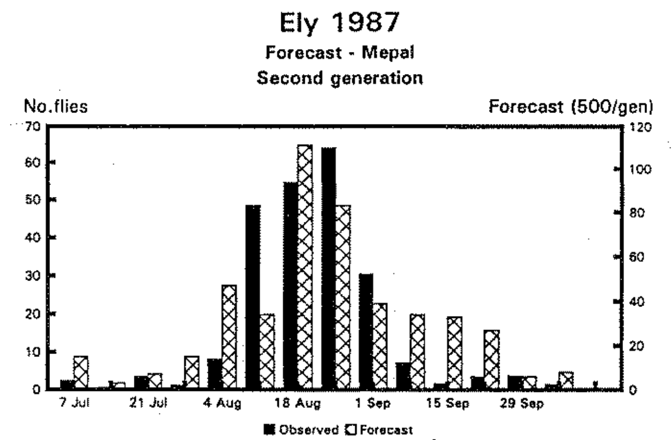
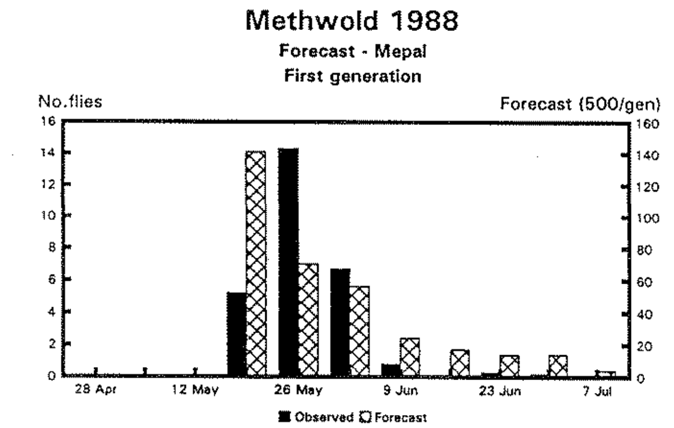
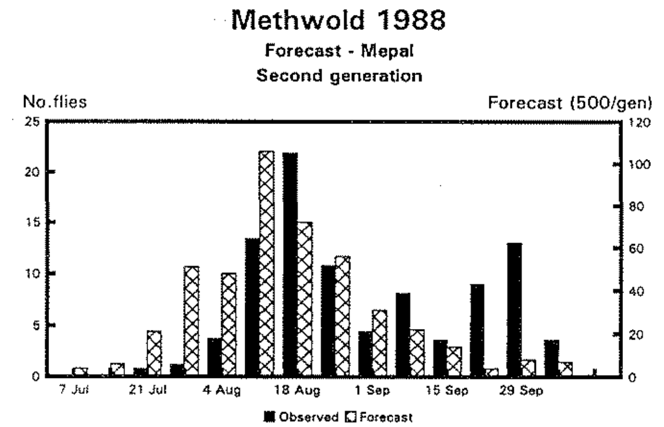


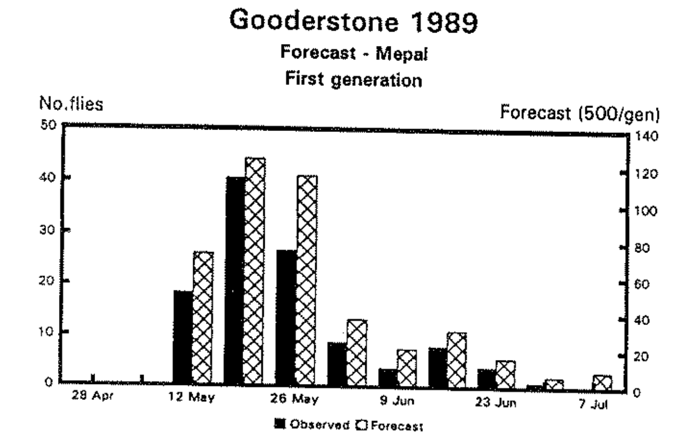
Figure 6a. Comparisons of observed and forecast carrot fly activity in the Fens from 1987 to 1989. Comparisons are made only for the period of carrot fly monitoring.

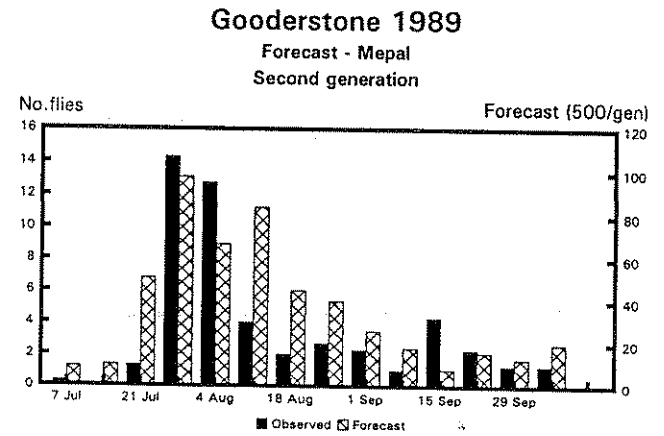


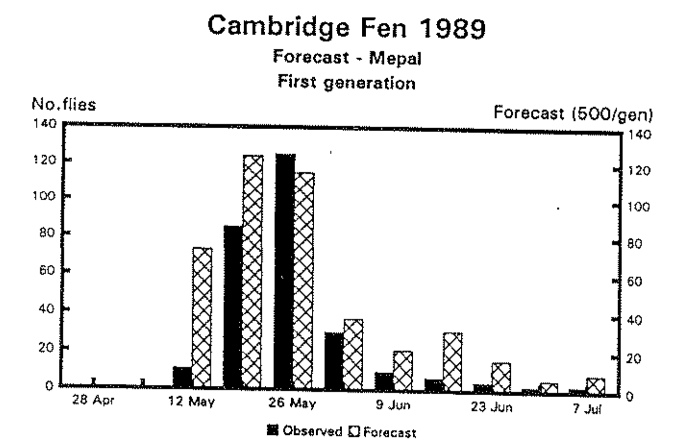












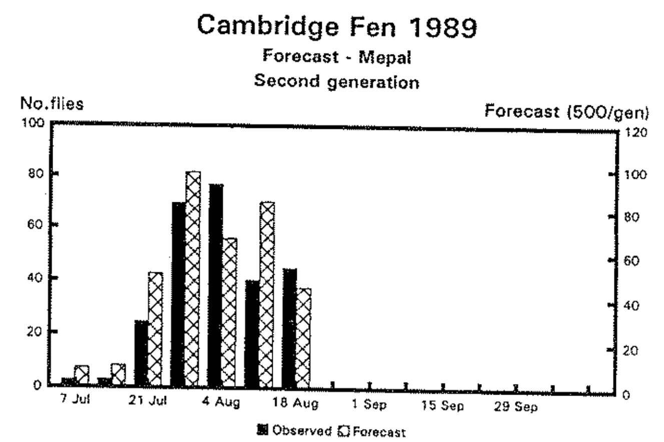


Figure 6b. Comparisons of observed and forecast carrot fly activity in the Fens in 1991. Comparisons are made only for the period of carrot fly monitoring.

