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Project Report No. 504

Development of an integrated pest management strategy for control of pollen beetles in winter oilseed rape

by

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CONTENTS

1. ABSTRACT

We have developed an integrated pest management strategy (IPM) for pollen beetles in winter oilseed rape (OSR) based on risk assessment, monitoring and alternative crop management that can be used as a framework by growers and crop consultants to manage pollen beetles with reduced insecticide inputs - and the confidence to do so. This will prolong insecticide life by reducing selection for resistance, reduce environmental impacts and contribute towards the sustainability and profitability of OSR in the UK. One of the major limitations to the use of action thresholds is that proper monitoring of the populations is time consuming and has to be conducted over a prolonged period. To encourage and facilitate their use, we tested and developed tools to improve risk assessment and monitoring. We conducted a pollen beetle monitoring study over 4 years in 178 OSR crops across the UK. Pollen beetles were sampled using sticky traps and plant sampling along transects in the crop. The data were used to help test a decision support system (DSS) for pollen beetles and to develop a monitoring trap. proPlant Expert is a DSS available in mainland Europe that uses a model of pollen beetle immigration and local meteorological data to forecast the start and end of pollen beetle immigration into the crop and main risk periods and advises when to monitor. We tested the model under UK conditions using data from our study and compared monitoring advice with the current advice system on the CropMonitor website (advises monitoring when the crop is at green-yellow bud stage and temperature >15°C). Both performed reassuringly well in prompting monitoring that would detect breaches of spray thresholds. However there were considerable reductions provided by proPlant in the need for consultation of the system (30%) and advised monitoring days (34-53%) in comparison with current advice. Use of the proPlant DSS could therefore focus monitoring effort to when it is most needed. It could also help to reduce unnecessary sprays in cases where beetle numbers are *approaching* threshold but consultation of the system returns a poor immigration risk forecast or an immigration complete result. The proPlant tool is now freely available to growers and crop consultants in the UK via the Bayer CropScience website. A monitoring trap for pollen beetles would help to more easily and accurately identify when spray thresholds have been breached than monitoring plants in the crop. We developed a baited monitoring trap for pollen beetles which will be commercially available from Oecos. The trap comprises a yellow sticky card mounted at 45°, baited with phenylacetaldehyde, a floral volatile produced naturally by several plant species. Unfortunately using data from our study we were unable to calibrate the trap catch to a given action threshold expressed as the number of beetles per plant using a simple linear relationship. However, the monitoring trap still has value for risk assessment, especially if used together with DSS. We tested the potential of turnip rape (TR) trap crops, planted as borders to the main OSR crop to reduce pollen beetle numbers in a field scale experiment conducted over three years on two sites. We found evidence that the strategy worked well in some years, but not others. This tactic is probably practically and economically worthwhile only for organic growers.

2. SUMMARY

2.1. Introduction/Background and aims

Resistance to pyrethroid insecticides in pollen beetles (*Meligethes aeneus*), a major pest of oilseed rape (OSR), is now widespread in Europe including the UK. Pollen beetles are almost exclusively controlled by pyrethroids, many applied prophylactically and sometimes repeatedly, exerting selection pressure for resistance. At a time of increasing demand for rapeseed oil for biofuel and food use and as increasing areas are grown, the risk of resistance presents a significant threat to the sustainability of the UK OSR crop and to farm incomes. Measures are urgently required to ensure that insecticide treatments are used only when required and to optimal effect.

If we examine data on the historic number of pollen beetles per plant and relate them to the action thresholds of the time (5 or 15 beetles/plant), it is clear that pyrethroids are often sprayed unnecessarily, as action thresholds are rarely breached in the UK. Because of their relatively low cost, many treatments are probably applied prophylactically in tank mixes with spring fungicides. Many growers and crop consultants are reluctant to use monitoring methods and action thresholds due to time constraints and may lack confidence in them. Current advice on monitoring the population of beetles in the crop recommends that at least 10 plants should be sampled along a transect at least 30m long starting from the headlands towards the centre of the crop. However the crop is often at its damage-susceptible green-yellow bud stage for several weeks and pollen beetle immigration occurs sporadically over prolonged periods of c. 4 weeks; so monitoring is time consuming and requires several visits to the field to do properly. Better risk assessment and decision support could help to focus monitoring effort to when it is most needed, but systems used by our competitors in mainland Europe that forecast the risk of immigration up to 2 days in advance were not available in the UK before this project.

Where thresholds are used, they may be inaccurate as the number of beetles active on the crop (that can be dislodged easily) depends on weather conditions and the time of day of the sample. Plant sampling represents only a snapshot in time of what is cumulative immigration. Furthermore as pollen beetles are not evenly distributed on the crop, the average number derived from plant sampling may depend on where in the field transects are selected. It is possible that the numbers of beetles per plant are often overestimated, especially if, for ease, plants are selected for crop monitoring mainly from the crop edge. Beetles are naturally more abundant here as they infest the crop from the edges. Reliable, quick and simple methods of monitoring densities of pollen beetles are therefore needed. Easy to use, accurate monitoring traps for pollen beetles would help to refine the identification of threshold levels of these pests, but there were none commercially-available before this project.

In 2007 the European Plant Protection Organization (EPPO) workshop on insecticide resistance of pollen beetles on OSR produced a set of recommendations to help reduce selection for insecticide resistance in pollen beetle. As well as recommending the reduction in number of applications through use of action thresholds, it was recognized that clear and scientifically robust methods of monitoring populations were needed to achieve this. It was also highlighted that non-chemical control measures needed to be developed including trap cropping. This meeting was the stimulus for the current Project.

Aims

This project aimed to develop an integrated pest management (IPM) strategy for control of pollen beetles based on monitoring, risk assessment and crop management to reduce the number of insecticide applications and area treated, thereby maximising profit margins, and minimising development of resistance and the environmental footprint of pest control.

Objectives

1. Develop and test monitoring and risk assessment systems for pollen beetles to enable use of action thresholds

Task A. Develop a reliable monitoring trap for pollen beetles to enable easy and effective detection of threshold levels of these pests

Task B. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle

Task C. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape

2. Demonstrate the extent to which trap cropping can reduce the number of insecticide sprays applied and area treated

Task D. Evaluate on a field scale the potential of a turnip rape trap crop for reducing the abundance of pollen beetles in winter oilseed rape crops

Task E. Assess the cost effectiveness of the trap cropping tactic

3. Develop a future IPM strategy for pollen beetles in winter oilseed rape

Task F. Initiate a programme to develop a trap cropping strategy based on winter oilseed rape to replace the less practical turnip rape component

Task G. In small plot experiments test any plants derived from Task F for their relative attractiveness to pollen beetles compared with turnip rape cultivars used in Objective 2

Task H. Propose an IPM strategy for controlling pollen beetles in winter oilseed rape based on the combination of the most effective elements tested in this project

2.2. Materials and methods

2.2.1. Develop a monitoring trap for pollen beetles (Objective 1, Task A)

Investigate responses of pollen beetles to colour to optimize trap colour

The general mechanisms underlying pollen beetle colour choice behaviour were investigated to optimize trap colour. The electrophysiological responses of the pollen beetle light receptors in the eye to light flashes given at varied wavelengths and intensities were measured using the electroretinogram technique in the laboratory. In the field, attraction (landing response) of pollen beetles to colour cues was tested using coloured water traps with known spectral reflectance. One hundred water traps (two each of 50 different colours) were placed in the field in a randomized design. The number of pollen beetles in each trap was recorded after 24h. A colour choice model was developed using data from the results the two experiments.

Identify and develop semiochemical lures for a monitoring trap with minimum catch of non-targets

Several field experiments were performed to test the best coloured trap to maximise pollen beetle catch while minimizing catch of non-target parasitoids, and to find the most effective volatile lure to bait the trap. In the final year, a commercial trap mount and dispensers for the bait were field tested against those used in experiments in years 1-3.

To compare beetle and parasitoid response to colours, white and blue sticky card traps (Oecos) and a prototype trap painted grass green were compared to a standard yellow sticky card trap, each with and without a 2-phenylethyl isothiocyanate lure (2-PE ncs; this is a compound released by damaged OSR plants which has been found in previous experiments to be very attractive to pollen beetles, but it is toxic so not ideal for a lure for a commercial trap). For experiments testing the volatile baits, each experiment comprised yellow sticky card traps (Oecos) which were either unbaited (control) or baited with test compounds or a lure of 2-PE ncs. To identify new compounds as potential lures, the volatiles of 10 different OSR types were collected by air entrainment. Compounds that were detected by the beetles in electrophysiological experiments were tested at different release rates in the field. In the final year, the experimental dispensers used in years 1-3 to release the lures were tested against commercial dispensers obtained from International Pheromone Systems (IPS). In each experiment, experimental traps were angled at 45° to the vertical using a plastic mount and raised to crop canopy height using a metal post. In the final year this system was tested against the commercial angled mount for the carrot fly trap produced by Oecos. In all experiments traps were placed 10m apart from each other in any direction and set out in a randomized orientation in OSR crops. Sticky cards were changed approximately weekly from the green bud stage of the crop until it was fully in flower and insects were identified and counted in the laboratory.

Calibrate trap catch with numbers of beetles per plant in oilseed rape crops to enable use of action thresholds

Pollen beetle monitoring study This experiment addressed 3 experimental aims:

1. To establish a relationship between the numbers of pollen beetles caught on traps with the number of beetles per plant in the OSR crop (this section)
2. To establish a relationship between trap catch and position of the trap with respect to prevailing wind direction and surrounding landscape features (see the following subsection)
3. To assess the relationship between immigration of pollen beetles into the OSR crop through time relating to climatic conditions and the growth stage of the crop (phenology) (see Section 2.2.2)

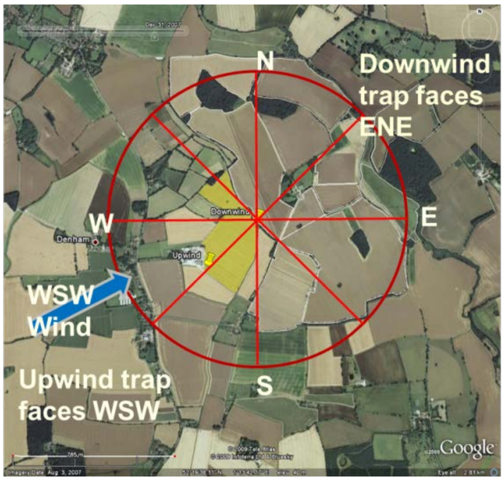
We ran a pollen beetle monitoring study in each of the 4 years of the project (2008-2011). In each year, winter OSR fields were selected on Rothamsted Farm, Woburn Farm and on as many other farms as possible across the UK. At each site, two yellow sticky traps were placed on different sides of the field; one was placed upwind and the other downwind along the plane of an assumed west-south-west prevailing wind. The traps were angled at 45° and placed on top of a metal pole so that the trap could be maintained at crop canopy height throughout the trapping period. Traps were placed 3m into the crop from the edge and orientated to face away from the crop centre, in order to trap incoming beetles. Monitoring started on March 1st each year and continued until the crop was at BBCH growth stage 61. Traps were changed either once or twice each week. Each time the traps were changed the growth stage of the crop and weather variables were recorded then the average number of pollen beetles per plant in the crop at each trap position was calculated from 10 plants selected at random every ~5m along a 50m transect from the crop edge towards its centre. Volunteers were also asked to map the positions of the traps on the study field, and provide information on the surrounding landscape within a 1km radius of each trap/transect, including positions of OSR crops in both the current and previous year.

Correlation analysis The following correlations were calculated: between pollen beetle numbers on traps vs. numbers on plants in the crop; between upwind traps vs. upwind numbers in the crop; between downwind traps vs. downwind numbers in the crop. We also calculated correlations between pollen beetle numbers in upwind vs. downwind traps; and between numbers on plants in the crop on upwind vs. downwind. Analyses were restricted to data recorded from crops at the damage susceptible stage (between GS 50-59).

Develop models to determine the best trap position

We attempted to model the effect on pollen beetle trap catch of meteorological conditions and landscape features using data on the trap catch of pollen beetles from the Pollen beetle monitoring study (see previous subsection), meteorological data, and landscape information derived from information collected during the Monitoring study.

Digital mapping of environmental features surrounding sticky trap sites Landscape features that were hypothesised to influence beetle immigration were digitally mapped within a 1km-radius around each trap in the Monitoring study. Trap locations (upwind and downwind) were found using the maps provided by the volunteers hosting field sites, and were marked using place-marker 'points' in Google Earth (Summary Figure 1). Hedgerows, lines of trees, woodlands, residential gardens and OSR fields were marked on the map. ArcGIS was then used to extract information on the areas or lengths of these features from within eight directional segments (each 45 degrees) of the circular area mapped surrounding each trap (Summary Figure 1).



Summary Figure 1. Mapping environmental features surrounding the pollen beetle traps. Areas of woodlands, residential gardens, oilseed rape crops in the current year or previous year and the length of tree-lines and hedges were mapped (white lines) within a 1km radius of each trap (surround of downwind trap shown) and calculated for each of 8 segments (shown in red).

Weather data Weather data (temperature, wind speed and direction, rainfall) for Rothamsted and Woburn farms was obtained from the UK Environmental Change Network (http://www.ecn.ac.uk/). For the other sites it was obtained from the UK Meteorological Office 'Daily Sites' data set for the weather stations closest to each site.

Modelling As meteorological variables, particularly temperature, are known to strongly affect pollen beetle catch within crops it is necessary to adjust for these variables when trying to detect the effect of landscape. We expect that temperature, rainfall and wind speed might affect the number of beetles coming into the crop, and that wind direction might affect the direction from which beetles enter the crop, with beetles tending to fly upwind towards the crop. We also hypothesize that landscape features may affect the numbers of pollen beetles entering the crop –

we assume that beetles fly reasonably directly towards the crop, and so landscape features in the 3 landscape segments facing each trap were used as explanatory variables for that trap.

The first step in the modelling process is to build a model of daily counts for trapped beetles; these numbers can then be added across the trapping period. An initial model was fitted using weather variables only. The model included terms for the accumulated temperature (day-degrees), daytime rainfall, and windspeed at 12:00 each in a given field on a given day, and accounted for the discrepancy between the segment faced by the trap and the downwind segment from which beetles are expected to arrive (flying upwind). The overall constant included the effect of zero rainfall and no discrepancy between the trap and wind direction. The model was then extended by adding terms for field, trap and day variation. Terms for the weather variables temperature, rainfall and wind speed were added then landscape variables were added into the model. This gave the full model which was then simplified, dropping the variable with the least significant effect at each step.

2.2.2. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle (Objective 1, Task B)

CropMonitor

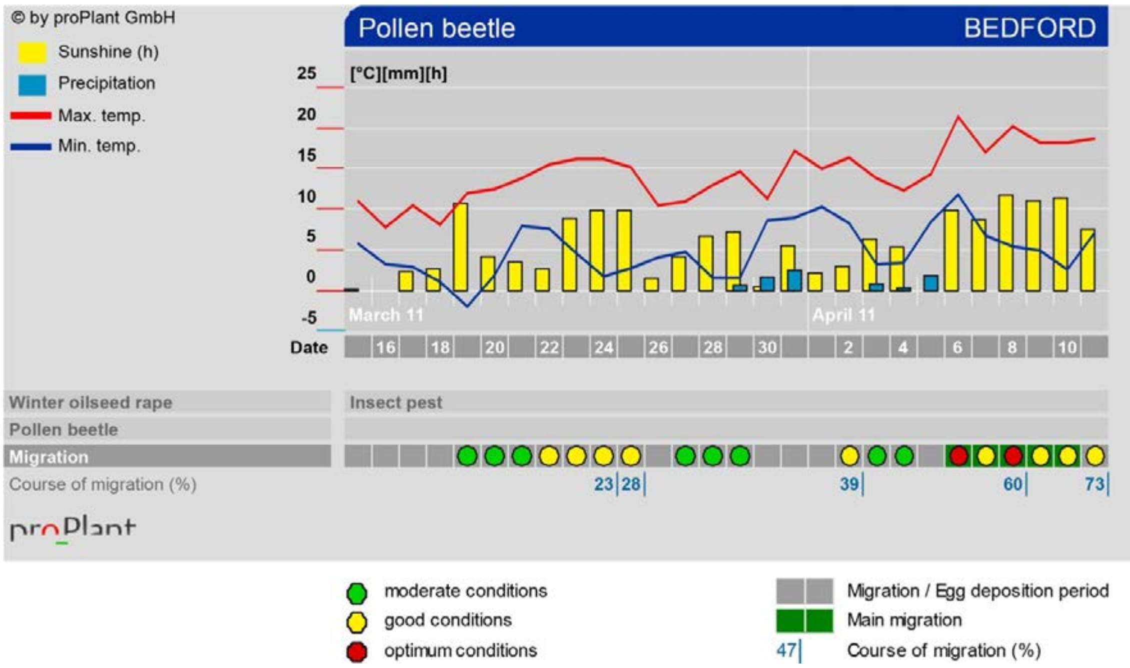
Advice on pollen beetle management is currently available to UK growers through the CropMonitor™ website http://www.cropmonitor.co.uk/ (hereafter referred to as 'current advice'). The period of risk from pollen beetles to OSR is defined in current advice in the UK as 'green-to-yellow bud stage' (BBCH 51-59) and it is advised that 'backward crops are most at risk'. Current advice states that 'pollen beetles fly at temperatures of 15°C or above'. Monitoring is therefore recommended by current advice on all days with a temperature ≥15°C during growth stages 51-59.

proPlant expert Decision Support System

proPlant expert www.proplantexpert.com (hereafter referred to as proPlant) provides local three-day forecasts of pest immigration risk that indicate whether monitoring is needed. Its forecasts are based on phenological models parameterised by daily records of air temperature, rainfall, sunshine and wind speed. proPlant output gives a graphical display of weather data together with an 'immigration' bar on which forecasts are given of the start, peaks and end of immigration (Summary Figure 2). The immigration bar indicates the daily level of risk of immigration with a traffic-light system of coloured dots (green = immigration possible, yellow = good conditions for immigration and red = optimal conditions for immigration Summary Figure 2). proPlant advises that monitoring is necessary only on days when the model indicates yellow or red dots (risk of significant immigration) during growth stages 51-59. Monitoring should start on the day with the first yellow or red dot. Thereafter, if a contiguous series of such days occurs, proPlant advises that monitoring is needed only every third day and the last day in the series.