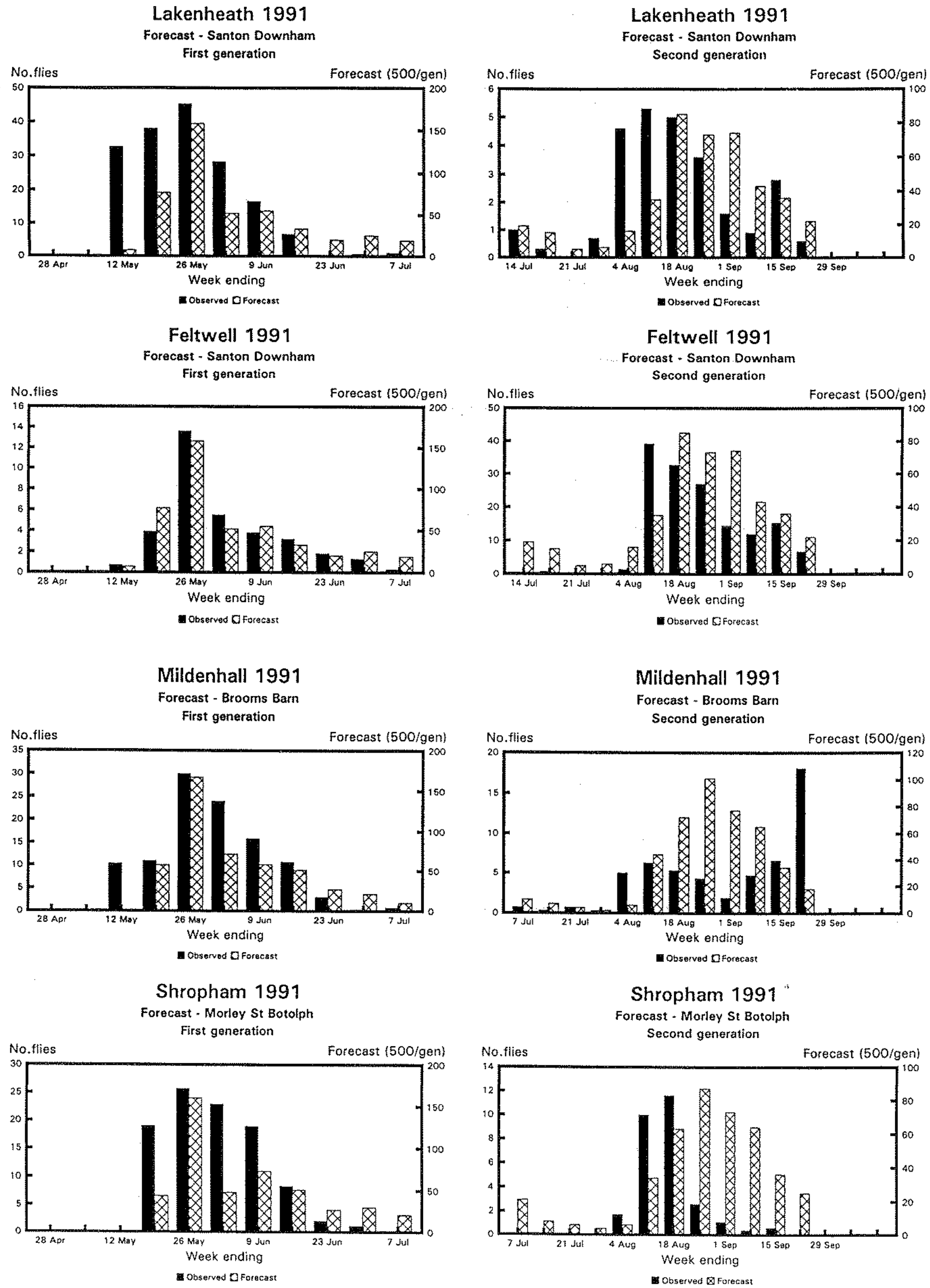


Figure 7a. Comparisons of observed and forecast carrot fly activity at a range of sites from 1973 to 1989. Comparisons are made only for the period of carrot fly monitoring.

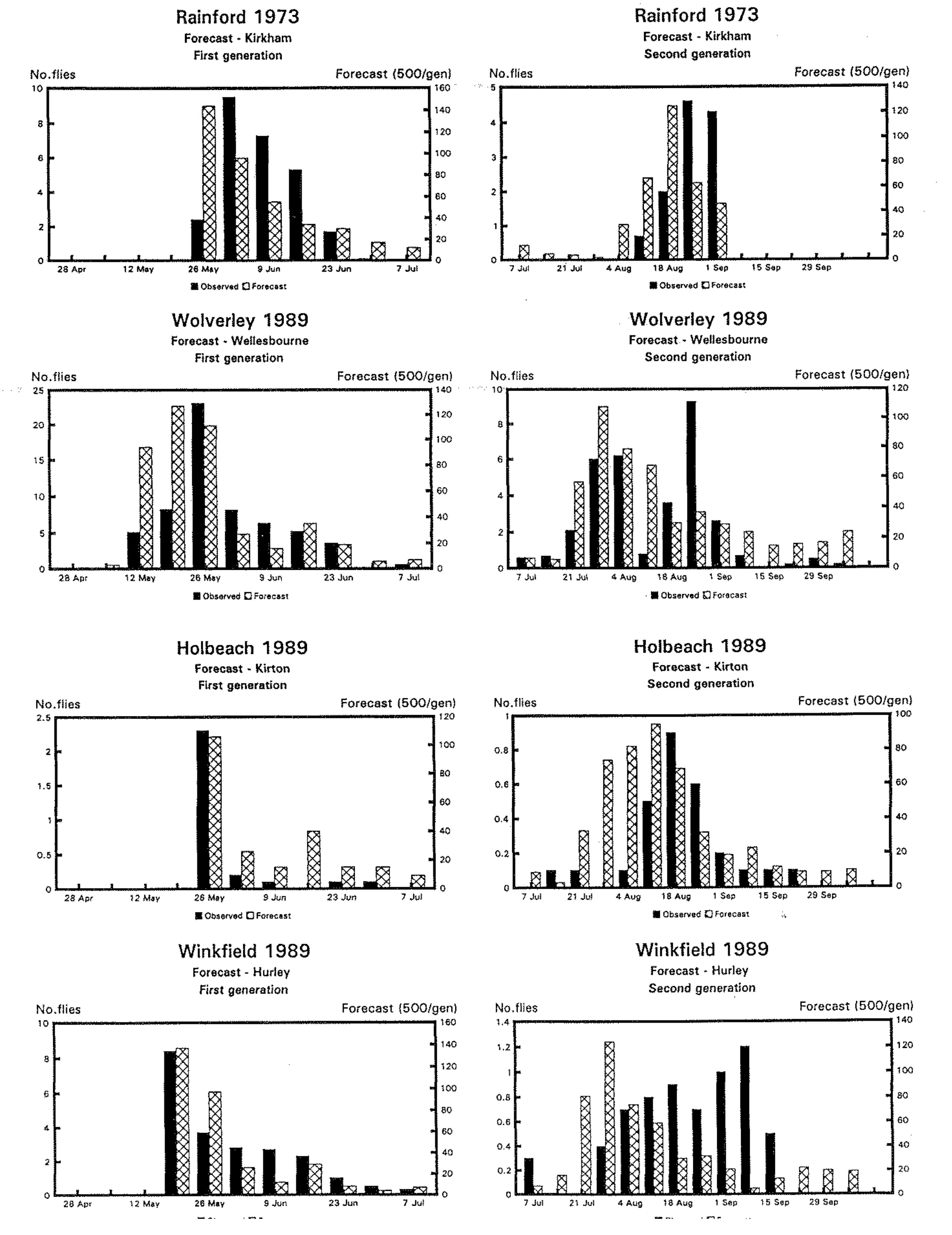


Figure 7b. Comparisons of observed and forecast carrot fly activity at a range of sites in 1991-92. Comparisons are made only for the period of carrot fly monitoring.

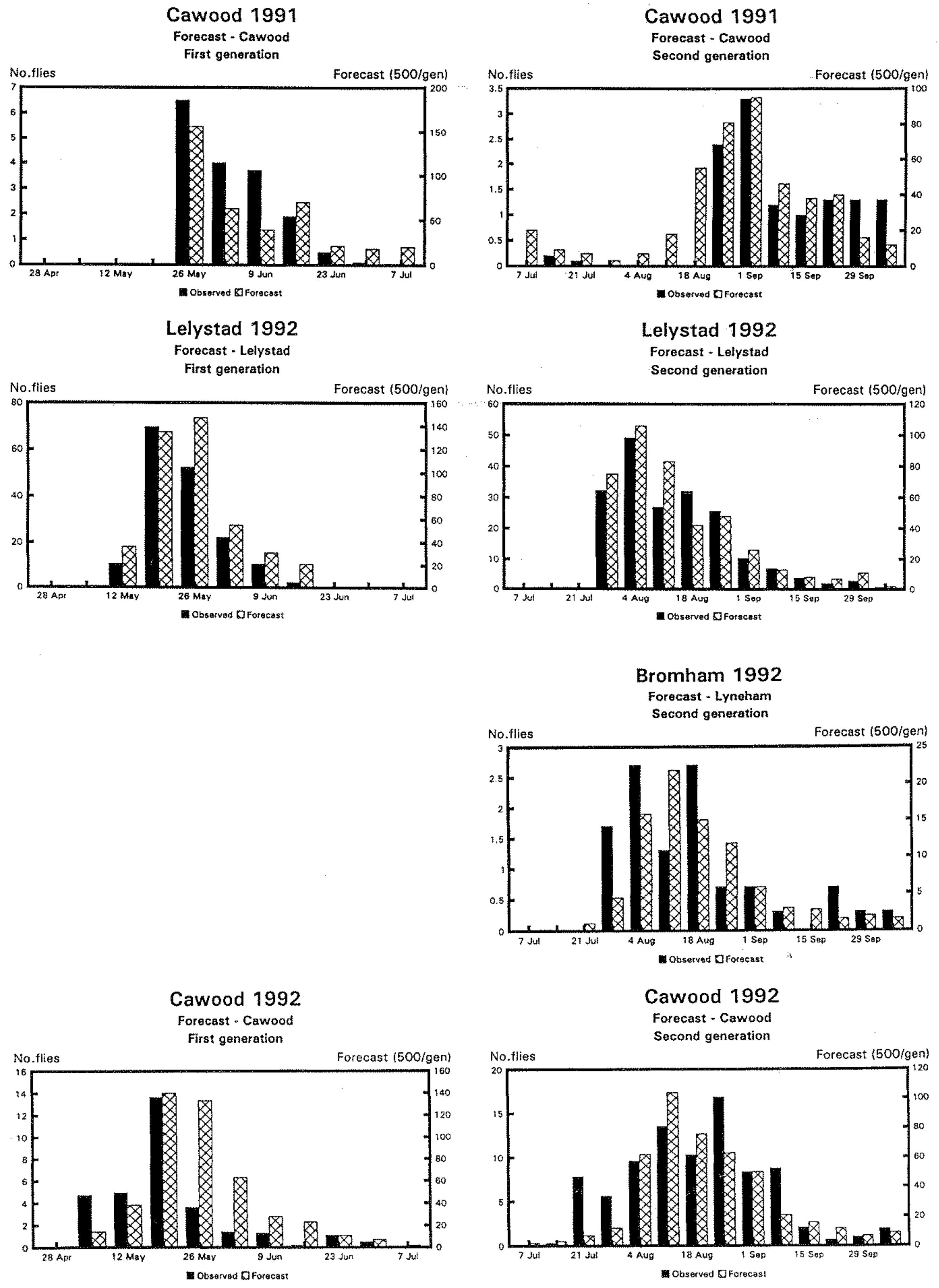


Figure 8. Observed and forecast carrot fly activity in south-west Lancashire in 1991. The forecast includes correction factors to account for the different dates the crops were drilled. Comparisons are made only for the period of carrot fly monitoring.