Data

For this study data from the OSR crops sampled in the Pollen beetle Monitoring study (see section on trap calibration in 2.2.1) were used. Observations following any spring insecticide applications were excluded from the analysis. The average number of pollen beetles per plant was calculated for each field site on each sample date and compared to the standard spray thresholds of 2, 5 and 15 beetles per plant. It was not possible to sample crops daily so it was assumed that any threshold breach took place on the sampling date on which it was observed.   Weather data were obtained from the closest UK Meteorological Office station to each sampled field.



Summary Figure 2. Example of proPlant output for the Bedford weather station 2011 (greyscale).

DSS performance measures and analysis

Advice derived from the two DSS's was compared in relation to the phenology of pollen beetles in the field from the Monitoring experiment and any breaches of the thresholds. The following performance measures were compared: (i) Number of monitoring days recommended, (ii) No. of breaches of threshold detected by the recommended monitoring, (iii) Risk of pollen beetle immigration - start (the first date that the DSS's forecasted immigration risk; temperature ≥15°C for current advice and the first dot of any colour for proPlant, were compared against the date at which the first pollen beetles were caught in the Monitoring study), (iv) Risk of pollen beetle immigration – no. days significant risk forecasted prior to each threshold breach (or until the end of GS 59).

2.2.3. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape (Objective 1, Task C)

Approach and Data set

The early flowering character of turnip rape (TR) plants grown as trap crops offers two scenarios for the potential use of TR as a sentinel plant for risk assessment in OSR: (1) predictive: the number of pollen beetles on the TR at its green-yellow bud stage could be used to predict future infestation levels of the OSR crop when it reaches its susceptible growth stage; (2) real-time monitoring: sentinel plants of flowering TR could be used as 'living monitoring traps' at the damage-susceptible stage of OSR to estimate the level of infestation in the OSR crop to enable use of action thresholds. For both scenarios, data were used from the Trap crop experiment (Section 2.2.4), extracted from Treatment 1 (in which plots of OSR had a TR trap crop which was not treated with insecticide; OSR-/TR-) and Treatment 2 (in which plots of OSR had a TR trap crop which was sprayed for pollen beetle (OSR-/TR+); in this case data were used up until the point where the TR was sprayed). For each analysis data from experiments done in 2009-2011 were combined.

Sentinel turnip rape plants for risk prediction in oilseed rape crops

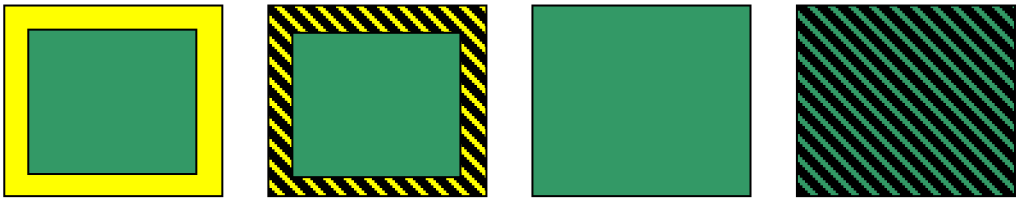
The relationships between pollen beetle numbers in TR borders during the bud phase (GS 50-59) against the numbers in the OSR centres of the same fields 1 week and 2 weeks later were examined.

Sentinel turnip rape plants as 'living monitoring traps' for threshold detection in oilseed rape

The relationship between the numbers of pollen beetles on OSR plants in the centres with the numbers on TR plants in the trap crop at the same point in time was investigated.

2.2.4. Evaluate on a field scale the potential of a turnip rape trap crop for reducing the abundance of pollen beetles in oilseed rape crops (Objective 2, Task D)

We tested the potential of a turnip rape trap crop planted as a border around the main OSR crop for reducing the abundance of pollen beetles in the OSR crop in comparison with untreated crops without a trap crop. We also compared the effect of spraying the turnip rape trap crops with insecticide and compared trap cropping treatments with a scenario of prophylactic insecticide treatment on OSR crops. A replicated experiment was done on two farms (Rothamsted and Woburn Farms) over three years (2009-2011). In each year, four treatments were established on each site (see Summary Figure 3); each was grown as a 1 ha plot in a separate field. In each year winter OSR cv. Astrid was used and for treatments with a trap crop and Pasja (a hybrid cross between a forage turnip and forage rape) was used as a model 'turnip rape' (hereafter referred to as the TR trap crop). The TR trap crop was sown as a 9 m border around the main OSR crop and therefore represented approximately 10% of the area of the whole plot. Both OSR and the trap crop were autumn-sown on the same day.



Treatment 1 **Treatment 2** **Treatment 3** **Treatment 4**

OSR-/TR- **OSR-/TR+** **OSR-/OSR-** **OSR+/OSR+**

Summary Figure 3. Diagrammatic representation of treatments in the trap crop field experiment. 1. OSR-/TR- oilseed rape with a turnip rape trap crop border (both untreated); 2. OSR-/TR+ oilseed rape (untreated) with a turnip rape trap crop border treated with an insecticide at its green-yellow bud stage; 3. OSR-/OSR- oilseed rape with no trap crop (i.e. with an OSR border; all untreated); 4. OSR+/OSR+ oilseed rape with no trap crop, all treated with insecticide at green-yellow bud stage.

The number of pollen beetles was assessed using the plant beating method. In each year assessments took place c. weekly starting when the temperature first reached 10ºC after March 1^{st} and continued until mid-flowering of the OSR crop (GS 63). On each assessment date the growth stage of the OSR and TR plants was recorded. At the end of the experiment in each year, seed samples were taken at harvest and yield (t/ha) was calculated.

2.2.5. Assess the cost effectiveness of the trap cropping tactic (Objective 2, Task E)

Approach

This analysis compared the relative costs and benefits of a number of different trap cropping and insecticide use scenarios for the control of pollen beetles. The core of the analysis was based on the treatments investigated in the Trap cropping experiment (Section 2.2.4); oilseed rape (OSR) with an unsprayed turnip rape (TR) trap crop border (OSR-/TR-), OSR with a TR trap crop border sprayed with a pyrethroid insecticide (to the border only; OSR-/TR+), OSR unsprayed, no trap crop (OSR-/OSR-) and insecticide-treated oilseed rape, no trap crop (OSR+/OSR+). Other options investigated include OSR treated with a more expensive insecticide (i.e. a neonicotinoid, indoxacarb or pymetrozine class), and TR trap crop options where the trap crop is harvested or destroyed.

Calculation of margins

A gross margin for each option was initially calculated. The costs of the field operations for a typical schedule of operations involved in growing an OSR crop from primary cultivations through to harvest were subtracted from this figure, giving a ‘margin less costs of field operations’ figure. This was used for each scenario for comparative purposes (but would not represent a profit or loss until further fixed costs, such as buildings, interest and rent were considered). Summary Figure 4 shows an example of the calculation for the OSR-OSR- treatment, along with notes on calculations and sources of data. Margin calculations were performed using yields achieved for the different treatments in the trap cropping experiment (see section 2.3.4 Summary Table 3). Yield measurement samples were taken from the border area of each plot (irrespective of whether or not the plot had a TR border), and also from the centres. Throughout the analysis, it is assumed that a border represents 10% of the total area of the plot. The ‘combined yield’ value shown in Summary Figure 4 assumes that a 10% contribution to total yield will be made at the level achieved in the border, and a 90% contribution will be made at the yield achieved in the centre. The combined yield value was used in the gross margin calculation. A price of £355 per tonne (spot price, 18th May 2012; source Farmer’s weekly) was assumed in making initial calculations.

Conventional oilseed rape, no insecticide for pollen	**OSR-OSR-**				
	OSR centre		**OSR 10% border**	**Combined yield**	**Notes**
Yield (t/ha)		4.389	3.853	**4.3354**	90% contribution (to total yield) from centre, 10% contribution from border, own values
Crop price (£/t)	£	355.00			Average spot price, Farmers weekly, 16th May 2012
Gross output £/ha	**£**	**1,539.07**			Combined yield x price
Variable costs (£/ha):					Variable costs from Nix, 2012
Seed	£	52.00			
Fertiliser	£	254.00			
Sprays excluding cost of pollen beetle control	£	131.71			Nix states £136 for sprays (this figure is £136 minus cost of typical pyrethroid @ £4.29 per ha)
Pollen Beetle control spray	£	-			
Total Variable costs	£	**437.71**			
Gross margin	**£**	**1,101.36**			Gross output - variable costs
Costs associated with operations (£/ha)					
Plough	£	57.00			Nix 2012, farmer's average cost, medium land (values for heavy and light averaged)
Combination Drill	£	51.00			Nix 2012, farmer's average cost
Roll	£	15.00			Nix 2012, farmer's average cost
Slug pellets broadcast	£	11.10			Nix 2012, contractor's average cost (not specified for farmers)
Autumn weed control / fungicide spray	£	12.00			Nix 2012, farmer's average cost
Autumn fertiliser broadcast	£	9.00			Nix 2012, farmer's average cost
Feb fertiliser broadcast	£	9.00			Nix 2012, farmer's average cost
Mar fertiliser broadcast	£	9.00			Nix 2012, farmer's average cost
Spring weed control / fungicide spray	£	12.00			Nix 2012, farmer's average cost
April insecticide (PB control)	£	-			Assume no tank mix
May Insecticide (SW, PM) / fungicide	£	12.00			Nix 2012, farmer's average cost
July / August dessicant	£	12.00			Nix 2012, farmer's average cost
Combine	£	83.00			Nix 2012, farmer's average cost
Grain cart	£	12.54			Nix 2012, adjusted contractor's average cost (not specified for farmers). hour for carting
Total field operation costs	**£**	**304.64**			
Margin less costs of field operations	**£**	**796.72**			

Summary Figure 4. Calculation of the ‘margin less costs of field operations’ figure for an untreated oilseed rape crop management scenario (OSR-/OSR-).

Standardisation of margin values

During the analysis, it became apparent that variation in the yields achieved in the experimental plots may be masking the effects on the margin of the cost differences associated with each scenario. To address how the differences in costs associated with each option would affect the margin at a standard yield and price, margins were calculated at a standardised yield (OSR) of 3.5

t/ha and standardised price of £350/t using the costs (variable + operations) associated with each scenario. For TR treatments we calculated a standard yield of 1.54 t/ha.

2.2.6. Initiate a programme to develop a practical and efficient trap cropping strategy for winter oilseed rape (Objective 3, Tasks F&G)

Approach

To improve practicality and maximize yield from the area cropped in a trap cropping strategy, higher yielding and later ripening cultivars of turnip rape (TR) are needed or highly attractive early-flowering cultivars of oilseed rape (OSR) are needed to replace the TR component of the strategy. Since there is little research into breeding new TR cultivars, and several growers have expressed a dislike to the idea of using TR in a trap cropping strategy, we decided to focus on the latter, with the ultimate aim of developing a trap cropping tactic based on two cultivars of OSR; one a highly attractive cultivar as the trap crop and one highly unattractive cultivar as the main crop.

A 'wish' list was drawn up of the varietal characteristics that are of most interest so that the plant breeders participating in this project could look for promising lines from their records and in current field trials:

1. Time to flowering (early for potential trap crop; late for improved main crop)
2. Leaf/bud colour (light yellow-green for trap crop; dark blue-green for improved main crop)
3. Flower colour (UV/bright yellow for potential trap crop; apetalous, not yellow or 'light' yellow for improved main crop
4. Inflorescence size (many, large and dense for potential trap crop; few, small and widely spaced for improved main crop

It was evident from a visit to Elsoms Seeds (13/5/2009) that there was very little phenological variation in any of the characteristics on the wish list other than flowering time. The agreed approach was therefore to focus effort on identifying early flowering lines of OSR that could be used in place of early flowering TR in a trap cropping strategy. This line should ideally fit in with any OSR cv selected by growers as their main crop. Seed from four early flowering lines identified from the Elsoms visit was bulked-up and provided by them for small plot trials on Rothamsted farm in the final year of the project to assess the potential of these lines in comparison with TR.

Field assessment of early flowering oilseed rape lines

The four early-flowering experimental lines supplied by Elsoms were tested in comparison with winter turnip rape cv. Jupiter, Pasja (the hybrid cross between a forage turnip and forage rape used as a model early flowering 'turnip rape' in experiments in Section 3.5), and a standard winter OSR cultivar, Castille. Plots were assessed weekly and the date that they reached green bud GS51, when they started flowering (GS 60) and when they finished flowering was recorded.

2.3. Results

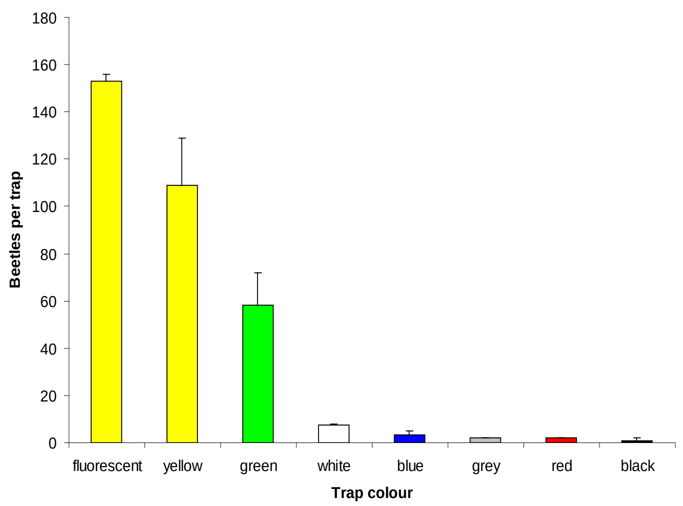
2.3.1. Develop a monitoring trap for pollen beetles (Objective 1, Task A)

Investigate responses of pollen beetles to colour to optimize trap colour

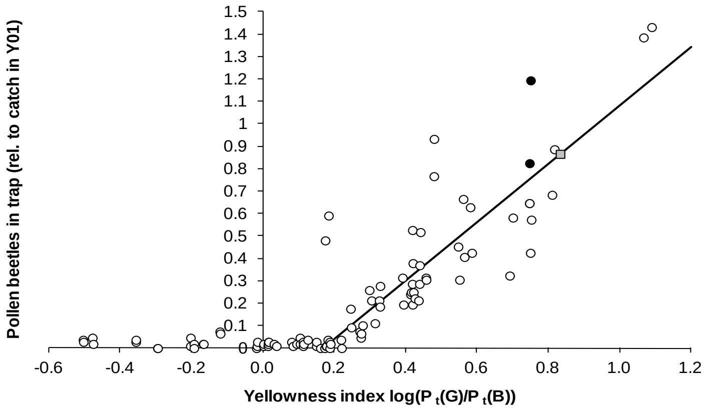
Electrophysiological determination of spectral sensitivity The mean spectral sensitivity curve in pollen beetles peaked at 520 nm; however, a model revealed a peak around 540 nm (green). The data also revealed the probable existence of blue and UV receptors.

Field experiment A total of 2,492 pollen beetles were caught in the different coloured water traps. Yellow traps caught many beetles and the pure fluorescent yellow traps attracted the highest numbers (306 in total). The number of beetles caught in red, blue, white, grey or black traps was generally very low (Summary Figure 5)

Colour choice model The colour choice model was built using information on the spectral sensitivity of pollen beetles with spectral reflectance data of the traps and information about the relative attractiveness of the trap colours from the field experiment. The number of beetles in a trap relative to the average number of beetles that had been caught with a reference colour (yellow, labelled Y01) was calculated. This had a positive correlation with the 'yellowness index' of the trap colour, expressed as the ratio of the input to Green vs. Blue receptors in a colour opponent mechanism model (Summary Figure 6). The model also indicated that higher UV reflection of a trap tended to increase beetle catch.



Summary Figure 5. Mean (± SE) number of trapped pollen beetles caught in selected trap colours in the field trapping experiment. The "yellow" trap was used as the reference trap (Y01).



Summary Figure 6. Colour opponency model of the behavioural response of pollen beetles to colours in the field: relationship between the no. pollen beetles in traps relative to the standard yellow trap (Y01) and the 'yellowness index' (a ratio between the input to Green: Blue receptors in the beetle). The theoretical position of a commercial yellow sticky card used to trap insects is marked by a grey square for comparison. The two reference traps (Y01) are shown with black circles.

Identify and develop semiochemical lures for a monitoring trap with minimum catch of non-targets

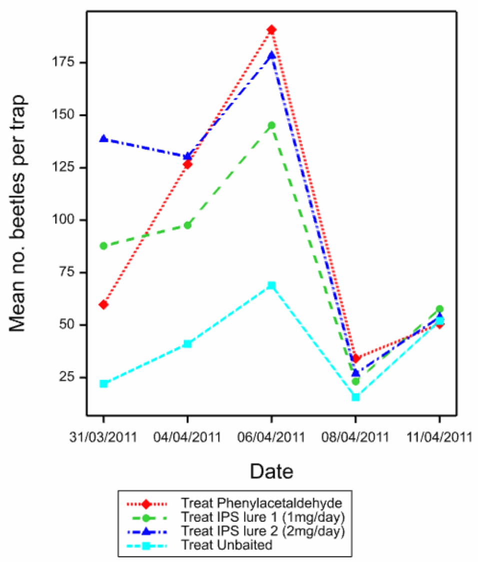
Optimise pollen beetle catch and minimize beneficial catch by investigating colour x odour interactions The different coloured sticky traps tested were much less effective at capturing pollen beetles than the yellow trap but they also caught more parasitoids. The addition of a lure increased pollen beetle catch on traps of less attractive colours and seemed to have little effect on parasitoids, such that with the exception of green, baiting the trap increased the proportion of pollen beetles with respect to parasitoids. The highest proportion of pollen beetles:parasitoids was found on baited yellow traps (Summary Table 1). Therefore we decided to proceed with developing a baited yellow sticky trap.

Collect, identify and field test volatiles for use as the trap bait We identified several new compounds that have not been collected previously from cut OSRplants. In the field experiment testing these new compounds, only the low release rate of phenylacetaldehyde (a common floral volatile) attracted significantly more beetles than the unbaited trap. These results supported those in previous experiments testing potential volatile baits (not detailed here) and low release phenylacetaldehyde was therefore selected for use in experiments in Year 4.

Testing commercial trap mounts and lure dispensers There was no difference in the performance between the Oecos carrot fly trap mount and the RRes experimental mount, indicating that the commercial mount is suitable for use. It was clear that both commercial IPS phenylacetaldehyde lures were as attractive as the RRes low release phenylacetaldehyde lure and all baited traps generally caught more beetles than unbaited traps (Summary Figure 7). There was a significant difference between the attractiveness of the treatments over time. On the last two sample dates when the crop was in flower there was no significant difference between trap catch between baited and unbaited traps (Summary Figure 7). This effect was also found in the trap mount experiment and suggests that once the crop comes into flower the volatiles compete with those from the trap, making it less effective at catching pollen beetles.