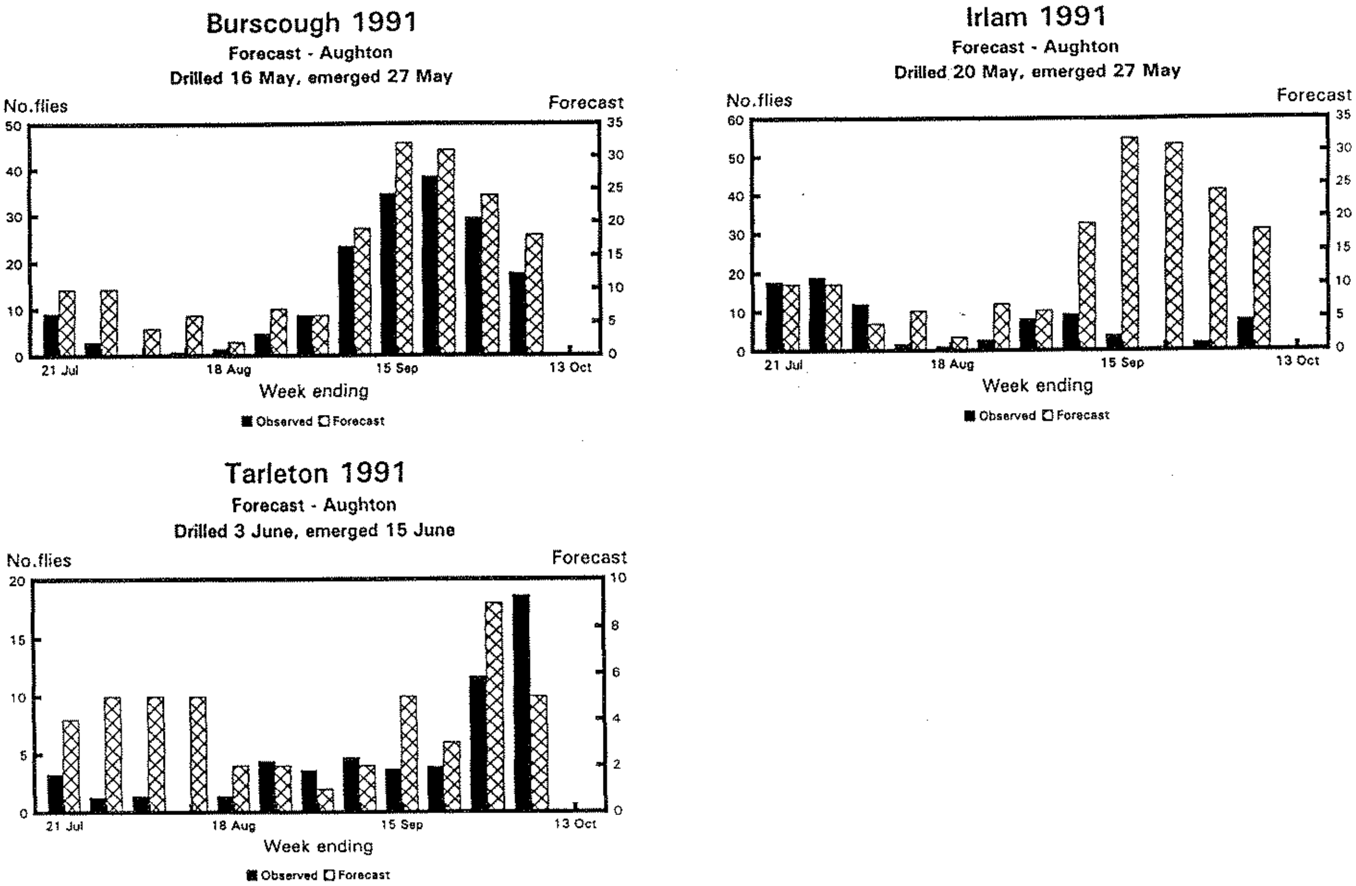
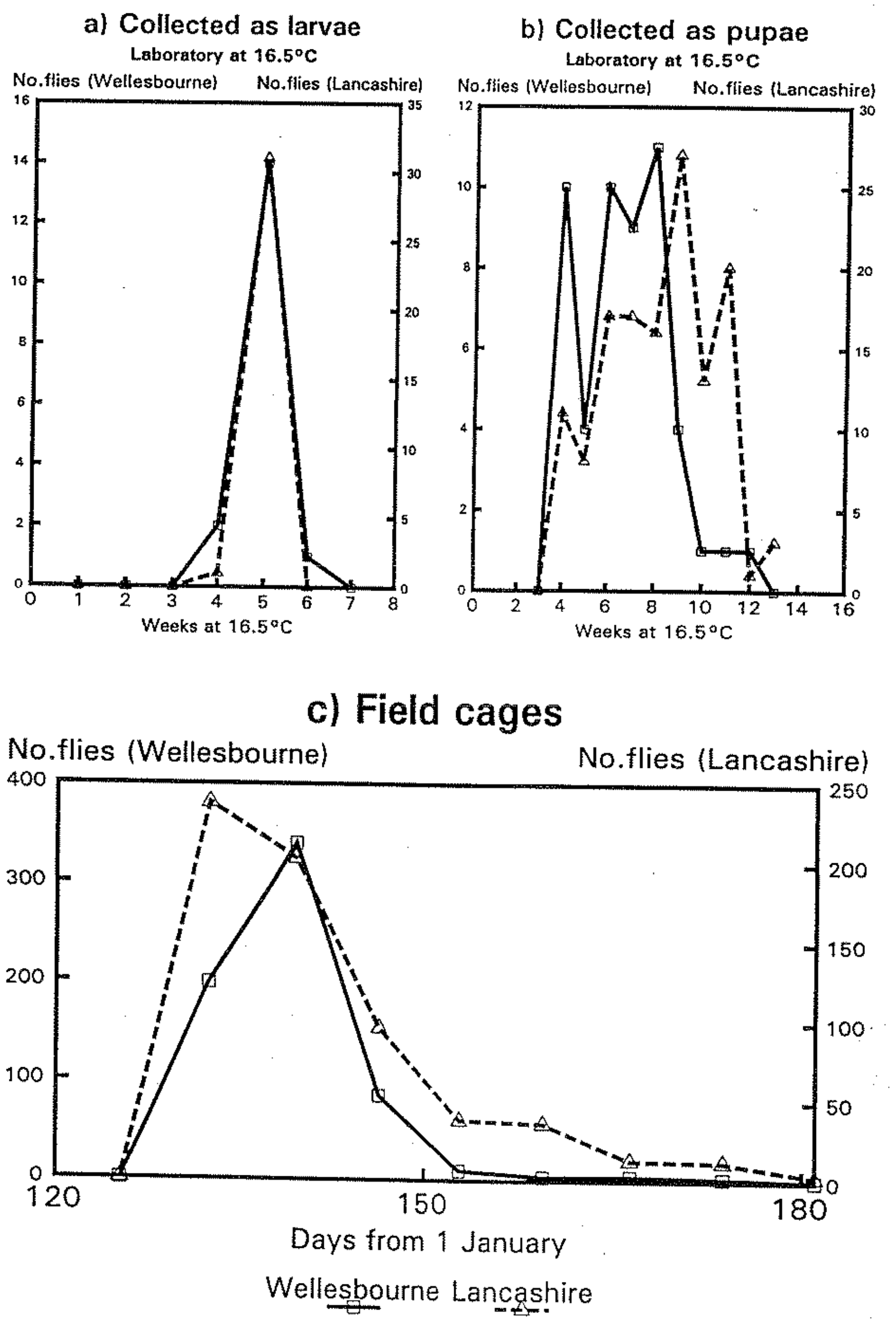


Figure 9. Emergence of carrot flies collected in Lancashire and at Wellesbourne during February 1992. Insects collected a) as larvae or b) as pupae were kept in the laboratory at 16.5°C or buried in field soil at Wellesbourne c) and covered by emergence cages.



Part 2. FORECASTING CABBAGE ROOT FLY ATTACKS

INTRODUCTION

The cabbage root fly, *Delia radicum*, is a major pest of brassica crops in Northern Europe and North America. In the UK, the fly completes between two or three generations each year, depending on climatic conditions. The first generation of cabbage root fly can usually be controlled effectively with insecticides applied to the soil at drilling or transplanting. However, sprays are usually required against the second and third fly generations, particularly on long-season crops like swedes. To be effective, these sprays must be applied to coincide with the most vulnerable stage in the life-cycle of the fly and this generally occurs as the eggs hatch and the newly-emerged larvae move through the soil to start feeding on the roots of plants.

In the past, several authors have used accumulated temperatures to forecast the timing of cabbage root fly activity. Originally air day-degrees, and more recently soil day-degrees, have been used to predict fly emergence and/or egg-laying activity. However, day-degree forecasts have severe limitations, as their accuracy is based on the assumption that the relationship between the rate of insect development and temperature is strictly linear. In addition day-degree forecasts can only be used to predict mean, peak or 50% activity of the population. They cannot be used to predict the spread of insect activity nor can they cope easily with populations that have more than one peak of activity. Extensive sampling of cabbage root fly populations throughout Northern Europe has indicated that cabbage root flies can be one of two biotypes, in which the flies either emerge 'early' (in April-May) or 'late' (in June-July). Within a particular locality, the insects may consist of only one biotype or be a mixture of the two.

Further problems in using day-degree models occur when attempts are made to interpret how changes in temperature or photoperiod induce the insects to enter either diapause or aestivation. Since there is considerable variation in the rates of development of the insects within a population, only a proportion of the population usually responds to a particular environmental cue at any one time. This is true of both cabbage root fly aestivation and diapause.

This report describes the development of a simulation model for forecasting the timing of cabbage root fly attacks. The model was developed to overcome some of the limitations imposed by forecasts based on accumulated day-degrees.

EXPERIMENTAL

1. <u>DEVELOPMENT AND VALIDATION OF THE FORECAST</u>

Data on cabbage root fly development, collected during 1980-87 with MAFF, AFRC and CEC funding, formed the basis of the cabbage root fly forecasting model. Additional information on the life-cycle, and further data on fly development times, were obtained from published studies.

The relationships between the rate of insect development and temperature were established for each phase of the insects life-cycle (e.g. spring emergence of early- and late-emerging flies, egg maturation, egg, larval and pupal development) by plotting the mean rate of development (100/time to completion of the stage) against temperature.

For those stages where rates of development were proportional to temperature, linear and non-linear (Gompertz) rate equations were fitted to the data to describe the relationship between rate of development and temperature. The most appropriate equation to describe each stage of development was selected by maximum likelihood analysis and inspection of residuals.

Equations for the following six phases in the life-cycle of the cabbage root fly formed the basis of the simulation model:

1. Development in the spring of pupae that give rise to early-emerging flies
2. Development in the spring of pupae that give rise to late-emerging flies
3. Pre-oviposition period - maturation of first batch of eggs
4. Maturation of second batch of eggs (by specified proportion of population)
5. Egg and larval stages
6. Pupal development

The equations were linked together in a FORTRAN program. The lower development thresholds were estimated by interpolation from linear equations or from other biological data. Upper development thresholds were set at 30°C, the extreme temperature normally experienced in the field.