Summary Table 1. Proportion of pollen beetles : parasitoids caught between 20 May – 9 June 2009 on yellow, white, blue or green sticky traps unbaited or baited with a 2-phenylethyl isothiocyanate lure

	Yellow 1	White	Yellow 2	Blue	Yellow 3	Green
Unbaited	2.0	0.3	2.0	0.5	2.3	0.1
Baited	3.1	1	2.9	0.9	3.5	0.1



Summary Figure 7 Number of pollen beetles caught in yellow sticky traps baited with two types of commercial lure and the RRes experimental lure releasing phenylacetaldehyde compared to an unbaited control

Calibrate trap catch with numbers of beetles per plant in oilseed rape crops to enable use of action thresholds

Pollen beetle trapping study Pollen beetles were trapped on a total of 178 sites over the 4-year study and a total number of 155,727 pollen beetles were caught. The mean number of beetles caught per trap increased dramatically from years 1-4 of the study (Summary Table 2). These data may represent increasing size of the pollen beetle infestations from one year to the next. As beetles fly upwind to colonize OSR fields, we expected to catch more beetles in the traps placed downwind than upwind on the field sites. However, we found little evidence to support this hypothesis (Summary Table 2, but see the following section on modelling trap position, which showed that this was the case when wind direction is accounted for).

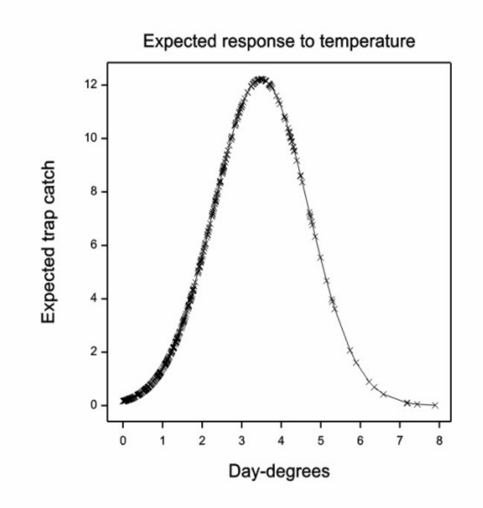
Summary Table 2. Number of pollen beetles caught on yellow sticky traps in oilseed rape crops in a pollen beetle trapping study 2008-2011

Year	Total number of pollen beetles caught	Mean (±SE) number of beetles caught per trap	Mean (±SE) number of beetles caught per trap - upwind	Mean (±SE) number of beetles caught per trap - downwind
2008	3,142	8.12 (0.82)	7.54 (1.32)	7.24 (1.30)
2009	16,344	18.85 (1.74)	15.64 (2.01)	15.96 (3.40)
2010	60,301	29.46 (2.08)	20.61 (3.04)	25.00 (3.61)
2011	75,670	40.49 (2.49)	45.76 (5.05)	28.76 (3.11)

Correlation analysis   There was evidence for a correlation between the numbers of pollen beetles trapped in the upwind and downwind traps and a strong positive correlation between the numbers of beetles per plant in the upwind and downwind crop scouting transects. Unfortunately there was no significant correlation between the trap catch and numbers on plants in the crop transects.

Develop models to determine the best trap position

Thirty fields were selected for modelling. These fields each had good landscape data provided by site hosts and several positive trap catches within the green bud period. They encompassed 12 sites across four years (2008-2011) with 616 trap catches in total. The final model contained terms for several meteorological variables: accumulated temperature, wind speed, daytime rainfall, and discrepancy between wind and trap direction. Several landscape variables were also retained in the model: area of residential gardens, length of hedgerow and length of treeline. Temperature, wind speed and direction were clearly the dominant explanatory variables. No beetles were found in traps when the temperature was <10°C and beetle numbers increased as temperatures increased from 0 to 3.5 day-degrees (corresponding to a constant temperature of 13.5°C); they then decreased as temperatures increase further (Summary Figure 8). Beetle numbers decreased as wind speed increased, and as the amount of rainfall increased. Beetle numbers increased as the area of residential gardens increased, as the length of treeline increased and as the length of hedgerow decreased, but these effects were much smaller than those for the meteorological variables.



Summary Figure 8. Expected trap catch of pollen beetles in response to accumulated temperature (day-degrees above 10°C) for no rainfall and other explanatory variables at their mean values.

2.3.2. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle (Objective 1, Task B)

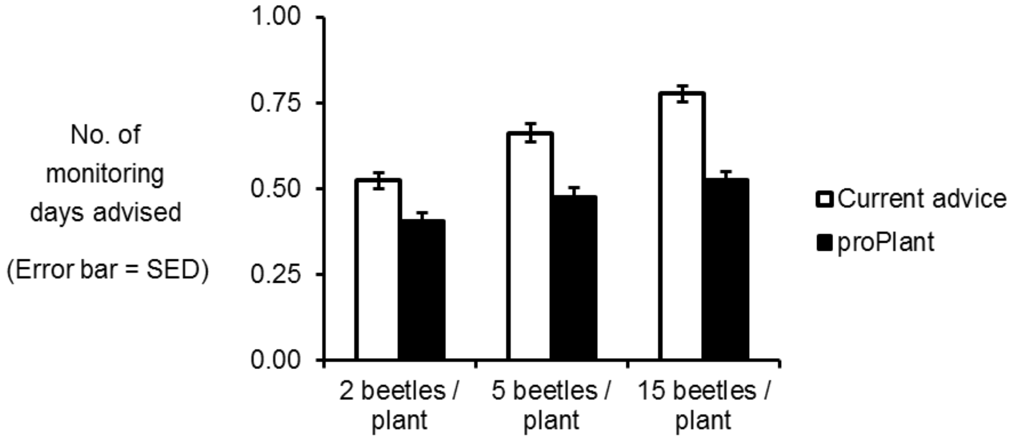
In total data from 44 sites were used in the comparisons. Although the 15 beetle threshold was breached at only one site, the 2 and 5 beetle thresholds were breached at 82% and 43% of sites, respectively, providing a good test of the performance of each DSS.

Number of monitoring days recommended up to the date that a threshold breach would be detected At every threshold level, proPlant consistently advised fewer pollen beetle monitoring days (34-53%; Summary Figure10) than did current advice.

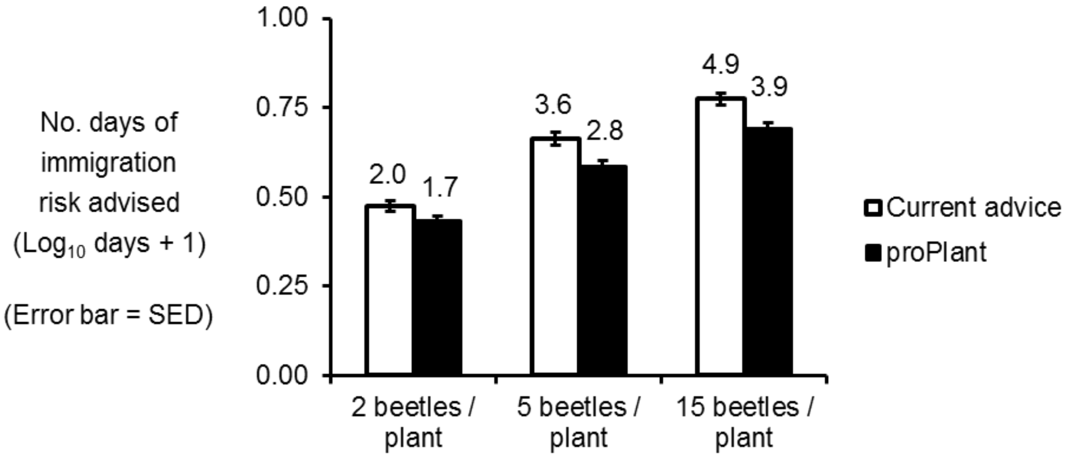
Number of breaches in threshold detected The performance of both current advice and proPlant in prompting monitoring that would lead to recognition of threshold breaches was very good. All threshold breaches at the 5 and 15 beetle thresholds would have been recognised using either DSS, as would almost all breaches of the 2 beetle thresholds.

Forecast of the start of immigration proPlant consistently preceded or accompanied the first recorded immigration of beetles to experimental fields with a risk warning in the form of a green dot. By contrast the first immigration was only preceded by temperatures of ≥15°C on 57% of occasions for current advice and by red or yellow dots (proPlant) on 40% of occasions.

Number of days of immigration risk At every threshold level, proPlant consistently advised fewer days of good immigration conditions (14-21%; Summary Figure 10).



Summary Figure 9. Number of monitoring days recommended up to the date that a threshold Breach(2, 5 or 15 beetles/lant) would be detected.



Summary Figure 10. Forecasted days of good immigration conditions up to breaches of different Thresholds (2, 5 or 15 beetles/plant) (back-transformed means are given above each bar).

2.3.3. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape (Objective 1, Task C)

Sentinel turnip rape plants for risk prediction in oilseed rape crops

There was a significant positive relationship between the number of beetles on plants in the TR border when they were in the green-yellow bud stage and on OSR plants one week later. However, there was no significant relationship 2 weeks later.

Sentinel turnip rape plants as 'living monitoring traps' for threshold detection in oilseed rape

There was a positive correlation between the mean number of beetles on plants in the OSR crop during the damage susceptible stage (GS 50-59) and the number on TR plants in the trap crop at the same point in time. This indicates that it may be possible to use the TR trap crop as a 'living monitoring trap'. An action threshold of 2 beetles on OSR plants in the main crop would be identified when approximately 7 beetles are found in the TR. A threshold of 5 beetles in the main crop would be identified by a mean number of 34 beetles in the TR. The data collected did not allow the model to accurately predict beyond 5 beetles/plant in the main crop, so a figure for the 15 beetles/plant threshold cannot be predicted at this stage.

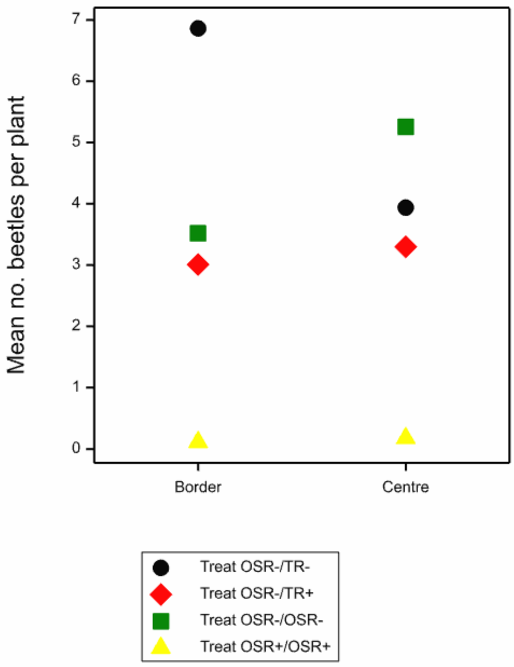
It must be noted for both scenarios that there were influential observations in the 2011 data and more data are required to improve the models before we can be confident enough to recommend these approaches for risk assessment to growers.

2.3.4. Evaluate on a field scale the potential of a turnip rape trap crop for reducing the abundance of pollen beetles in oilseed rape crops (Objective 2, Task D)

After all the treatments had been applied and the OSR crop was within the damage susceptible green-yellow bud stage, it was clear that turnip rape plants in the border were more attractive than OSR plants in the border; unsprayed TR plants (1. OSR/TR-) had a significantly greater number of beetles/plant than did unsprayed OSR plants in the border (3. OSR-/OSR-) (Summary Figure 11, L left hand side). This suggests that TR has good potential to act as a trap crop. Note that there were relatively large numbers of beetles on TR plants that had been sprayed (2. OSR-/TR+), compared with sprayed OSR plants (4. OSR+/OSR+) (Summary Figure 11, LHS). Data from observations in the plots immediately and c. 1 week after the TR had been sprayed showed a clear reduction in numbers – here we see evidence of continued beetle immigration and re-colonization c. 2 weeks after the treatment. In the OSR plot centres it is clear that the pyrethroid treatment had significantly fewest beetles (Summary Figure 11, Right hand side). There were more beetles on OSR plots without the trap crop (3. OSR-/OSR-) than on plots with trap crops (1. OSR-/TR- and 2 OSR-/TR+) but the difference was not significant (Summary Figure 11, RHS).

Yield

The treatments had no significant effect on the yield of the OSR main crop in the plot centres (Summary Table 3). The yield in the plot borders did differ significantly between treatments. This was due to different species (OSR or TR) grown in the borders; the yield of borders comprising TR yielded less than the borders comprising OSR. There was no effect of the insecticide sprays applied to the borders (Summary Table 3).



Summary Figure 11 Mean (±SE) number of pollen beetles per plant in the borders and centres of plots with the following four treatments 1. OSR-/TR- oilseed rape with a turnip rape trap crop border (both untreated) (black circles); 2. OSR-/TR+ oilseed rape (untreated) with a turnip rape trap crop border treated with an insecticide at its green-yellow bud stage for pollen beetle (red diamonds); 3. OSR-/OSR- oilseed rape with no trap crop (i.e. with an OSR border; all untreated) (green stars); (4. OSR+/OSR+ oilseed rape with no trap crop, all treated with insecticide at green-yellow bud stage (yellow triangles) - at key time points of the trap crop experiment: before any insecticide applications (A); following the treatment to the turnip rape trap crop border in Treatment 2 (OSR-/TR+) and following the insecticide application to the centre and border of Treatment 4 (OSR+/OSR+).

Summary Table 3. Mean (±SE) yield (t/ha) from 4 treatments in a trap crop experiment for the plot centres (main oilseed rape crop) and the borders (either turnip rape for treatments 1 and 2 or oilseed rape in treatments 3 and 4). Treatments were: 1. OSR-/TR- oilseed rape with a turnip rape trap crop border (both untreated); 2. OSR-/TR+ oilseed rape (untreated) with a turnip rape trap crop border treated with an insecticide at its green-yellow bud stage for pollen beetle 3. OSR-/OSR- oilseed rape with no trap crop (i.e. with an OSR border; all untreated); 4. OSR+/OSR+ oilseed rape with no trap crop

Treatment: Position	1. OSR-/TR-	2 OSR-/TR+	3 OSR-/OSR-	4 OSR+/OSR+
Centres	4.143 (0.32)	4.461 (0.35)	4.389 (0.29)	4.019 (0.35)
Borders	1.908 (0.32)	1.872 (0.35)	3.853 (0.29)	3.603 (0.35)

2.3.5. Assess the cost effectiveness of the trap cropping tactic (Objective 2, Task E)

Our analysis indicates that the best crop management strategy to maximize net margin return is to have an OSR crop (without a trap crop) and spray according to thresholds (net margin of £482/ha if the crop is not sprayed; note this does not include the cost of advice or monitoring aids associated with determination of thresholds) (Summary Table 4). If insecticides are used, the margin will be reduced to £466 if pyrethroids are used and to £455 if another more expensive insecticide class is used. The net margin for a strategy with a trap crop to reduce beetles to below spray threshold is £407. If trap crops are grown, they should be harvested; margins are reduced from £407 to £367 if the trap crop is destroyed (Summary Table 4).

Summary Table 4. Summary of the combined yield per plot, costs and margin for different crop management scenarios with and without trap crops and with and without insecticide applications.

Scenario	Combined yield (t/ha) based on experimental results	Costs £ (variable + field operations)	Margin less costs of field operations £ (based on experimental results)	Standardised net margin £ @ 3.5 t/ha and £350/t
OSR-/OSR-	4.335	742.35	796.72	482.45
OSR+/OSR+ (Pyrethroid)	3.977	758.64	653.34	466.36
OSR+/OSR+ (e.g. Neonicotinoid)	3.977[1]	769.12	642.86	455.85
OSR-/TR-	3.920	748.73	642.70	407.67[2]
OSR-/TR- (un-harvested)	3.729	735.17	588.52	367.33[2]
OSR-/TR+	4.202	751.56	740.19	404.85[2]
OSR-/TR+ (un-harvested)	4.015	738.00	687.30	364.51[2]

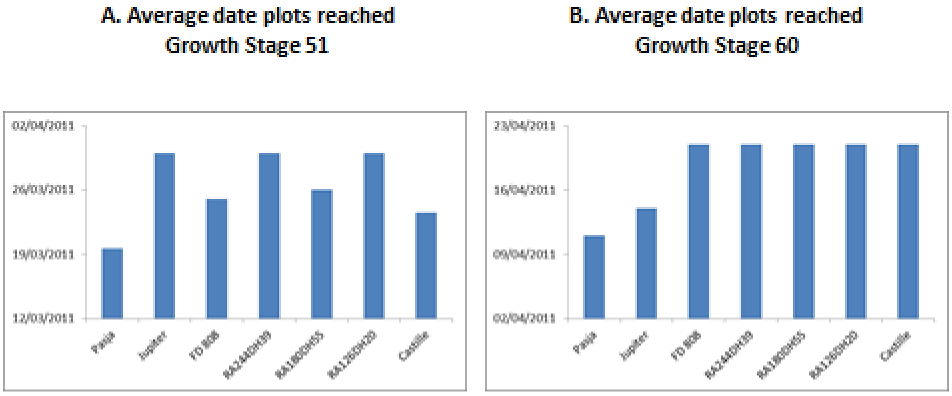
[1] assumed no difference in yield when sprayed with a pyrethroid versus a non-pyrethroid (neonicotinoid, indoxacarb or pymetrozine)

[2] Standardised margin adjusted for TR yield loss

2.3.6. Initiate a programme to develop a practical and efficient trap cropping strategy for winter oilseed rape (Objective 3, Tasks F&G)

Field assessment of early flowering oilseed rape lines

The early flowering experimental OSR lines got off to a promising start, with all four lines reaching green bud GS 51 before the standard OSR cv Casille (Summary Figure 12A). However, these lines did not start flowering earlier than the standard OSR cv Castille, and were considerably later than Pasja and TR cv. Jupiter (Summary Figure 12B).



Summary Figure 12 Average date plots of Pasja, winter turnip rape cv. Jupiter, Elsoms winter oilseed rape experimental lines FD 808, RA244DH39, RA180DH55 and RA126DH20 and winter oilseed rape cv Castile (A) reached the green bud stage (GS 51) and (B) started flowering (GS 60) in a replicated field plot trial.