The variation in the rate of insect development was estimated for each stage in the life-cycle of the fly. This was done using coefficients of variation (CV) derived from the mean and variance of the rates of development at each constant temperature under laboratory conditions. CVs were approximately constant. This variation was included in the model by simulating the development of groups of 10-500 individuals. At the start of each new phase of the life-cycle, each of the individuals was randomly allocated a personal development rate in such a way that at each temperature the resulting frequency distribution of rates was compatible with a normal distribution with the required mean and variance.

The forecast was started from 1 February, because this is normally the coldest time of the year. The percentage of early-emerging flies was specified at the start of the model. The model began with post-diapause development by overwintering pupae of both early- and late-emerging cabbage root flies. The percentage development of each individual insect was accumulated using the appropriate rate equations and hourly soil temperatures, until each stage was completed (100% development). The individual, now a newly-emerged adult, was then moved to the next stage, the pre-oviposition period. The simulation was run on this stage using the appropriate development equation and hourly air temperatures. Progress continued through each phase of the insects' life-cycle.

The model was used to predict cabbage root fly emergence and egg-laying activity throughout the year. It was used 1) to estimate the times of 10% and 50% activity in each generation, 2) the number of weeks when fly activity was high and 3) the likely occurrence of a third generation of flies.

Meteorological data used in the forecast

To model the development of egg, larval and pupal stages the cabbage root fly forecast required values of maximum and minimum soil temperatures at a depth of 6 cm. Maximum and minimum air temperatures were also required to model the period from adult emergence to oviposition, as this was the phase in the life-cycle that occurred out of the soil.

Standard temperature measures recorded at Agro-met stations include only the daily maximum and minimum air temperatures and a reading of the 10 cm soil temperature taken at 9.00 h. The appropriate maximum and minimum soil temperatures at a depth of 6 cm were therefore derived from standard temperature measures using empirical equations developed from field studies.

Size of the simulated population

The model was run with from 10 to 500 individuals, to determine the population size required to obtain repeatable simulations. A different random number seed was used for each simulation. A population of 500 individuals was chosen.

Numbers of insects sampled in the field

The number of insects required to produce a reasonable simulation also indicated the number of trapped insects required per generation to validate the forecast reliably. For robust validations, at least 100 flies (captured per three traps) or more than 100 eggs should be sampled during a generation.

Validation of the cabbage root fly forecast

The numbers of flies active in the field were monitored by capturing flies in fluorescent yellow water traps. The numbers of cabbage root fly eggs laid around the bases of brassica plants were recorded by sampling a 1-2 cm deep layer of soil containing the eggs, from around the bases of a standard number of plants. The eggs were extracted from the soil by flotation and counted.

Differences between years in fly activity at Wellesbourne

Changes in the numbers of flies and eggs at Wellesbourne were recorded at weekly intervals, or more frequently, from 1980 to 1992.

The simulation model used temperature data collected at Wellesbourne and was run for all years in which there were appropriate pest monitoring data. The goodness of fit of the model was estimated by comparing simulated insect activity, generated by the model, with actual insect activity, monitored in the field. The two or three broad peaks of insect activity that occurred annually were separated into generations, so that the data could be expressed as percentage insect activity during a generation. This enabled similar curves of insect activity to be produced for each generation and made the forecast independent of the vast changes in insect numbers that occur frequently from one generation to the next in certain years and/or localities.

The model was used to predict both the emergence and the egg-laying activity of cabbage root flies. First generation egg-laying occurred 2-5 weeks after fly emergence. Simulated emergence of the first generation agreed closely with field emergence recorded in emergence cages (Table 1) and simulated egg-laying activity agreed closely with field monitoring of female cabbage root flies and egg counts.

Between 1980 and 1992 at Wellesbourne, earliest first generation activity occurred on 30 April 1990 and latest activity on 8 June 1984. Earliest second generation activity occurred on 12 July 1989 and latest second generation activity on 5 August 1986. The average difference between observed and expected activity (50%) was 5.4 days for the first generation and 6.0 days for the second generation. Deviations of either the 10% or 50% activity dates were greater than 10 days on 2 occasions. In only one case were both the 10% and 50% times in error by more than one week. Figures 1a-d show observed and forecast cabbage root fly activity at Wellesbourne between 1980 and 1992. The two sets of data are plotted on separate scales, the monitoring data showing the actual numbers of eggs collected or flies trapped in the field and the simulations being based on a fixed population of 500 insects per generation.

Complete third generations (500 simulated flies) were predicted in 1989 and 1990 and large third generations did occur (i.e. more flies trapped than in the second generation) in these two years. Partial third generations (more than 20% of a complete generation, 100 simulated flies) were predicted in all other years apart from 1985 and 1986 when the third generation was insignificant.

Regional monitoring 1989

Cabbage root fly activity was monitored throughout the UK in 1989 to validate the forecasts at a range of different sites. This work was funded by MAFF. Adult cabbage root flies were trapped using yellow water traps and weekly catches were sent to Wellesbourne for sorting and counting. Figure 2 shows observed and forecast cabbage root fly activity at eight of the sites monitored in 1989.

Regions where early-emerging flies predominate

The majority of crops monitored were commercial crops subject to the normal regimes of pesticide application. With the exception of swede crops (mainly in the south west) pesticide sprays were not used against the cabbage root fly and so did not influence the numbers of flies trapped. Of the 33 sites monitored in each generation during 1989, more than 20 produced sufficient flies (100 flies trapped in three water traps per generation) to validate the forecast. A summary of the forecast validations is shown in Table 2. The mean absolute difference between observed and forecast first generation activity (50%) was 5.1 days. The difference between observed and forecast activity was greater than 7 days at 5 sites, but was always less than 10 days. The mean absolute difference between observed and forecast second generation activity (50%) was 5.8 days. The difference was greater than 1 week at six sites and greater than two weeks at one site.

Regions where late-emerging flies predominate

Cabbage root fly populations were monitored in swede crops in South Devon. The cabbage root fly forecast was run for the appropriate years using weather data collected at Starcross.

In previous years, pupal sampling of overwintering cabbage root fly populations in Devon had shown that they consist of a large proportion of late-emerging flies. This conclusion was confirmed at the five sites monitored in 1989. The forecast correctly predicted more or less continuous cabbage root fly activity throughout the summer, from late spring when the first flies emerged. The timing of activity of late-emerging flies is being investigated further in collaboration with colleagues at ADAS Starcross.

CONCLUSIONS

1. The timing of cabbage root fly generations can vary by as much as 3-5 weeks between years.

2. Cabbage root fly activity is earlier during warm years and in very warm years there may be a large third generation of flies.

3. The timing of cabbage root fly activity can be forecast using daily records of air and soil temperatures starting from 1 February.

4. The severity of cabbage root fly attacks in individual crops cannot be forecast, as this depends on the size of the local fly population.

5. The forecasts generally estimate the times of 10% and 50% fly activity to within a week of observed activity.

6. The forecast can be used to predict the timing of both early- and late-

emerging cabbage root flies. In areas such as Devon, where populations consist of mixtures of both early- and late-emerging flies, the risk of cabbage root fly attack can be virtually continuous from the start of the first generation.

7. The forecast can be used to predict both cabbage root fly emergence and egg-laying. At the time of the first generation, the flies emerge 2-5 weeks before they start to lay.

SUMMARY

For each stage of cabbage root fly development (egg, larva, pupa, adult) the relationship between the rate of development and temperature was described by a mathematical equation.

The equations relating the rate of cabbage root fly development to temperature were linked in a computer program that was used to forecast the timing of cabbage root fly attacks in the field. The program used air and soil temperatures collected locally. The accuracy of the forecasts was tested using sets of monitoring data collected from both experimental and commercial brassica crops.

ACKNOWLEDGEMENTS

We are grateful to growers, ADAS colleagues, particularly Dr J. Blood-Smyth, Mr B. Emmett and Dr W. Parker, consultants and scientific colleagues for providing us with valuable monitoring sites and data and to Mrs K. Phelps and Mr R. Reader for help in developing the computer model.

Table 1. Observed and simulated dates of peak of first generation cabbage root fly emergence.

Year	Peak fly emergence in field cages	Forecast 50% fly emergence	Difference (days) (obs - forecast)
1980	22 Apr	18 Apr	4
1981	12-15 Apr	8 Apr	4-7
1982	15-18 Apr	18 Apr	-3-0
1983	28-29 Apr	26 Apr	2-3

Table 2. Results obtained from the monitoring data used to validate the cabbage root fly forecast during 1989.

	First generation	**Second generation**
Number of sites	25	22
Mean difference in 10% activity (days)	4.1	4.5
No. sites with error > 1 wk	1	1
No. sites with error > 2 wk	0	1
Mean difference in 50% activity (days)	5.1	5.8
No. sites with error > 1 wk	5	6
No. sites with error > 2 wk	0	1

Figure 1a. Observed and forecast first generation cabbage root fly activity at Wellesbourne from 1980 to 1987. Comparisons are made only for the period of cabbage root fly monitoring.

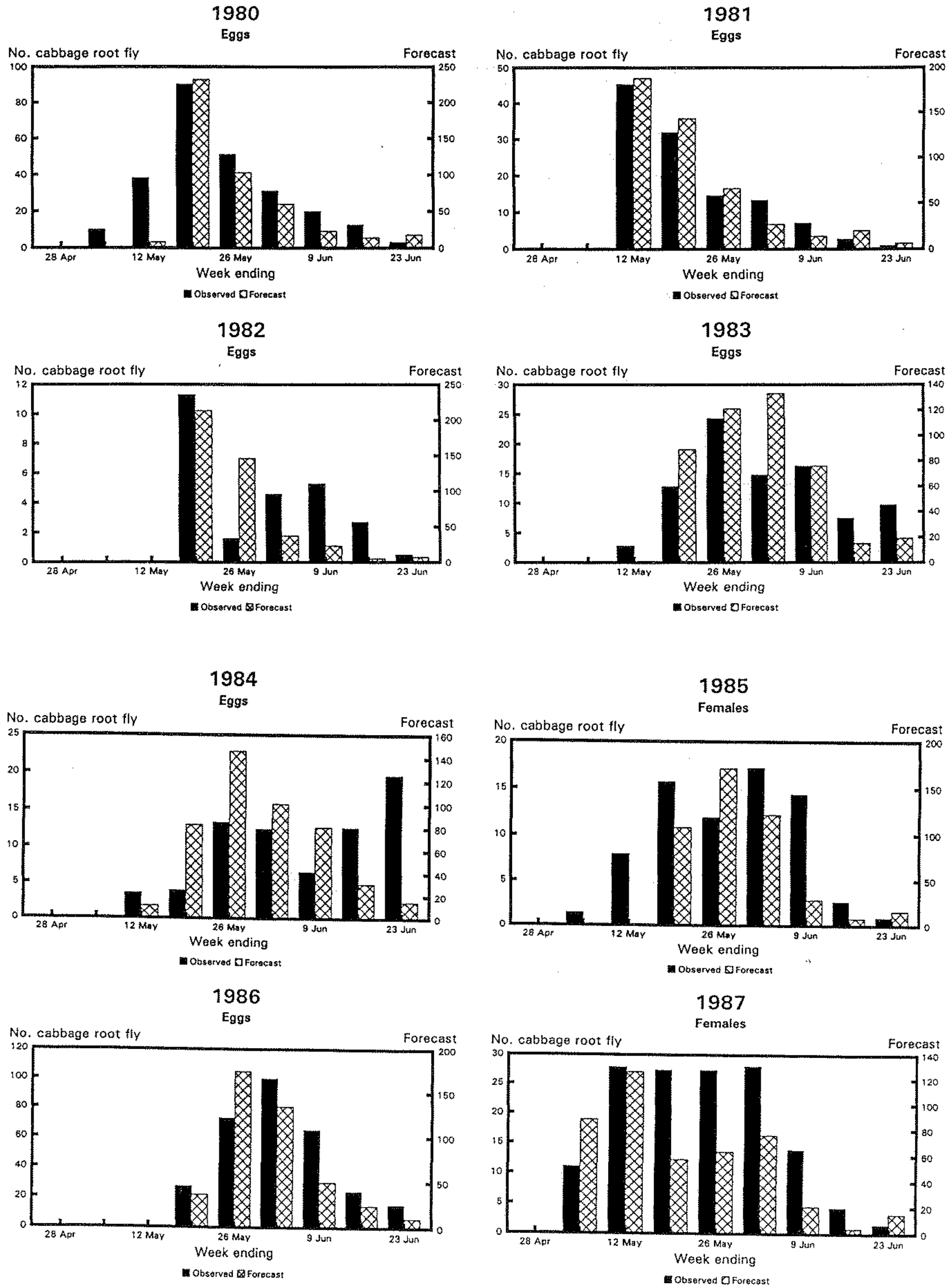
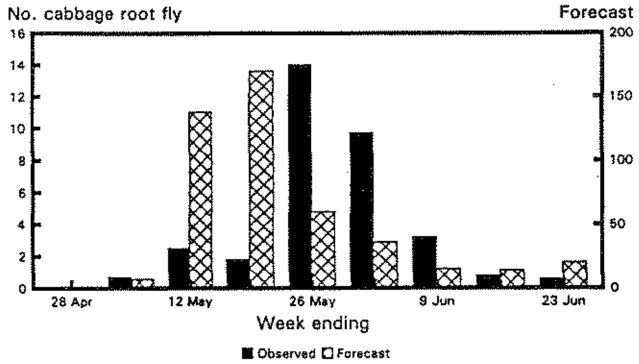
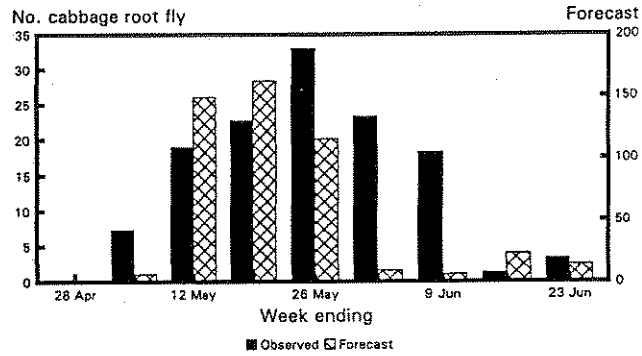


Figure 1b. Observed and forecast first generation cabbage root fly activity at Wellesbourne from 1988 to 1992. Comparisons are made only for the period of cabbage root fly monitoring.