2.3.7. Propose an IPM strategy for controlling pollen beetles in winter oilseed rape based on the combination of the most effective elements tested in this project (Objective 3, Task H)

An IPM strategy for pollen beetles is proposed based on the use of decision support systems to forecast immigration risk, monitoring methods to enable the use of action thresholds and alternative crop management (trap crops) to reduce the number of insecticide sprays needed. It is intended for use by growers, crop consultants and policy makers.

The damage susceptible stage of the crop is the green-yellow bud stage only (BBCH GS 50-59). Monitoring of pollen beetle populations should be concentrated within this period and any insecticide applications should not be applied after flowering has started.

Action thresholds should be used. Insecticides should only be applied if action thresholds have been breached. For many years the accepted HGCA action thresholds were: 2 beetles/plant for varietal associations, 5 beetles/ plant for backward crops and 15 beetles/ plant for otherwise good crops. However, a recent HGCA-funded study proposed a threshold scheme in which pollen beetle threshold is negatively related to plants/m^2. As a rule of thumb, new action thresholds are c.30 beetles/plant for thin crops (<20 plants/m^2), 20 beetles/plant for optimal crops with 40 plants/m^2 and c. 10 beetles/plant for thick crops with >60 plants/m^2. There is no distinction between spring and winter sown crops (see HGCA Information sheet 13, 2012).

Risk of crop damage is related to pollen beetle immigration risk. As a rule of thumb, the crop is at a lower risk due to pollen beetle immigration when temperatures <10°C, when there are strong winds and if it is raining. The crop is at greatest risk when temperatures >15°C.

Forecasting risk of pollen beetle immigration: Decision support systems (DSS) that provide risk assessments of pollen beetle immigration should be used to minimize monitoring effort and focus it to when it is most needed**.** proPlant www.proplant.de is a decision support system that uses a phenological model of pollen beetle immigration and local meteorological data to produce forecasts of immigration risk and advises monitoring days for up to 2 days in advance. As a result of this project, the proPlant forecasting tool is freely available on the Bayer CropScience website www.bayercropscience.co.uk. The maps showing immigration risk for the next 2 days and % completion of migration should be used to help decide whether or not plant monitoring is necessary. Use of these maps has great potential to save unnecessary 'insurance' insecticide applications.

Detection of action thresholds (population monitoring): The recommended method for population monitoring of pollen beetles is from plant sampling in the crop; the main raceme of the plant is beaten firmly two or three times against the base of a tray. Action thresholds are expressed as an *average* number of pollen beetles per plant. At least 10 should be sampled at random, taken along a transect of at least 30 m, starting at the headland and heading towards the crop centre. Ideally four transects should be performed on each side of the crop however if there is only time to do one, it should be done on the down-wind side of the crop according to the wind direction at the time of sampling, as beetles fly upwind towards the crop.

A baited monitoring trap for pollen beetles has been developed as part of this project and will be commercially available from Oecos www.oecos.co.uk. Unfortunately at present the monitoring trap cannot be used to determine action thresholds in the crop and should not replace the monitoring of plants directly in the crop. However, the uncalibrated monitoring trap still has value for risk assessment. Traps can be used to detect the start of immigration, peaks of immigration and end of immigration and can be used to verify at a local level the forecasts provided by the DSS. Ideally one monitoring trap should be placed on each side of the field but if only one is used it should be placed downwind of the prevailing wind on the site. Monitoring traps should be used during the green-yellow bud stage of the crop only and should then be removed from the crop.

Alternative crop management (trap cropping). A turnip rape trap crop comprising c.10% of the area of the field planted as a border around the edge of the main OSR crop can be used to reduce the population of pollen beetles to below spray thresholds. It is essential that the flowering differential between the trap crop and the main crop should be maximized; the earliest flowering cultivar of turnip rape possible should be selected as the trap crop (e.g. Buko) and the latest flowering OSR cv possible should be selected as the main crop. Both the trap crop and the main crop can be planted on the same day; do not plant the OSR crop before the TR trap crop. Crop management can then proceed as normal until harvest. We do not recommend spraying the trap crop for pollen beetle. We recommend that the trap crop should be harvested at the optimal time. This prevents seed shed leading to volunteer problems later and economically, the returns are worthwhile compared with management options where the trap crop is destroyed.

Insecticide resistance management: Currently there are insecticides from four chemical groups registered for pollen beetle control: Pyrethroids, Noenicotinoids, Indoxacarb and Pymetrozine. Growers should rotate use of these such that successive generations of the pollen beetle are not treated with, or exposed to, compounds from the same group within the insecticide regime used over the life time of the crop.

2.4. Discussion/Conclusions and implications

The Integrated Pest Management (IPM) strategy for pollen beetles we propose is based on the use of decision support systems (DSS) to forecast immigration risk and focus monitoring effort, improved monitoring methods to enable the use of action thresholds and alternative crop management (trap crops) to reduce the pest population. These three tactics represent the three major achievements of our project.

One of the major limitations to use of action thresholds is that proper monitoring of the populations is time consuming and has to be conducted over a prolonged period. Better risk assessment and decision support could help to focus monitoring effort. proPlant is a decision support system available in mainland Europe that uses a phenological model of pollen beetle immigration and local meteorological data to forecast the start and end of pollen beetle immigration into the crop and main periods of risk up to 2 days in advance and advises when to monitor. We tested the model under UK conditions using data from our pollen beetle monitoring study and compared monitoring advice given with the best current advice system on the CropMonitor website. Both systems performed reassuringly well in prompting monitoring that would detect breaches of spray thresholds for pollen beetles in OSR. However there were considerable reductions provided by proPlant in the need for consultation of the system (30%) and advised monitoring days (34-53%) in comparison with current advice. Use of the proPlant system could therefore save growers and crop consultants time and money. It could help to reduce unnecessary insecticide applications by preventing insurance sprays when beetle numbers are *approaching* threshold, and by forecasting the end of migration, when sprays are not necessary even if the crop is still at the damage-susceptible stage. We are delighted that as a result of work in this Project, a simplified version of the proPlant model which forecasts start of migration, risk of significant immigration in the next 2 days, and end of immigration is now freely available (2012/2013 seasons confirmed at time of writing) to growers and crop consultants in the UK via the Bayer CropScience website www.bayercropscience.co.uk.

Use of action thresholds is reliant on reliable and effective methods for monitoring populations of pollen beetles in the crop. Current crop monitoring methods involve time consuming plant samples from transects 30m into the crop. Unless several transects are performed, results can be inaccurate as a measure across the whole field and can vary according to the position of the plants sampled and the time of day and weather conditions. A monitoring trap for pollen beetles would help growers and crop consultants to more easily and accurately identify when pollen beetle immigration has started and when spray thresholds have been breached. A baited monitoring trap for pollen beetles has been developed as part of this project and will be commercially available for the 2013 season from Oecos www.oecos.co.uk. The monitoring trap comprises a yellow sticky card mounted at 45° to the vertical, baited with phenylacetaldehyde, a floral volatile produced naturally by several plant species. Unfortunately at present the monitoring trap cannot be used to determine action thresholds in the crop. There was no correlation between the number of beetles caught in the traps and the number of beetles present on plants in the crop and so we were unable to calibrate trap catch to a given action threshold expressed as the number of beetles per plant using a simple linear relationship. However, the monitoring trap still has value for risk assessment, especially if used in conjunction with decision support systems.

Trap crops of turnip rape (TR) planted as a border to an oilseed rape (OSR) crop consistently reduced populations of pollen beetles to below spray thresholds in a spring OSR system in previous studies. We tested the strategy for a winter OSR cropping system on a realistic field scale over three years. We found evidence that the strategy worked well in some years, but not in others. In years when the tactic did not work, the growth stage differential between the main crop and the trap crop was probably too short. To optimize efficacy, growers will be restricted to using the earliest of TR cultivars and the latest of OSR cultivars possible, and this tactic is probably practical and economically worthwhile only for organic growers.

We believe that use of these IPM tools will facilitate use of action thresholds and help encourage more growers and crop consultants to use spray thresholds. Use of the strategy or components of it will undoubtedly save growers time, money and prevent unnecessary insecticide sprays.

As well as practical IPM tools, our project has also considerably increased the knowledge base of pollen beetle physiology and its behavioural and chemical ecology. We have determined the spectral sensitivity of pollen beetles, identified putative green, blue and UV receptors and explained how their preference for yellow is physiologically determined. As well as being of great academic interest, this work has produced a colour choice model that can be used to assess the relative attractiveness of traps, plants or other materials for use in IPM strategies that exploit colour preference – without the need to run expensive field trials. We have identified several new volatile compounds not previously found in OSR plants and identified plant genotypes that may be useful in future plant breeding programmes to develop super attractive cultivars for trap plants or unattractive 'resistant' cultivars for improved main crops, each of which exploit the host-location process of pollen beetles. Lastly, and perhaps most significantly, we have gained considerable additional knowledge on the immigration behaviour of pollen beetles into OSR crops. This knowledge has several future practical applications. Further analysis of our data will help to inform on better plant monitoring practices: are transects at least 30m long really needed? Can we not correlate numbers on plants in headlands with numbers in the crop to enabling sampling just from the crop edge? We have shown that pollen beetles fly at lower temperatures than previously thought (c. 13°C, rather than 15°C) and we have confirmed that they fly upwind towards crops. We have shown immigration is also affected by wind speed and rain. It is commonly understood that pollen beetles overwinter in woodland, but sites near to woodlands did not necessarily result in larger populations in the field. Further work may enable growers to predict the likely direction of immigration on a site so that insecticide applications are better targeted spatially (reducing area treated), monitoring transects and traps could be more accurately selected and sited and fields most at risk from pollen beetles identified, all given the surrounding landscape features.

We believe our project was a great success and we are proud of our achievements. We have worked together to develop an IPM for pollen beetles in winter OSR that can be used as a framework by growers and crop consultants to manage pollen beetles with reduced insecticide inputs and the confidence to do so. This will prolong insecticide life by reducing selection for resistance, reduce environmental impacts and contribute towards the sustainability and profitability of OSR in the UK.

3. TECHNICAL DETAIL

3.1. Introduction

Management of insecticides in winter oilseed rape (OSR) is an increasingly urgent issue in the light of the increased area of the crop grown and the threat to its sustainability posed by insecticide resistance in pollen beetles. OSR is currently valued at over £350 /t (Farmers weekly spot prices, Oct 2012) and is no longer restricted to 'break crop' status; it is recognised as a valuable commodity in its own right. Consequently, it is now the second most widely grown crop in the UK (after wheat), representing 47% of the area cropped; 641,562 ha were grown in 2010, 97% of which was winter sown (Garthwaite *et al.*, 2011). The frequency at which the crop is planted in rotations is also increasing (Booth *et al.*, 2007). There are concerns over the environmental consequences of such increases, as well as implications for the severity of pest and disease problems that could threaten the sustainability of the crop in the UK. In 2010 less than 1% of OSR crops were untreated with pesticides.

The pollen beetle (*Meligethes aeneus*) is the most numerous of a suite of pests that attack OSR (Alford et al., 2003). It is economically the most important spring pest and is the major target of spring-applied insecticides (Garthwaite *et al.,* 2011). Adults migrate to OSR crops in spring. They bite holes in the buds to feed on the pollen within the developing anthers and it is mainly this damage that causes bud abscission and yield loss. Once the plant begins to flower the beetles feed on the pollen in the open flowers. Females lay eggs in the flower buds and the first instar larvae feed within the bud. This damage is usually only economically significant when populations are large. Second instar larvae feed on pollen from open flowers and do not cause significant damage (Williams and Free, 1978). Only plants at the green-yellow bud growth stages are susceptible to yield-limiting damage (Tatchell, 1983; Axelsen and Nielsen, 1990). Backward OSR and spring OSR crops are most at risk, as the damage-susceptible growth stage occurs after pollen beetles have emerged from overwintering and populations immigrating into crops are often large. If present in large enough numbers pre-flowering, the beetle can completely devastate the crop. The UK, to date, has not seen levels high enough to have such a catastrophic effect, but, in 2006, Northern Germany experienced 100% crop loss in many fields (> 30,000 ha) and serious losses in a further 200,000 ha due to loss of control of pollen beetles which had become resistant to pyrethroid insecticides. The estimated loss was in the region of € 22-25 M (Eppo, 2007).

Chemical control of the pollen beetle has relied almost exclusively on the pyrethroid class of insecticides. Insecticide sprays were applied to 85% of crops in 2006, 13% receiving four or more sprays and >99% of applications being pyrethroids (Garthwaite *et al.,* 2006). Half of sprays were applied in spring and pollen beetles are often exposed to at least two treatments: once as a direct target at the green-yellow bud stage and again, when the larvae are also active, during flowering (targeted at seed weevils (*Ceutorhynchus assimilis*), pod midge (*Dasineura brassicae*) and cabbage aphids (*Brevicoryne brassicae*). This practice has increased selection pressure for resistance to pyrethoids in populations of the pollen beetle.

Resistance to insecticides can be defined as' a heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that species' (IRAC, 2012). Pyrethroid resistance in pollen beetle was first reported in the Champagne region of France in 1997 (see Hansen, 2003) and resistant populations were later confirmed throughout France, Denmark, Germany and Poland, and in parts of Sweden, Switzerland, and Belgium (Thieme *et al*., 2010). Resistance has been much slower to develop in the UK. The first case of pyrethroid resistance in pollen beetles was detected in Kent in 2006 (Thieme *et al*., 2010). Monitoring programmes in 2007 found strongly resistant individuals at further sites in Kent and in East Anglia (Pollen beetle working group of the Insecticide Resistance Action Committee). For the next few years resistance was confined to areas in the East and South-east of the UK, then in 2010, resistance in Herefordshire was detected in the West. Resistance is has recently been confirmed in the North-east, borders and Scotland (HGCA 2012). Resistance is now widespread and over 50% of tested populations had some degree of resistance (Figure 1).

The European Plant Protection Organization (EPPO) workshop on insecticide resistance of pollen beetles on OSR produced a set of recommendations to help reduce selection for insecticide resistance in pollen beetle. These included: reduce the number of applications (do not employ prophylactic sprays) and use action thresholds. It was highlighted that clear and scientifically robust methods of monitoring populations are needed; insecticide applications should aim to have minimal impact on beneficial organisms; cultural and biological control methods should be utilised alongside insecticides in IPM; and non-chemical control measures need to be developed including trap cropping (EPPO, 2007). This meeting was the stimulus for the current Project.

For many years the accepted action thresholds for pollen beetle in the UK were: 2 beetles/plant for varietal associations, 5 beetles/ plant for backward crops and 15 beetles/ plant for otherwise good crops (e.g. Oakley, 2003; HGCA, 2010). These thresholds reflected the risk of the crop to the likely size of the beetle population. However, varietal associations are no longer widely grown and results of a recent HGCA-funded study proposed a threshold scheme in which pollen beetle threshold is negatively related to plants/m^2 (Ellis & Berry, 2011). This scheme is based on the number of flowers that can be lost by plants and still produce maximum yield. The 'number of excess flowers' could be predicted by plants/m^2 at the bud stage. Crops with fewer plants/m^2 had more excess flowers than more dense crops; thus the threshold for thin crops is greater than that for a thick crop and the system therefore takes into account the compensatory ability of the crop.

As a rule of thumb, new action thresholds are c.30 beetles/plant for thin crops (<20 plants/m^2), 20 beetles/plant for optimal crops with 40 plants/m^2 and c. 10 beetles/plant for thick crops with >60 plants/m^2. There is no distinction between spring and winter sown crops. Although this system requires further validation, the new thresholds have been adopted and published by AHDB-HGCA (HGCA 2012).

If we examine data on the number of pollen beetles per plant and relate them to the action thresholds of the time, it is clear that pyrethroids are often sprayed unnecessarily (see Figure I). Although pollen beetle populations rarely exceed even the lower action threshold for backward crops, according to Defra data collected though the FERA CropMonitor project, 20% of insecticide treatments were targeted against them in 2006 (Garthwaite *et al.*, 2006). Because of their relatively low cost, many treatments are applied prophylactically in tank mixes with the spring fungicides. Where thresholds are used, it is possible that the numbers of beetles per plant are overestimated. Current advice on crop monitoring (scouting) is to walk a transect into the crop, but it is likely that, for ease, growers/advisors select plants mainly from the crop edge, where beetle density is naturally at its highest as these pests infest the crop from the edges (Free and Williams, 1979; Cook *et al.*, 2004).

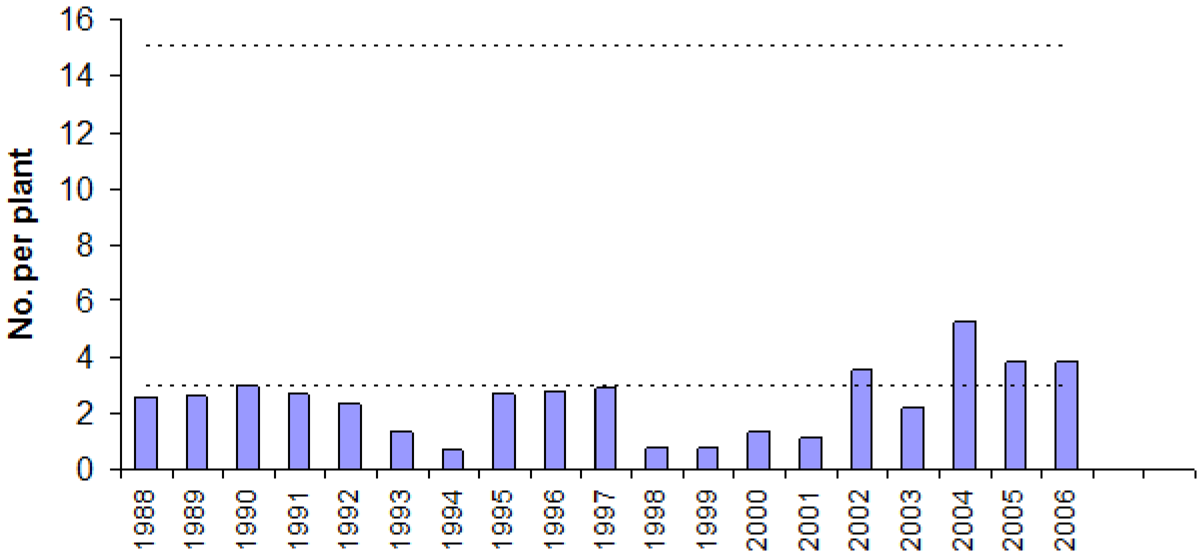


Figure I Mean number of pollen beetles per plant on oilseed rape crops 1998-2006 in England and Wales (data courtesy of FERA). Dotted lines represent action thresholds of 15 beetles/plant for good crops and 5 beetles/plant for backward crops.

Many growers and crop consultants are reluctant to use monitoring methods and action thresholds due to time constraints and may lack confidence in them. Reliable, quick and simple methods of monitoring densities of pollen beetles are needed. Easy to use, accurate monitoring traps for pollen beetles would help to refine the identification of threshold levels of these pests, but there are none commercially-available at present.

Decision support systems that identify the main period of risk by modelling the population dynamics of insect pests could focus monitoring efforts and further reduce unnecessary treatments. No such system is commercially available to UK growers, although this approach has been adopted to great benefit in parts of mainland Europe. 'proPlant Expert' www.proplant.de is a web-based decision support system produced in Germany that is used commercially throughout Germany, France, Austria, Finland and the Czech republic. It is used by OSR growers (up to 70% of users), major agrochemical companies including Bayer CropScience, DuPont and BASF, and crop consultants and growers' support services including CETIOM (France). The system alerts the user to the start and progress of migration of pests, including pollen beetle and seed weevil. It is driven by data automatically downloaded from a local meteorological station and historical data on pest phenology related to weather. Users of proPlant in Germany apply less insecticide against spring pests than those not using this system (Johnen, 2006).

Trap cropping can be used to reduce the area that needs to be treated with insecticides, and can potentially eliminate the need for insecticide use altogether. This tactic needs to be tested in winter OSR at a field scale. Trap crops are plant stands deployed to attract, intercept and retain insects thereby reducing damage to the main crop (Cook *et al.*, 2007a). The trap crop, which comprises highly attractive host plants of a growth stage, cultivar or species preferred by the pest, is planted in proximity to the main crop to be protected. Defra-funded studies PS2107 & PS2113 identified turnip rape (*Brassica rapa*) as an effective trap crop for pollen beetles in spring OSR because it flowers ~3 weeks earlier and retains beetles until the OSR is past its damage-susceptible phase (Cook *et al.*., 2006b). A border trap crop was selected following modelling studies (Potting *et al.*, 2005) and reduced numbers of pollen beetles to below threshold levels (Cook *et al.*, 2004). Work in PS2113 transferred the model to a winter OSR cropping system more relevant to UK agriculture, and it shows potential for control of flea beetle (*Psylliodes chrysocephala*) (Barari *et al.*, 2005) and pollen beetle. However, these studies were conducted on small plots (30 x 30 m) and the tactic needs to be tested on a more realistic field scale before commercial uptake can occur.

Aims

This project aimed to develop an integrated pest management (IPM) strategy for control of pollen beetles based on monitoring, risk assessment and crop management to reduce the number of insecticide applications and area treated, thereby maximising profit margins, and minimising development of resistance and the environmental footprint of pest control. The project aimed to devise and evaluate a suite of tactics that could be implemented in the short-term in an IPM strategy to reduce the abundance of pollen beetles on winter oilseed rape and ensure that insecticide treatments are used only when required and to optimal effect.

Objectives

1. Develop and test monitoring and risk assessment systems for pollen beetles to enable use of action thresholds

Task A. Develop a reliable monitoring trap for pollen beetles to enable easy and effective detection of threshold levels of these pests

Task B. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle

Task C. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape

2. Demonstrate the extent to which trap cropping can reduce the number of insecticide sprays applied and area treated

Task D. Evaluate on a field scale the potential of a turnip rape trap crop for reducing the abundance of pollen beetles in winter oilseed rape crops

Task E. Assess the cost effectiveness of the trap cropping tactic

3. Develop a future IPM strategy for pollen beetles in winter oilseed rape

Task F. Initiate a programme to develop a trap cropping strategy based on winter oilseed rape to replace the less practical turnip rape component

Task G. In small plot experiments test any plants derived from Task F for their relative attractiveness to pollen beetles compared with turnip rape cultivars used in Objective 2

Task H. Propose an IPM strategy for controlling pollen beetles in winter oilseed rape based on the combination of the most effective elements tested in this project (WP1-4) objectives.

3.2. Develop a monitoring trap for pollen beetles (Objective 1, Task A)

We need reliable, quick and simple methods to monitor the size of a pollen beetle population in an oilseed rape (OSR) crop in order to enable growers and crop consultants to use action thresholds. Currently, methods based on plant scouting are most commonly used, in which several plants are selected at random along a transect across the field and beaten into a tray; the pollen beetles dislodged are counted and the mean/plant calculated (Williams *et al*., 2003). However there are several limitations to the accuracy of this method. Firstly, the method is time consuming to do properly, requiring several visits to the field to check on the population levels as pollen beetle immigration occurs over a prolonged period and crops are susceptible to damage throughout the green-yellow bud stage which can last up to 3-4 weeks. Secondly, plant scouting only represents a snapshot in time of the number of beetles on the plants in the crop; pollen beetle catches in the crop vary according to time of day and weather conditions (Ferguson *et al.,* in press). Thirdly, as populations of beetles in the field are not homogenous, the method could lead to inaccurate values. If plants for sampling are selected mainly from the crop edge (where they are most easily and quickly accessible) the average no. beetles/plant may be high and not representative of the rest of the crop, as beetles are naturally most numerous on plants at the crop edge (Williams *et al.*, 2003). This practice could result in unnecessary sprays. Populations may also be underestimated, resulting in missed sprays, for example if only one transect is done and it is positioned in the part of the field that has received little beetle immigration. A simple, cheap monitoring trap that is easy to use would overcome many of these problems but there are none commercially available at present.

There have been many recent developments in the behavioural ecology of pollen beetles and in technologies that assist monitoring. We know that pollen beetles locate their host plants using a combination of visual and olfactory cues (Blight & Smart, 1999; Jonsson *et al.*, 2007). In a previous Defra funded project (PI038) extracts of volatiles from flowering racemes and leaves cut from an historically early (OSR) cultivar, Willi, were collected by air entrainment (Blight, 1990) and 25 compounds, which stimulated the antennae of pollen beetles were located (Blight *et al*., 1995). Slow release dispensers were developed to test the responses of OSR pests to OSR volatiles in field trapping trials (Smart *et al.*, 1997). These trials determined some effects of trap colour and the most attractive bait for pollen beetles (Blight & Smart, 1999; Smart & Blight, 2000). Trapping trials also determined the best trap design; sticky devices were found to be most effective and are considered more practical for growers and advisors compared with (for example) water traps (Blight and Smart, 1999). Beetles were most attracted to a yellow sticky card trap angled at 45° to the vertical and baited with a slow release dispenser of 2-phenylethyl isothiocyanate (ncs). However, trap catch of non-target species was high with this colour, and pollen beetle parasitoids were particularly attracted by this lure. The isothiocyanate is also toxic and therefore not suitable for use with a commercial trap.

This project investigated optimization of trap colour (3.2.1) and bait (3.2.2) to pollen beetles whilst minimizing catch of non-target insects, particularly natural enemies. Trap calibration was also investigated to enable detection of action thresholds related to the number of beetles/plant in the crop (3.2.3) and studies were conducted to optimize trap positioning (3.2.4).

3.2.1. Investigate responses of pollen beetles to colour to optimize trap colour

The pollen beetle is known to respond to colour cues during host plant location. In particular, beetles are known to strongly prefer 'yellow' colours over others (Giamoustaris & Mithen, 1996; Blight & Smart, 1999; Cook *et al.*, 2006a). Unfortunately, the value of this information is relatively limited when it comes to accurately predicting the response of the pollen beetle to any given colour (e.g. of traps or plants), because colour vision in insects is fundamentally different to colour perception in humans, and human colour names do not necessarily correlate with insect behaviour (Chittka & Döring, 2007). We therefore aimed to improve the understanding of the general mechanisms that underlie colour choice behaviour in the pollen beetle in order to help develop and optimise strategies for control that rely on the disruption of colour-guided host finding behaviour. We combined electrophysiologically-determined spectral sensitivity functions in pollen beetles with behavioural experiments in the field. We are able to show that the insect's behaviour follows a green-vs.-blue colour opponent mechanism, resulting in a preference for colours that appear yellow to the human eye. From this we developed a model specific to pollen beetles which can be used to predict the relative attractiveness of any given colour with known spectral reflectance.

Materials & Methods

Electrophysiological determination of spectral sensitivity

To determine spectral sensitivity of pollen beetles we used the electroretinogram (ERG) technique (Kirchner, *et al.*, 2005). The apparatus used for the ERG recordings was the same as described in two previous studies (Döring & Skorupski, 2007, Skorupski, *et al*., 2007) and was adapted for extracellular ERG recordings. Adult pollen beetles were collected from fields of OSR in spring 2008. Beetles were mounted individually onto a cork platform and immobilized with dental wax. A borosilicate glass electrode filled with 2 M potassium acetate was inserted into a hole in the insect eye using a micro-manipulator. The indifferent electrode, a chlorided silver wire, rested in the abdomen. After this preparation the beetle was left to dark-adapt for 30 min. Light flashes (0.1 s length) were varied over wavelengths (340 - 650 nm in 10 nm steps) and light intensities. The strength of the light stimuli, measured as relative quantum flux, was calibrated with a spectrophotometer. Responses were recorded with an AxoClamp 2B device, and analysed using the programme Spike 2 (CED, Cambridge, UK, version 5.07). Spectral scans from 10 beetles were chosen from all recordings for further analysis. Sensitivity calculations for the ERG recordings followed methods described elsewhere (Kirchner, *et al*., 2005). In order to identify the peak spectral sensitivities of the receptor with the longest wavelength sensitivity (i.e. a putative green receptor), exponential templates (Stavenga, *et al.,* 1993) were fitted via least squares to the long wavelength tail (560–650 nm) of the normalized spectral sensitivity data.

Field experiment

A field experiment to test the responses of beetles to coloured traps was conducted on Rothamsted Farm in spring 2008. Petri dishes (14 cm diameter) were used as traps and were painted 50 different colours (2 traps of each colour) (as in Döring *et al.* 2009). The colours were various mixtures of several water-based commercial masonry paints (yellow, three hues of blue, green, red, white and black). These mixtures resulted in several colour series ranging in hue (yellow, green, blue), saturation and brightness. In addition, colour treatments with a UV reflectance component were prepared by mixing yellow and green masonry paint with Barium sulphate ($BaSO_4$) powder and a binder. The reflectance spectra of the traps when filled with water and detergent (Lipsol®,Bibby Sterilin Ltd., UK), were measured with a RAMSES-ARC spectrophotometer (from TriOS GmbH, Oldenburg, Germany, range 320–950 nm) against a $BaSO_4$ white standard.

The traps were set out within a field on bare soil in 4 rows with 25 traps in each, and with 2 m between each row and between each trap within a row. Traps were maintained 30 cm above the ground on poles. The two replicates of each colour treatment were assigned to one of two blocks (consisting of two rows each), and within blocks the colours were randomised. Traps were filled with water and Lipsol and left in the field on three trapping dates in May 2008 (5-10, 15-18, and 22-24 May). All insects were collected from the traps and stored and later the number of pollen beetles in each trap was counted.

Colour choice model

In order to build a colour choice model, the response variable y was calculated as the number of beetles n_t in a trap t relative to the average number of beetles n_{ref} that had been caught with a reference colour (yellow, labelled Y01, for reflectance spectrum see Figure 2) thus,

$$y = n_t/n_{ref} \qquad \text{(eqn.1)}$$

From the field experiment, n_{ref} =109. To find the best explanatory variables in a colour-choice model we then converted reflectance spectra of the traps into quantum catch values $P_R(t)$ that a trap t elicits in a photoreceptor R, with

$$P_R(t) = \int I_t(\lambda)\, S_R(\lambda)\, D(\lambda)\, d\lambda \,/ \int I_b(\lambda)\, S_R(\lambda)\, D(\lambda)\, d\lambda, \qquad \text{(eqn.2)}$$

where $I_t(\lambda)$ is the reflectance spectrum of the trap t; $S_R(\lambda)$ the sensitivity function of the photoreceptor R, with the sensitivity peak of R varying between 320 nm and 610 nm in 10 nm steps; $D(\lambda)$ the standard sunlight illumination spectrum D65; and $I_b(\lambda)$ the reflectance spectrum of the background against which the trap is seen (Chittka *et al.*, 1992) (bare soil). Photoreceptor sensitivity curves $S_R(\lambda)$ were generated using model templates (Stavenga *et al.*, 1993). Physiological experiments revealed that the green receptor of the pollen beetle has a maximum sensitivity at 540 nm (see results). We therefore calculated output values of a colour opponency mechanism (COM) as a difference between the excitation of a fixed green receptor G peaking at

λ_{max} =540 nm and a second opponent receptor R_{opp}, with the peak sensitivity of this second receptor varying between λ_{max} =320 nm and λ_{max} = 610 nm in 10 nm steps.

$$COM_t(R_{opp}) = \log(P_t(G)) - \log(P_t(R_{opp})) \qquad \text{(eqn.3)}$$

After plotting the normalized number of beetles y against $COM_t(R_{opp})$ we then used split linear regression (Crawley, 2007) to determine the relationship between the colour opponency values and the behavioural response of the beetles. Ordinary Least Square optimization was used to determine the optimal position λ_{max} of the opponent photoreceptor R_{opp}. For all statistical calculations the programme R, v. 2.12.1 was used (R Development Core Team, 2011; Crawley, 2007).

Results & Discussion

Determination of spectral sensitivity of the pollen beetle

The maximal sensitivity determined from the ERGs was found at 520 nm (Figure 1). Most insect species measured so far show evidence of possessing two or more classes of photoreceptor (Briscoe & Chittka, 2001) i.e. as well as green receptors, many species have additional blue and UV receptors. The ERG response function stems from the summed response of all photoreceptor classes and it is therefore not possible from these measurements to determine the sensitivity of individual photoreceptor classes. However, using exponential templates for modelling sensitivity functions (Stavenga, *et al.,* 1993), we determined the spectral sensitivity of a putative green receptor underlying the ERG response. This modelled sensitivity function peaked at λ_{max} = 540 nm.

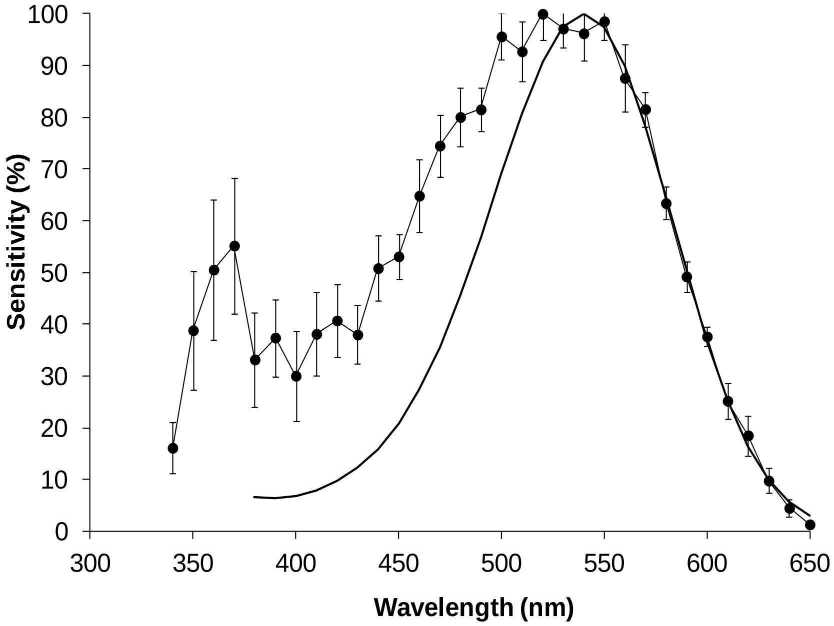


Figure 1 Spectral sensitivity functions from extracellular recordings of pollen beetle photoreceptors (filled squares, average ± standard error; n = 10), and modelled from the long wavelength tail of these measurements (bold line, no symbols).

Colour choice behaviour in the field

In total, 2482 pollen beetles were caught in the traps. The pollen beetle showed a strong response to the colour of the traps (see Figure 2 for reflectance spectra). The most beetles were caught in the fluorescent yellow traps, whereas the number of beetles caught in red, blue, white, grey or black traps was generally very low (Figure 3). These results support those of previous studies which document a preference for colours appearing yellow to the human eye over other colours (Blight & Smart, 1999, Cook, *et al.,* 2006a, Giamoustaris & Mithen, 1996). However, the importance of the UV component is shown for the first time; fluorescent yellow traps were more attractive than yellow traps without fluorescence.

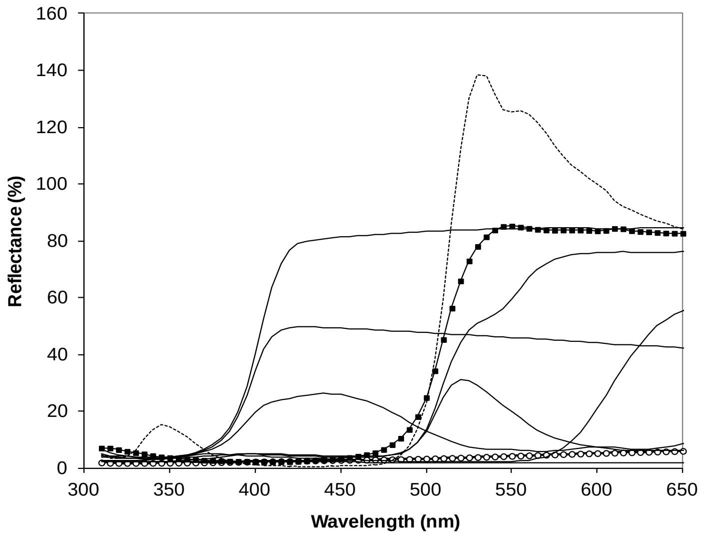


Figure 2 Reflectance spectra of selected traps. The dotted line shows the yellow fluorescent trap. The yellow reference trap (Y01) is indicated by the line with the filled squares.