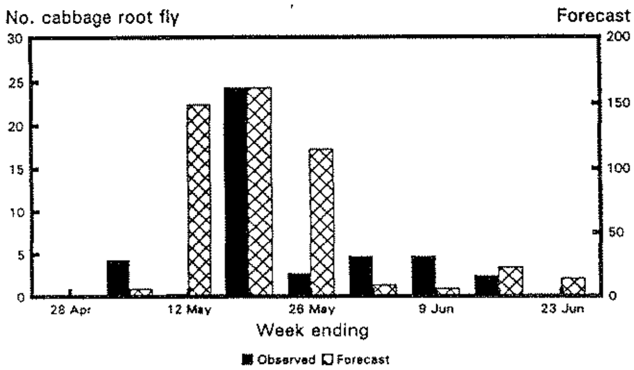
1988
Eggs



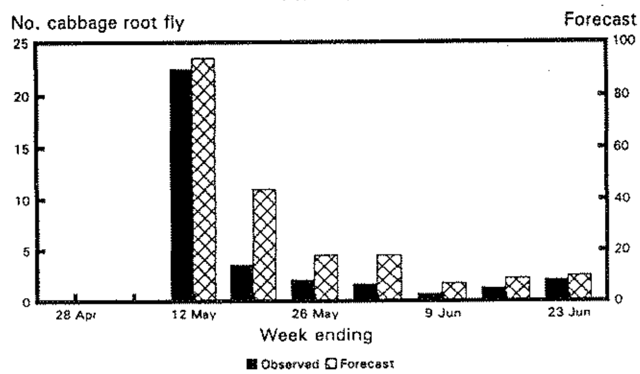
1989
Females



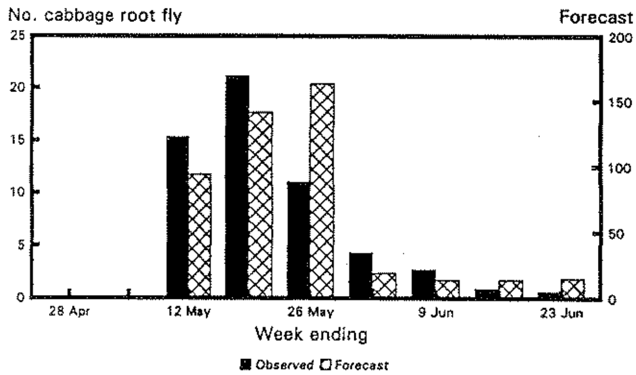
1989
Females



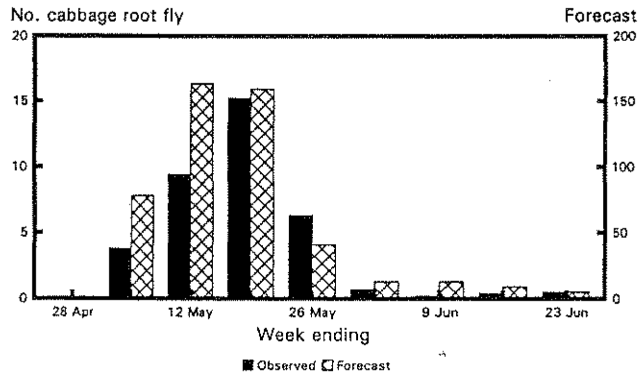
1990
Females



1991
Females



1992
Eggs



1992
Females

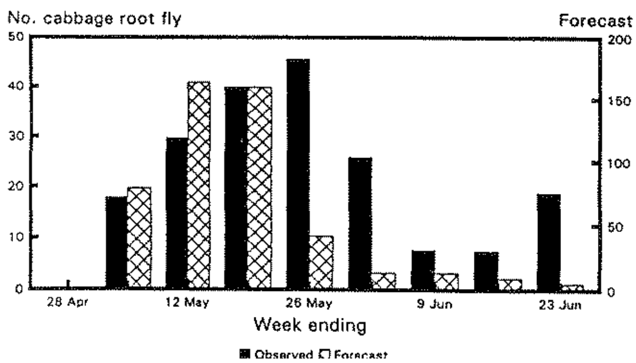


Figure 1c. Observed and forecast second and third generation cabbage root fly activity at Wellesbourne from 1980 to 1987. Comparisons are made only for the period of cabbage root fly monitoring.

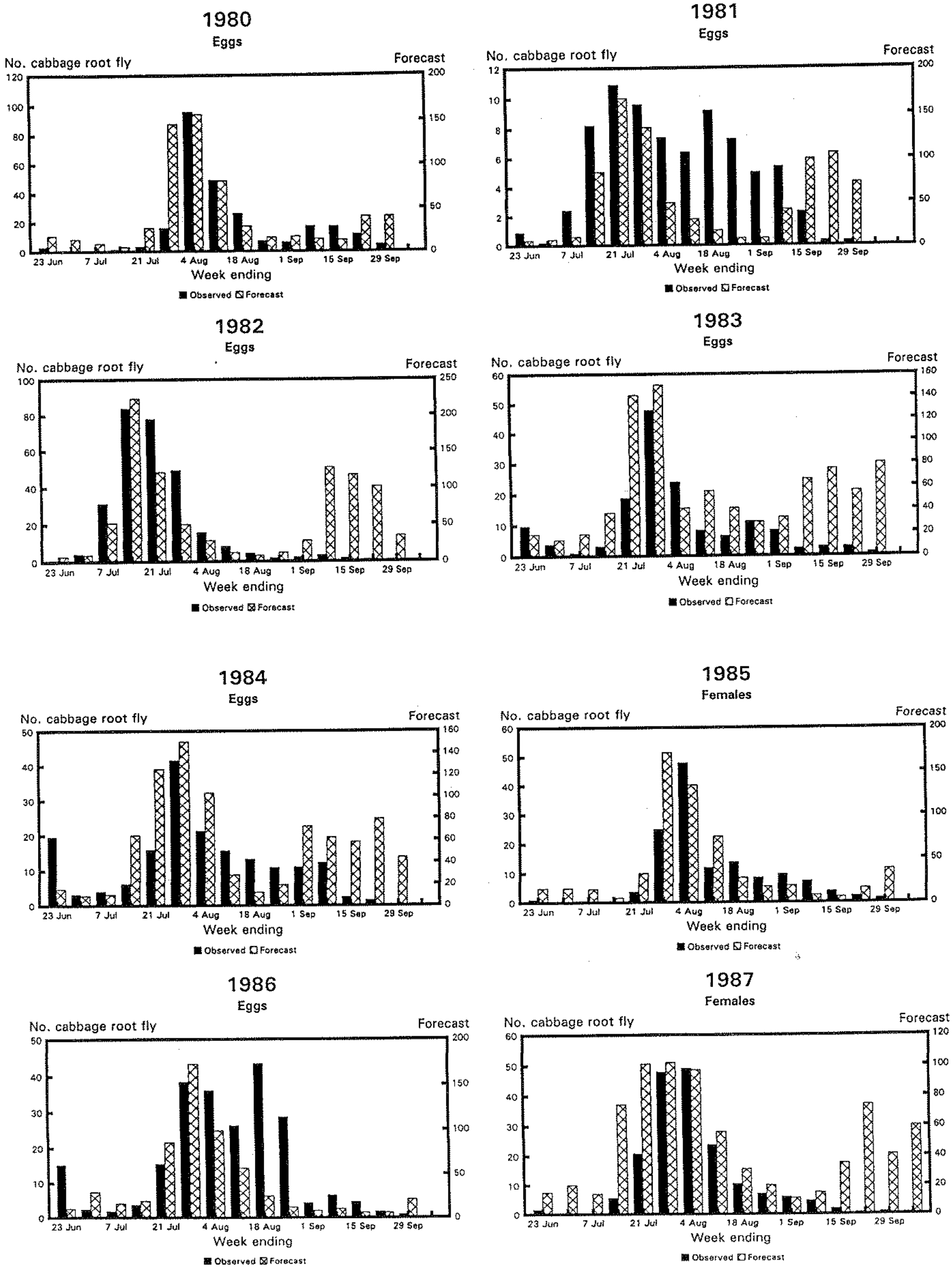


Figure 2. Observed and forecast cabbage root fly activity at eight monitoring sites in 1989. Comparisons are made only for the period of cabbage root fly monitoring.