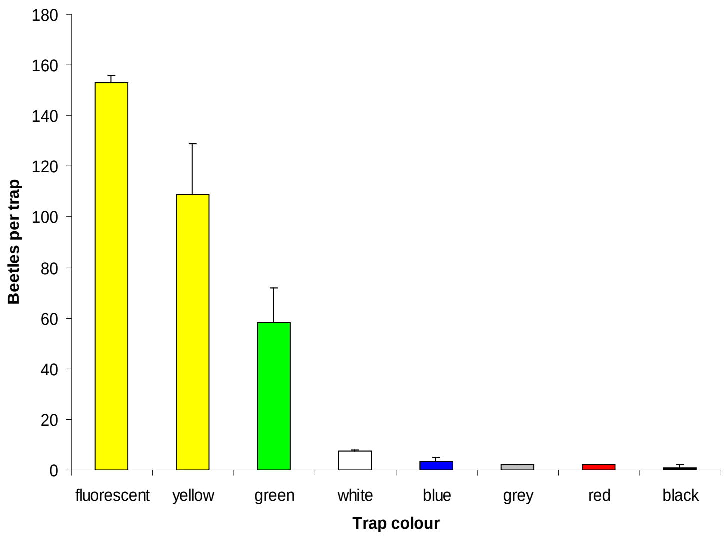


Figure 3 Mean (± SE) number of trapped pollen beetles caught in selected trap colours,
For reflectance spectra of these traps see Figure 2. The “yellow” trap was used as the reference trap (Y01).

Colour choice model

When the number of beetles relative to the reference catch is displayed against the respective value of $COM_t(R_{opp})$ of each trap (Figure 4), the relationship between the two variables can be modelled with a simple piecewise regression, with a split point at $COM_t(R_{opp}) = 0.2$. In this case, the best fit (SED = 0.0977, R^2=0.7982, df=94) was found for $\lambda_{max}(R_{opp})$ = 440 nm, whereas $\lambda_{max}(G)$ was held fixed at 540 nm.

Block effects were not significant. For the left-hand part of the model (i.e. left of the breakpoint where $x<x_0$), the slope was found to be not significantly different from 0. The intercept of the right hand side of the graph ($x>x_0$) was not significantly different from the intercept of the function left of the breakpoint ($x<x_0$). Thus, with y being the number of beetles relative to the number caught in the yellow reference trap (eqn. 1), the model had the shape

$y = a\,(x-x_0) + b$, for $x>x_0$, and $y = b$ for $x \leq x_0$, (eqn.4)

with $x = \log(P_t(G)) - \log(P_t(B))$, x_0=0.2 (breakpoint), a = 1.2997 ± 0.0650 and b = 0.0425 ± 0.0152 (mean ± s.e., R^2=0.7982, df=94, p<0.001). Here, the green receptor G peaks at λ_{max} = 540 nm and the opponent blue receptor peaks at λ_{max} = 440 nm; x can be interpreted as a yellowness index. Finally, we tested whether residuals u_t between the values $\hat{y}_M$ predicted by the split linear regression model M and the observed values y_i of the beetle catch

$u_t = y_t - \hat{y}_M$ (eqn.5)

were still correlated with the photon catch $P_t(R)$ of any modelled photoreceptors R (peak sensitivities at λ_{max} = R). This was the case; in particular, there was a positive correlation between photon catch in the UV and the residuals u_t indicating that higher UV reflection of a trap tended to increase beetle catch.

The model suggests that pollen beetles use a Green vs. Blue colour opponent mechanism which results in their preference for ‘yellow’ (in effect a super green stimulus). The model also confirms the possibility of a UV receptor in the pollen beetle. The model could have potential in predicting the relative attractance of any coloured trap with known spectral reflectance, thereby saving the need for time consuming and expensive field trials. The model could also be applied to other IPM strategies that exploit colour-guided host finding behaviour, for example the development of new OSR cultivars that have less attractive petals (e.g. Cook *et al.,* 2006b) or leaves.

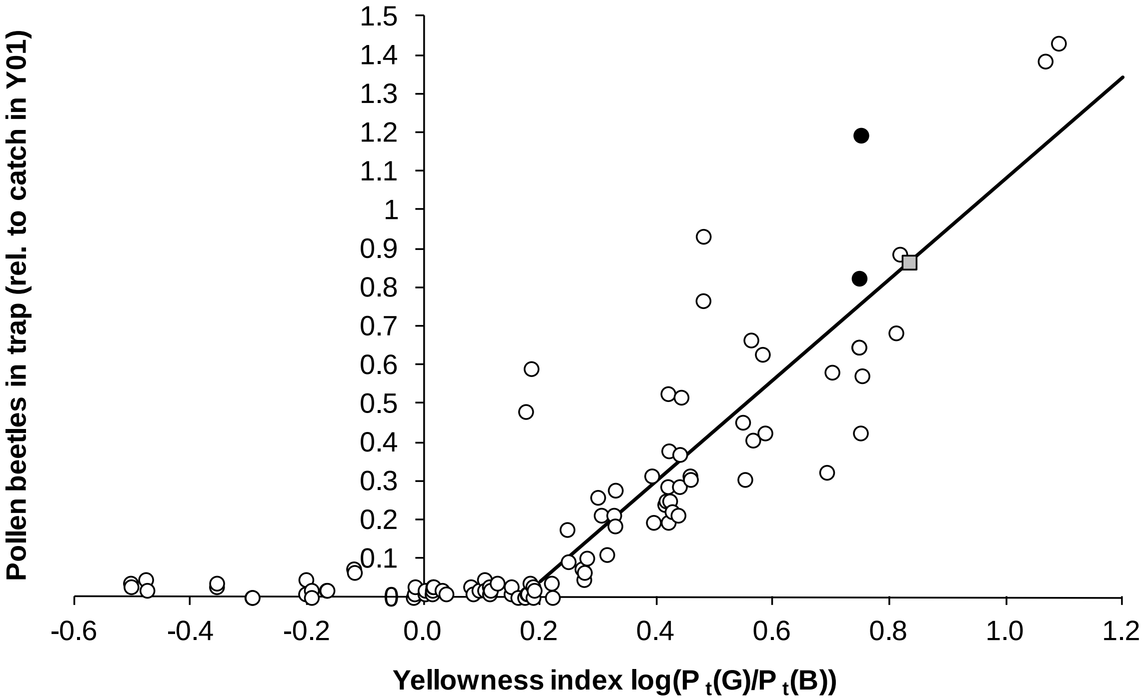


Figure 4 Colour opponency model (equation 4) of the behavioural response of pollen beetles to colours in the field. The theoretical position of a commercial yellow sticky card used to trap insects is marked by a grey square for comparison. The reference traps (Y01) are shown with black circles.

Summary & Conclusions

We confirmed the findings of previous studies which report a preference of the colour yellow in pollen beetles. However, we also demonstrated for the first time the importance of UV in this species. Traps with a UV reflectance component were most preferred, so we can predict that yellow sticky traps with a UV reflectance would be most attractive. After consultation with our Project partners at Oecos, this was considered to be too difficult to achieve for a plastic trap in the short term, so we conclude that until plastic colouration technology improves, the best colour for a monitoring trap is yellow, with the Oecos standard yellow sticky trap being relatively very attractive (Figure 4). The model we have developed could be used to help predict the relative attractance of any colour to pollen beetles, once its spectral reflectance is measured, and therefore could be of use for plant breeders when developing new oilseed/turnip rape lines for trap crops (highly attractive colours sought) or main crops (less attractive colours sought).

3.2.2. Identify and develop semiochemical lures for a monitoring trap with minimum catch of non-targets

Introduction

Since the initial attempts to develop a monitoring trap for pollen beetles carried out in the 1990s (see Introduction), Rothamsted has acquired a more sensitive mass spectrometer capable of accommodating the very low levels of semiochemicals to which insects respond. Methods of air entrainment have also been refined to enable plant volatiles to be sampled from intact plants *in situ*. These techniques, in conjunction with improvements in electrophysiology, have enabled the quantities and ratios of the attractive volatiles discovered in PI308 to be confirmed and new components to be identified. Field trials with turnip rape as an early flowering attractive trap crop to protect OSR against pollen beetles at the vulnerable green/yellow bud stage have been very successful (Cook *et al.,* 2004, 2006b). The attraction of pollen beetles to turnip rape was discovered to be due to not only its early flowering, but also to its production of different ratios of attractive plant volatiles, in particular, phenylacetaldehyde and indole (Cook *et al.,* 2007a). These compounds have been field tested in this project, along with new compounds identified from modern OSR varieties, allowing us to establish the best component for use as an attractive lure for a monitoring trap

Materials and Methods

Air entrainment. Samples of the volatiles released by plants, grown under glass house conditions, were taken to isolate and identify the range of volatiles in the profiles at green and yellow bud growth stages and during flowering. Single racemes were enclosed in a custom made glass vessel open at the bottom and closed with a collection port at the top. The bottom of the vessel was closed with two semi-circular aluminium plates that fitted around the stem of the plant and were clipped to a flange on the open end enabling volatile collections to be made with live rather than cut material. One of the aluminium plates was drilled to accommodate an inlet port, and purified air that had passed through a charcoal filter was pushed into the vessel at a rate of 500ml/min. Air was drawn from the vessel at a rate of 400ml/min passing through a Porapak Q filter, inserted into the collection port on the top, on which volatiles were collected. Air flow rates were controlled so that more purified air was pumped in than was drawn out, ensuring that unfiltered air was not drawn into the vessel from outside and obviating the need for a tight seal around the stem, which would have caused damage to the plant. All connections were made with PTFE tubing and ferrules, and as much as possible the equipment, particularly the glassware, was heated at 180°C for at least 2 hr before use. Porapak Q tubes were conditioned at 140°C in a stream of purified nitrogen for at least 2 hr before use. Plants were entrained for 1 week to collect sufficient material for subsequent analysis and bioassays. Porapak Q filters were eluted with 0.5 ml of redistilled diethyl ether, and the samples collected were stored in vials in a freezer (−20°C) and analysed by gas chromatography (GC). Where possible 4 entrainments of each plant/growth stage were made.

Gas Chromatography (GC). Air-entrained volatiles were separated on a 50 m x 0.32 mm i.d. methyl silicone bonded-phase fused silica capillary column (HP-1) fitted in a Hewlett Packard 5890 gas chromatograph equipped with a split/splitless injector and a flame ionization detector (FID). The carrier gas was hydrogen and the oven temperature was maintained at 40°C for 5 min and then programmed at 5°/min to 150°C, then at 10°/min to 250°C. Co-injections with reference samples were made under the same conditions.

Gas Chromatography-Mass Spectrometry (GC-MS). The capillary column (50 m x 0.32 mm i.d. HP-1) of the gas chromatograph was directly coupled to the MS and integrated data system (70-250 VG Analytical). Ionization was by electron impact at 70 ev, 230°C. The GC was maintained at 30°C for 5 min and then programmed at 5°/min to 180°C and then held isothermally. Identifications were made by comparison of the mass spectral data with those of authentic samples and confirmed by peak enhancement when the extracts of volatiles were co-injected with authentic compounds using GC, as above.

Electrophysiology: To identify the volatiles from the entrainment samples that are perceived by pollen beetles, coupled gas chromatography-electroantennography (GC-EAG) recordings were made as described previously (Wadhams, 1990) using Ag-AgCl glass electrodes filled with saline solution (composition as in Maddrell, 1969, but without glucose). Adult pollen beetles were field-collected by sweep-netting OSR and maintained overnight at 18°C, without food, before use and their sex was determined later by dissection. Antennae were excised and suspended between the two electrodes. The signals generated by the antenna were passed through a high impedance amplifier (Syntech UN-06, Hilversum, the Netherlands), and data storage and processing were carried out with a PC-based interface and customised software package (Syntech). Separation of the entrained volatiles was achieved on an AI 93 gas chromatograph equipped with a cold on-column injector and a FID. The carrier gas was hydrogen and the column (50 m x 0.32 mm i.d. HP-1) was maintained at 40ºC for 1 min and then programmed at 5º/min to 100ºC and then at 10º/min to 250ºC. The outputs from the EAG amplifier and FID were monitored simultaneously and analysed using Syntech software (Syntech, The Netherlands). Replicates for each compound comprised preparations from five individual insects

Slow release dispensers. Possible attraction of pollen beetles to compounds, identified as being electrophysiologically active, was tested in the field using yellow sticky traps (Oecos) baited with dispensers releasing each compound at two different rates where possible. Each compound was released individually by diffusion from polyethylene bags. Undiluted liquids were applied to pieces of cellulose sponge (3 mm thick or 10 mm thick, J Sainsbury plc) that were heat-sealed into bags made from polyethylene bags or tubing (A1 Packagings Ltd., London) or in closed lid polythene vials (Just 001: Just Plastics Ltd, UK). Indole lures were formulated with the antioxidant butylated hydroxytoluene (BHT). Acetone solutions of indole and BHT were applied to pieces of sponge and the acetone allowed to evaporate before the treated sponges were sealed into bags. Different release rates were obtained by altering the type and surface area of the cellulose sponge and the gauge of the polyethylene. Nominal release rates were measured by weight loss in the laboratory at 20°C and 0.2 m/ sec airflow.

Field Trapping Experiments. The orientation responses of pollen beetles to electrophysiologically active odours and to different coloured traps were tested in a series of replicated field trapping experiments conducted on Rothamsted Farm. To compare beetle response to odours, each experiment comprised yellow sticky card traps (10 x 20cm Oecos, UK), angled at 45° to the vertical using a plastic mount maintained on a metal post (Oecos). Traps were maintained at crop canopy height and were 10m apart from each other in any direction. Traps were unbaited (control) or baited with slow release dispensers (see above) of test compounds or a lure of 2-phenylethyl isothiocyanate (NCS) released at 5 mg/day (Smart and Blight, 1997). The latter compound, a component of OSR volatiles, had been shown in previous field experiments (Blight and Smart, 1999) to attract pollen beetles and was used here as a standard. Trials were set out as a Latin square (Experiments 1 and 2) or using a replicated Latinized row-column design (experiments 4 and 5). Sticky cards were changed approximately weekly until the crop was fully in flower and were stored in a freezer at -20°C, and insects were identified and counted in the laboratory. Total trap catch data were transformed by $\log_{10}(x+1)$ and analysed using ANOVA or, for the Latinized row-column design, by REML using GenStat (14^{th} edition, VSN International, 2011). The mixed model accounted for the different sources of variation: fields, replicates within fields and position of plots within reps. The data were $\log_{10}$ (n+1) transformed and LSD differences at the 5% level on the transformed scale are presented.

Experiment 1 Optimise pollen beetle catch and minimize beneficial catch by investigating colour x odour interactions using commercially available coloured traps

Although experiments in Section 3.2.1 indicated that the most effective trap for pollen beetles was yellow (and preferably with a component of UV), we explored the possibility that the relative trap catch of pollen beetles : beneficial parasitoids could be improved by the use of a different coloured trap. Pollen beetle and parasitoid catch on commercially available white and blue sticky card traps (Oecos) and a prototype trap painted grass green were compared to the standard yellow sticky card trap, each with and without a 2-phenylethyl ncs lure (2-PE ncs) in field experiments (see Materials & Methods section above) using 4 x 4 Latin square designs in spring OSR crops during the green-yellow bud growth stage in 2009. The ratio of pollen beetles:parasitoids was calculated and compared between the differently coloured traps with and without the bait.

Experiment 2. Compare the standard 2-phenylethyl isothiocyanate lure with lures of turnip rape volatiles

In order to improve the safety and attractiveness of the prototype yellow sticky trap, slow release dispensers (see Materials & Methods section above) were designed to release different ratios of phenylacetaldehyde and indole, the key odours identified from previous work as accounting for the obvious difference between the increased attraction of TR over OSR plants (Cook *et al.,*2007b). These were compared to the standard 2-phenylethyl ncs lure (2-PE ncs) in a field trapping trial (see Materials & Methods section above) in replicated 5 x 5 Latin square designs. The baited yellow sticky traps were tested during the main colonising period of winter OSR crops (March – April) in two different winter OSR crops over two seasons (2008 and 2009) to determine if they could be used in place of the 2-PE ncs lure (which is toxic). They were also deployed in combination with the 2-PE ncs lure to determine if the efficacy of the trap could be improved by use of a multilure. Release Ratios of Phenylacetaldehyde : Indole were as follows

2 : 1 equivalent to that found in TR buds

3 : 1 equivalent to that found in TR flowers

1 : 10 equivalent to that found in OSR flowers

Experiment 3. Collect, identify and field test volatiles from different rape varieties

To improve our understanding of the importance of volatiles released by host plants for the attraction of pollen beetles and to identify any new active compounds, the volatiles of 10 different rape types were collected by air entrainment (see Materials & Methods section above) at the green bud and flowering growth stages. Included were spring turnip rape cv Agena and Agat; spring oilseed rape cv Heros; Pasja winter turnip rape; winter oilseed rape cv Astrid and Grizzley; and some experimental lines kindly provided by project partner Dr Peter Werner of KWS Ltd, which included a white petalled and an apetallous line together with their near-isogenic yellow-petalled counterparts. The volatiles collected were identified using gas chromatography-mass spectroscopy (GC-MS) (see Materials & Methods section above) and tested in electrophysiological studies using female pollen beetles (see Materials & Methods section above). New compounds not found in volatiles collected previously from cut plants (Blight *et al.,* 1995) included: nonane, nonanal, methyl benzoate and acetophenone and, specifically from green bud samples, methyl benzene.

Dispensers releasing the new compounds, at two different release rates where possible, were produced for testing in field trials. Fifteen volatile bait treatments plus an unbaited control were tested in trapping trials (see Materials & Methods section above). A Latinized row-column trial design was used in which traps were arranged in 2 rows of 8 treatments and replicated twice per field on 3 OSR sites in April 2010, to test the response of the over wintered generation of beetles, and four times on 1 wheat site in May/June 2010, to test the response of new generation beetles.

Experiment 4. Towards the development of a commercial trap

Trap mounts: Project partner Oecos produce an angled sticky trap for use with a lure for carrot fly monitoring. This trap was compared in field trapping trials (see Materials & Methods section above) with the RRes 45° angled trap used in Experiments 1-3. Both were used to mount yellow sticky cards (Oecos) and the RRes low release phenylacetaldehyde lure (300ul/ thick sponge/ 250 gauge bag, pre-conditioned for 5 days to obtain a steady release of 1.7mg/day over 35 days).

Lure dispenser: International Pheromone Systems (IPS Ltd) supply lures for a range of commercial pheromone trapping systems and they developed prototype phenylacetaldehyde lures for possible commercial use. They provided samples of the lures, initially for release rate determination by air entrainment and weight loss over time. Two of the prototype lures released the volatile at similar rates per day as the RRes low release phenylacetaldehyde lure (see Appendix A) and were chosen for testing in comparative field trials (as above) with the RRes 45° angled yellow sticky trap. Both trapping trials used the Latinized row-column trial design described in Experiment 3 above.

Results & Discussion

Experiment 1 Optimise pollen beetle catch and minimize beneficial catch by investigating colour x odour interactions using commercially available coloured traps

It is important to minimise non-target catch, particularly that of beneficial insects so to conserve as many individuals for biocontrol services as possible, but mainly to make it as simple as possible to count the target pest on the trap. This becomes increasingly difficult as non-target catch increases. The different coloured sticky traps tested were much less effective at capturing pollen beetles than the yellow trap (Figure 5A-C). The addition of a bait increased pollen beetle catch on traps of less attractive colours, but numbers caught remained very low in comparison to the unbaited yellow trap (Figure 5A-C). The coloured traps caught fewer parasitoids than the yellow traps and in these trials the lure had little effect (Figure 6A-C). With the exception of green, baiting the trap increased the proportion of pollen beetles with respect to parasitoids. The highest proportion of pollen beetles:parasitoids was found on baited yellow traps (Table 1). Therefore we decided to proceed with developing a baited yellow sticky trap.

Table 1 Proportion of pollen beetles : parasitoids caught between 20 May – 9 June 2009 on yellow, white, blue or green sticky traps unbaited or baited with a 2-phenylethyl isothiocyanate lure

	Yellow 1	White	Yellow 2	Blue	Yellow 3	Green
Unbaited	2.0	0.3	2.0	0.5	2.3	0.1
Baited	3.1	1	2.9	0.9	3.5	0.1

Experiment 2: Compare the standard 2-phenylethyl isothiocyanate lure with lures of turnip rape volatiles

Results for both years were similar and are presented for 2009 in Figures 7 & 8. Trap catch was very variable within and between sites, but showed that the baited traps were more attractive than the unbaited trap; the P:I ratio of 1:10, representative of the volatiles found in OSR flowers, was most attractive (Figure 7 A&B) and phenylacetaldehyde:indole lures were as effective as the standard 2-phenylethyl ncs lure (Figure 7A). Addition of 2-phenylethyl ncs did not improve the efficacy of the lure (Figure 7B). The baited traps caught more non-target parasitiods than the unbaited trap, but parasitoids were not caught until one week after the peak pollen beetle catch and overall numbers caught were low, therefore unlikely to have much impact on local populations or swamp the traps (Figure 8A&B). These results suggest that the bait with the toxic 2-PE ncs lure developed in previous studies can be replaced with a lure based on low release rates of Phenylacetaldehyde, a floral volatile common in several species. As indole is difficult to formulate, (as it is relatively unstable) we decided to attempt to further simplify the bait and test the effects of these volatiles individually in 2010.

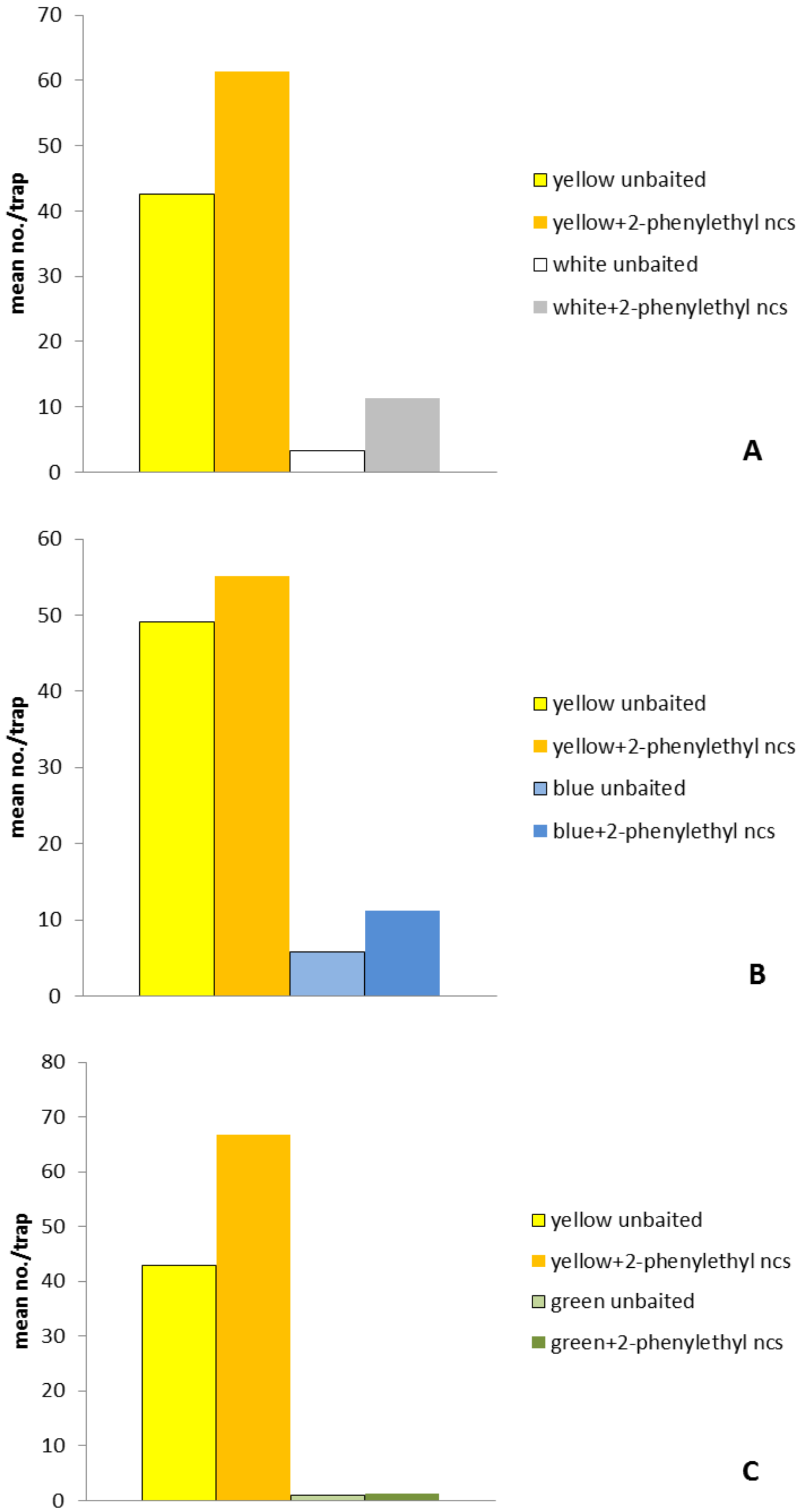


Figure 5A-C Mean number of pollen beetles caught between 20 May – 9 June 2009 on sticky traps baited with a 2-phenylethyl isothiocyanate lure or on unbaited traps coloured yellow versus (A) white, (B), Blue or (C) or green

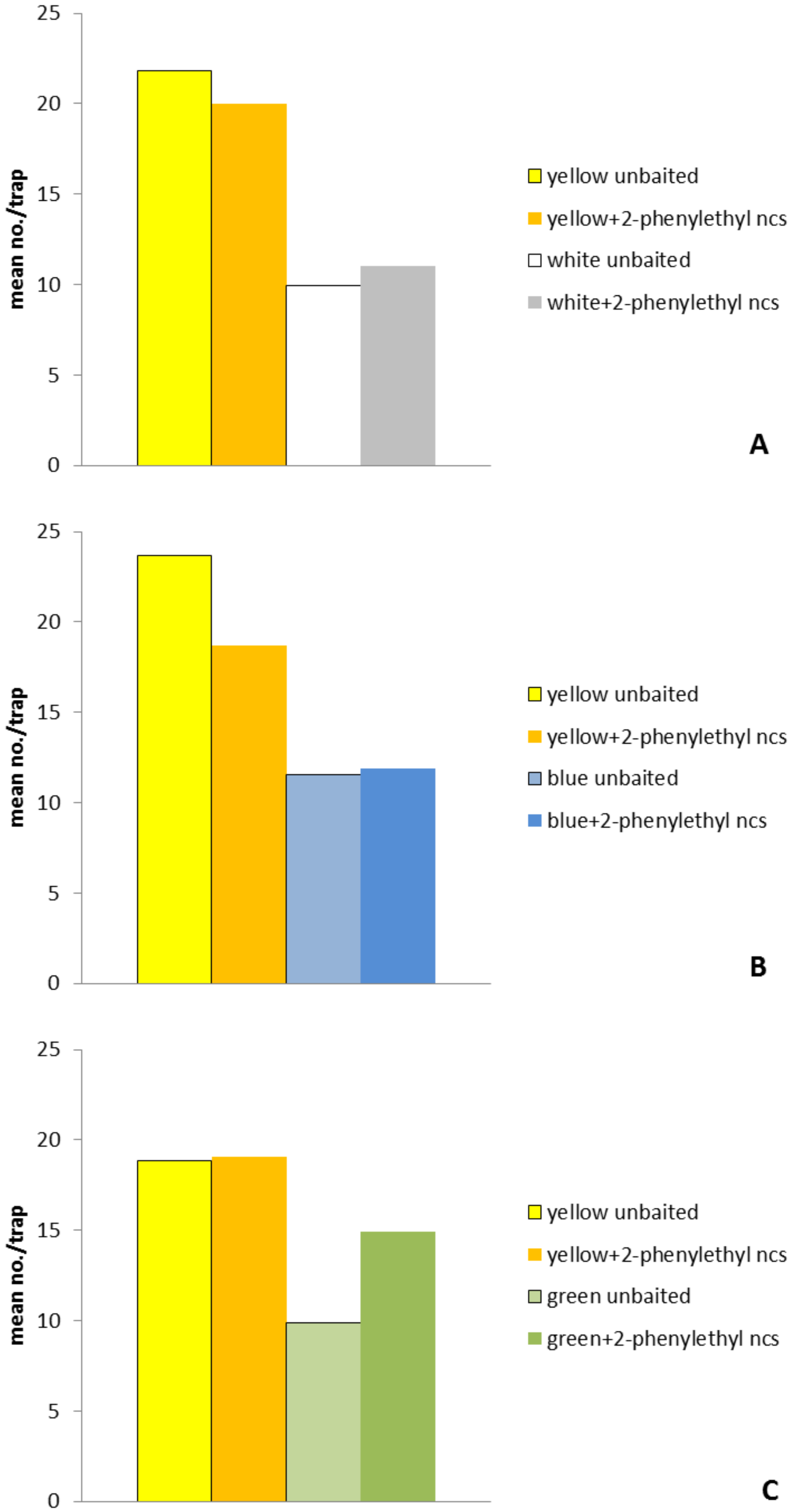


Figure 6A-C Mean number of non-target parasitoids caught between 20 May – 9 June 2009 on sticky traps baited with a 2-Phenylethyl isothiocyanate lure or on unbaited traps coloured yellow versus (A) white (B) Blue or (C) or green.

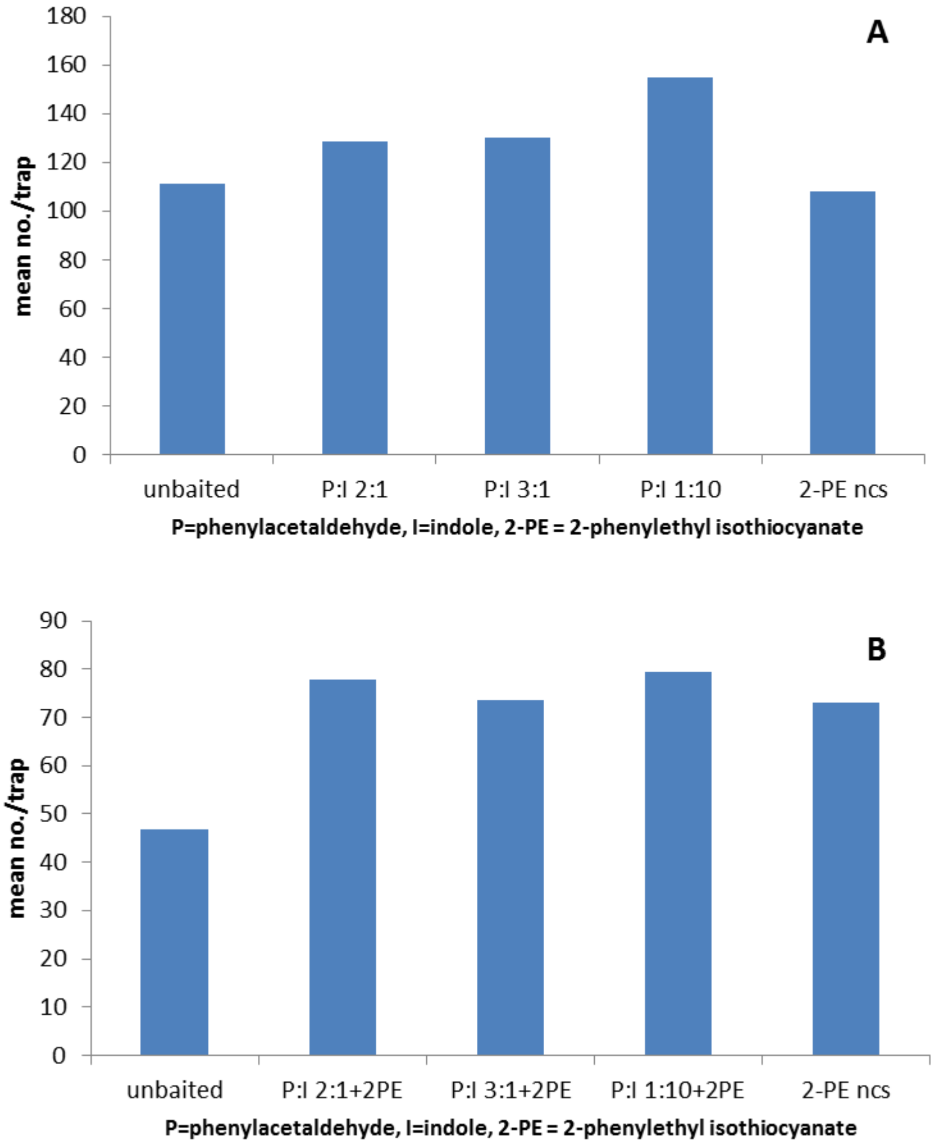
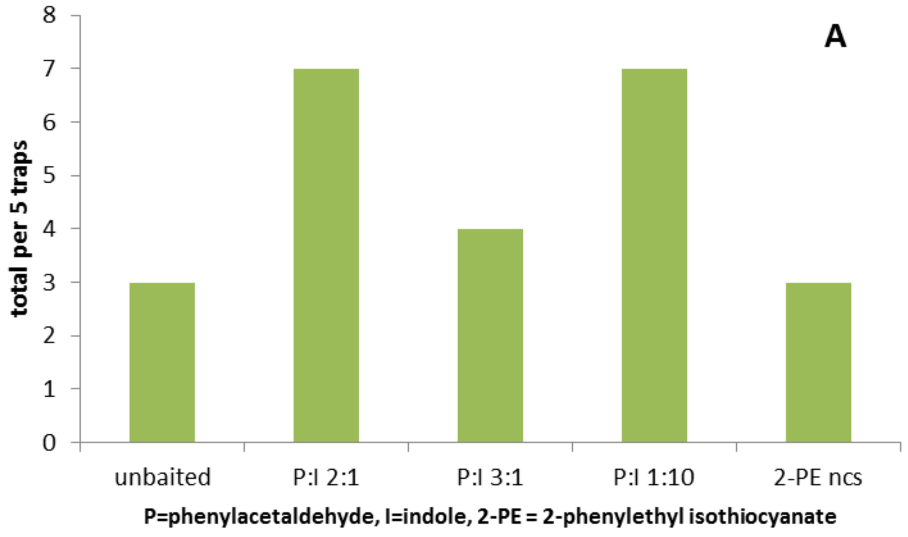


Figure 7 Mean number of pollen beetles caught on yellow sticky traps baited with different volatiles (31 March – 15 April 2009) (A) unbaited traps tested against 3 different ratios of phenylacetaldehyde : indole (P:I) and 2-phenylyethyl isothiocyanate (2-PE) (B) unbaited traps tested against 3 different ratios of P:I + 2-PE and 2-PE alone. Rations of P:I represent volatiles as released in nature from: turnip rape buds (2:1), turnip rape flowers (3:1) and oilseed rape flowers (10:1)



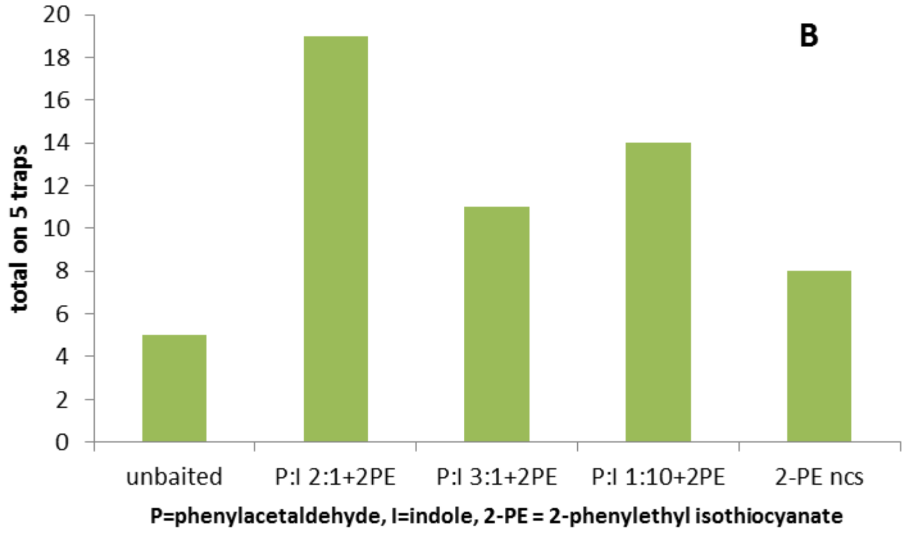


Figure 8A&B Mean number of parasitoids caught on yellow sticky traps traps baited with different volatiles (31 March – 15 April 2009) (A) unbaited traps tested against 3 different ratios of phenylacetaldehyde : indole (P:I) and 2-phenylyethyl isothiocyanate (2-PE) (B) unbaited traps tested against 3 different ratios of P:I + 2-PE and 2-PE alone. Rations of P:I represent volatiles as released in nature from: turnip rape buds (2:1), turnip rape flowers (3:1) and oilseed rape flowers (10:1)

Experiment 3. Collect, identify and field test volatiles from different rape varieties

There was quantitative and qualitative variation in the volatiles collected from the different OSR and TR types tested. Some new electrophysiologically active compounds were detected from the *in vivo* entrainment samples and provide a more detailed picture of the natural volatile profiles that the pest encounters in the crop. Those not found in volatiles collected previously from cut plants (Blight *et al.*, 1995) included: nonane, nonanal, methyl benzoate and acetophenone and specifically from green bud samples, ethyl benzene.