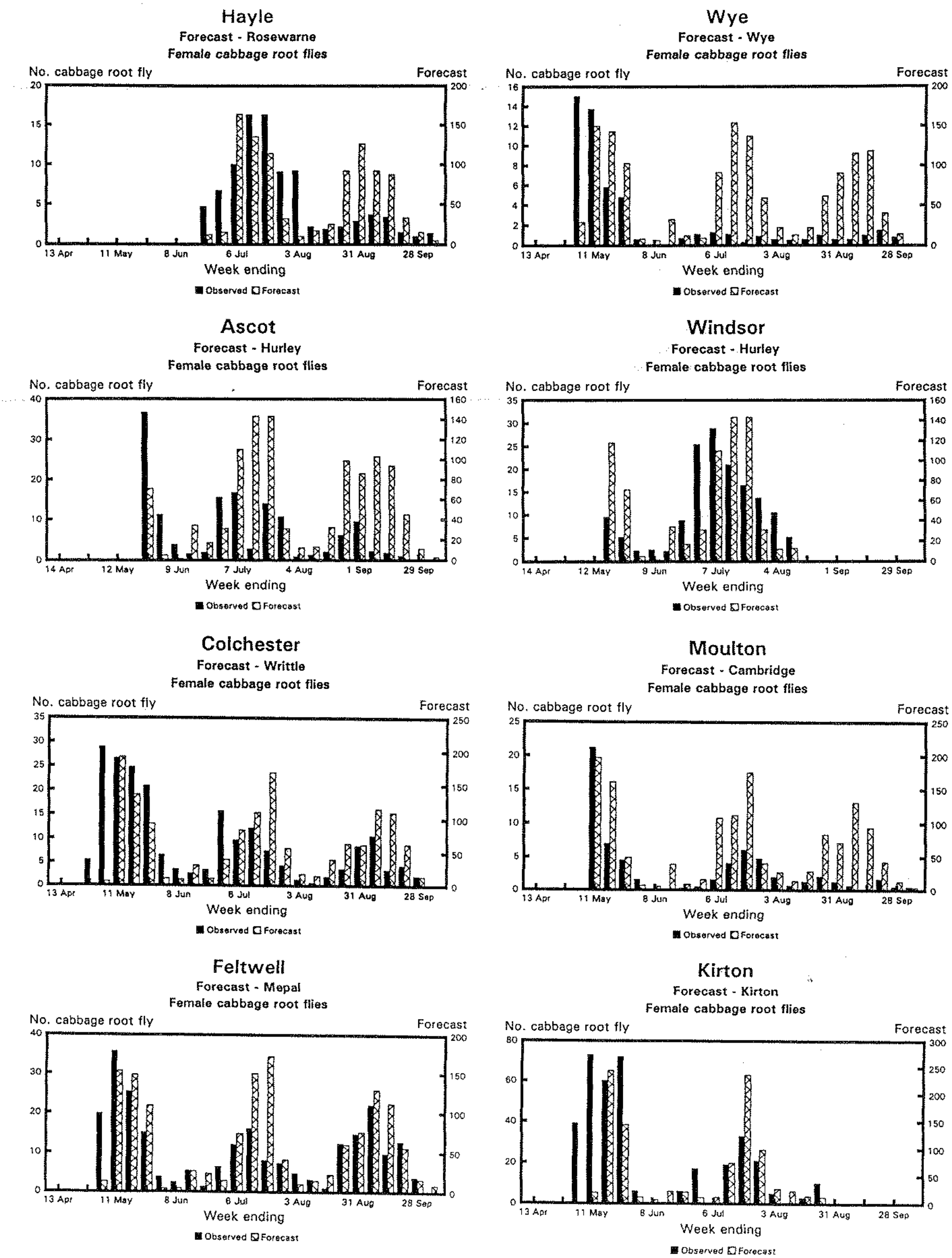
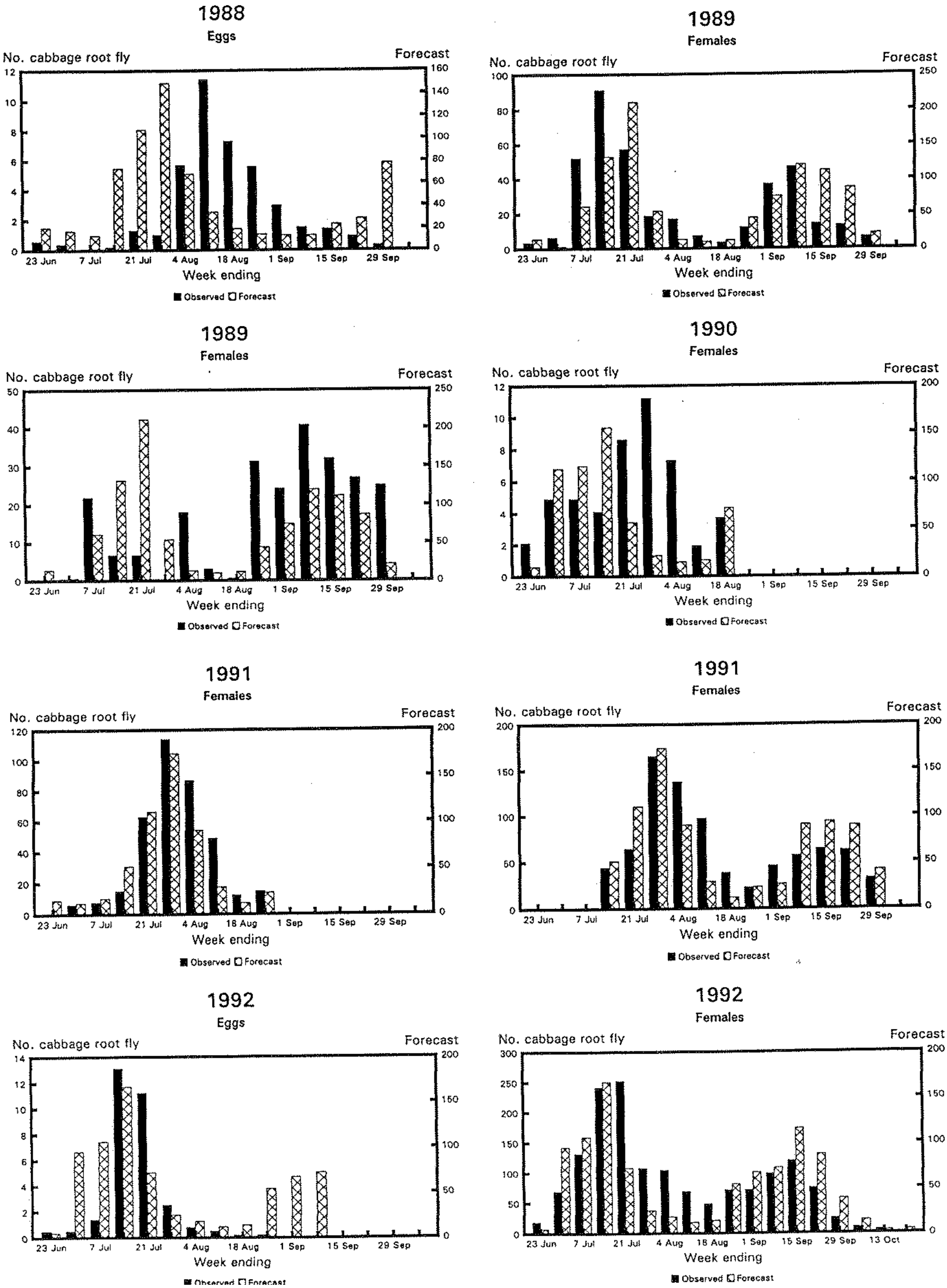


Figure 1d. Observed and forecast second and third generation cabbage root fly activity at Wellesbourne from 1988 to 1992. Comparisons are made only for the period of cabbage root fly monitoring.



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