In the field experiment testing these new compounds, there was a significant difference between treatments in the mean number of pollen beetles caught in the traps ($F_{15, 132.5}$ = 5.49 P<0.001). Only the low release rate (1.7 mg/day) of phenylacetaldehyde attracted significantly (LSD = 0.1663) more beetles than the unbaited trap on the OSR sites (Figure 9). The indole, when released individually at the high rate as in 2008/09 was not significantly more attractive than the control, and when released at a lower rate it attracted significantly fewer (LSD = 0.1663) (Figure 9). Both rates of nonanal, the high rates of acetophenone and methyl benzoate also attracted significantly fewer beetles than the unbaited trap (LSD = 0.1663). These may provide leads for further investigation towards developing crop cultivars that are less attractive to pollen beetles.

In the absence of competition from the crop, the 2-phenylethyl isothiocyanate lure attracted the highest number of beetles in the wheat crops (Figure 10) followed by the low rate of phenylacetaldehyde. The low release rate of phenylacetaldehyde (LSD = 0.1958) and indole - low rate (LSD = 0.1989) and indole - high rate (LSD = 0.1958) both also attracted significantly more beetles than the unbaited trap. The high rates of nonanal (LSD = 0.1989) and of acetophenone (LSD = 0.1988) attracted significantly fewer beetles than the unbaited control.

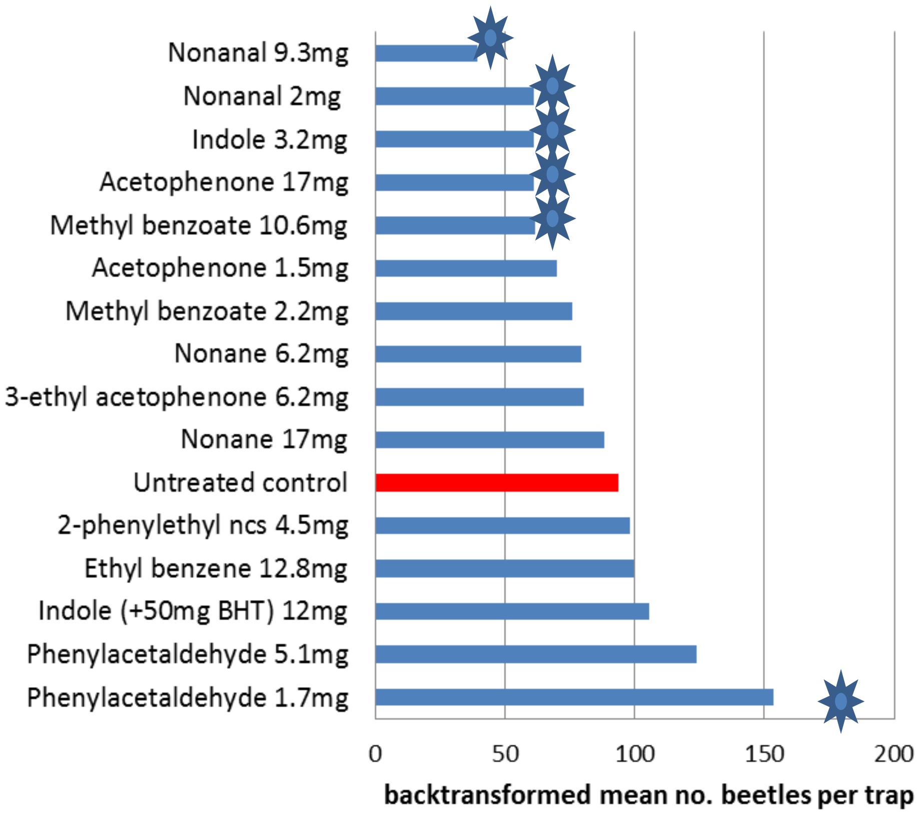


Figure 9 Mean number of pollen beetles caught on yellow sticky traps baited with dispensers releasing different oilseed rape volatiles (mg/day) set out in crops of oilseed rape (2010). Stars above bars represent a significant difference from the unbaited control according to LSD values

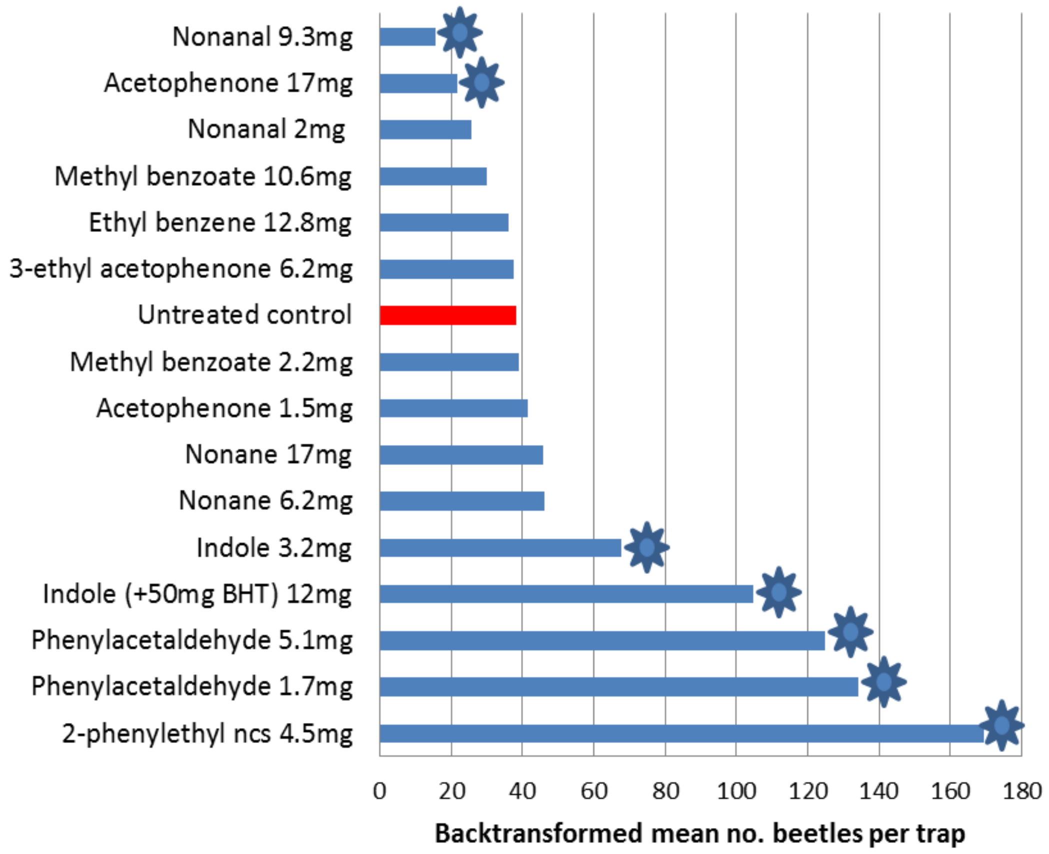


Figure 10 Mean number of pollen beetles caught on yellow sticky traps baited with dispensers releasing different oilseed rape volatiles (mg/day) set out in crops of wheat (2010). Stars above bars represent a significant difference from the unbaited control according to LSD values on the transformed scale.

The low release of phenylacetaldehyde (1.7 mg/day) performed most consistently overall and was further investigated as the possible lure for the baited commercial trap at Rothamsted field sites in 2011.

Experiment 4. Towards the development of a commercial trap

Trap mounts: There was no difference in the performance between the Oecos carrot fly trap mount and the RRes experimental mount ($F_{6,125}$ = 1.38; P = 0.228) (Figure 11). However, the performance of the baits changed over time ($F_{6,142}$ = 4.19; P<0.001) in that more beetles were generally caught earlier in the trapping period than in the final couple of assessments. This could be due to the baits becoming less effective over time.

Lures: One of the field sites for this experiment was excluded from the analysis as the crop was poor; ANOVA rather than REML was used. However, it was clear that both commercial IPS phenylacetaldehyde lures were as attractive as the RRes low release phenylacetaldehyde lure and all baited traps generally caught more beetles than unbaited traps (Figure 12). As with the trap mounts experiment, there was a significant difference between the treatments over time ($F_{12,48}$ = 3.57; P<0.001). On the last two sample dates there was no significant difference between trap catch between baited and unbaited traps. Given the results of the Trap mount experiment, this suggests that it is not only the bait that is responsible for the loss in attraction of the trap in relation to the crop in flower. The IPS lures were shown to release relatively constant amounts over c. 30 days (Appendix A). It is more likely that the traps became relatively less attractive as competition from the crop increased as it came into flower and became relatively more attractive to beetles in comparison to the trap than when the crop was at the green bud stage. However, as the traps would normally be used for monitoring during the damage-susceptible green-yellow bud stage of the crop, the reduction in attraction is not a problem. Relatively low numbers of non-target species were trapped in these experiments (data not shown), however it was noted that traps that were left out beyond the period of the experiment caught extremely high numbers of parasitoids of the wheat blossom midge. Traps should therefore be removed as soon as possible at the start of flowering, and certainly before the end of May to avoid this. Furthermore, as the crop develops it gets taller and there is a danger that traps will get swamped by the crop and difficult to locate and remove later in the season.

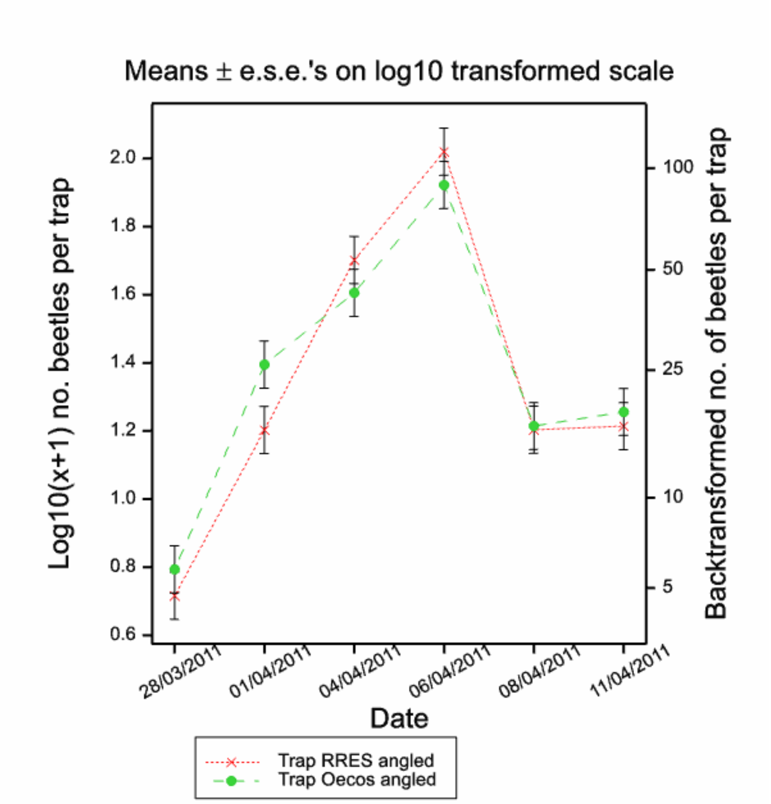


Figure 11 Pollen beetles caught by RRes and modified Oecos trap mounts with sticky traps baited with a low release dispenser of phenylacetaldehyde (1.7 mg/day).

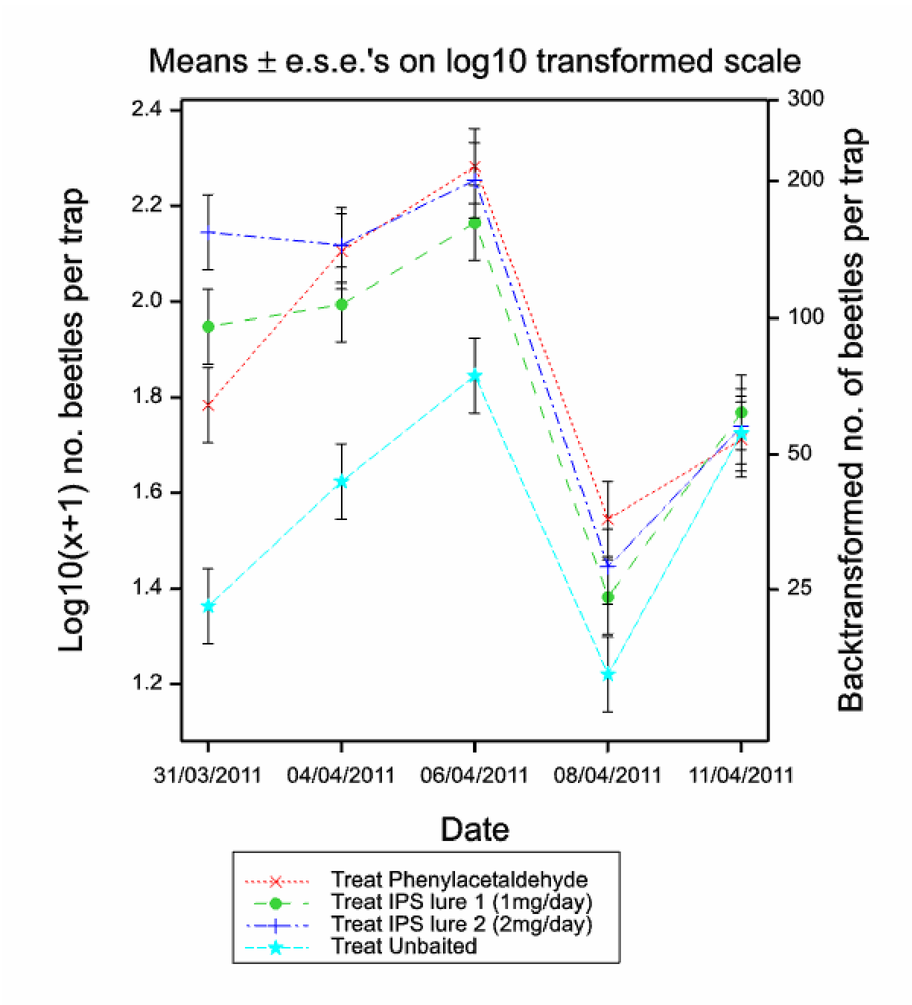


Figure 12 Comparison of IPS phenylacetaldehyde lures (1 mg and 2 mg/day) with the standard RRes phenylacetaldehyde lure (1.7 mg/day).

Summary & Conclusions

These results suggest that a modified Oecos yellow sticky trap baited with an IPS commercial type lure are suitable for a commercial trapping system for pollen beetles. We are delighted that a trap with these components will be made commercially available for the 2013 season by Oecos.

3.2.3. Calibrate trap catch with numbers of beetles per plant in oilseed rape crops

Introduction

Commercial monitoring traps usually have a given number of target insects or a threshold above which action is taken. Currently, action thresholds for pollen beetles are related to the number of beetles on oilseed rape (OSR) plants during the damage susceptible green-yellow bud stage of the crop. Throughout the duration of the project the action threshold for pollen beetles was 15 beetles per plant for good crops and 5/plant for backward crops. However, the threshold has recently changed to relate to crop plant density plants/m^2; 20 beetles per plant for optimal crops (40 plants/m^2), 30/plant for thin crops and 10/plant for thick crops (Ellis & Berry, 2011; HGCA, 2012). We therefore hoped to be able to determine a linear correlation between the trap catch and the number of beetles present on plants in the crop to enable calibration of trap catch to any given action threshold. We used data from trap catches and no. beetles/plant data derived from plant scouting along monitoring transects on 178 fields of winter OSR across the UK over 4 years. Unfortunately, we were unable to find a simple correlation between beetle numbers on the traps and numbers on plants in the crop.

Materials & Methods

Pollen beetle monitoring study

There were 3 aims to the monitoring experiments:

1. To establish a relationship between the numbers of pollen beetles caught on traps with the number of beetles per plant in the OSR crop (this section)
2. To establish a relationship between trap catch and position of the trap with respect to prevailing wind direction and surrounding landscape features (see section 3.2.4)
3. To assess the relationship between immigration of pollen beetles into the OSR crop through time relating to climatic conditions and the growth stage of the crop (phenology) (see section 3.3)

We ran a pollen beetle monitoring study in each of the 4 years of the project (2008-2011). In each year, sites (winter OSR fields) were selected on Rothamsted Farm, Woburn Farm and on as many other farms as possible across the UK. At each site, two yellow sticky traps were placed on different sides of the field; one trap was placed upwind and the other downwind along the plane of an assumed west-south-west prevailing wind (Figure 13). Upwind and down-wind designated traps remained fixed for the duration of the trapping period (i.e. even though the wind direction may have changed at a local level). The traps (yellow sticky cards, Oecos) were mounted on the RRes plastic mount so that they were angled at 45° and placed on top of a metal pole (Oecos) so that the trap could be maintained at crop canopy height throughout the trapping period. Traps were placed 3m into the crop from the edge and orientated to face outwards, away from the crop centre, in order to trap incoming beetles (Figure 13). Trapping started on March 1st each year and continued until the crop was at BBCH growth stage 61 (early flowering, when ~ 10% flowers on the main raceme were open). Traps were then removed from the site.

Traps were changed either twice each week (every 3-4 days preferable) or once each week, depending on time availability of the volunteers running each site. Each time the traps were changed the mean number of beetles per plant in the crop at each trap position was calculated using a plant scouting method based on that recommended by CropMonitor www.cropmonitor.co.uk. Pollen beetles were sampled from 10 plants selected at random every ~5m along a 50m transect from the crop edge towards its centre using the beating method (Williams *et al.*, 2003). The results were recorded on an assessment form together with the growth stage of the crop using the BBCH scale (Lancashire *et al.*, 1991). Weather variables (temperature, wind direction, whether or not it had rained within 12h prior to the assessment and general weather conditions at time of assessment) and notes on crop damage or insecticide treatments were also recorded. Spent traps were carefully labelled (upwind or downwind trap, site name and dates set out and taken in) and returned with the transect assessment form by post to Rothamsted for processing; each assessment form and trap was logged and traps were stored in a freezer at -20°C until the number of pollen beetles, pollen beetle parasitoids, beneficial insects (bees, butterflies, hoverflies etc) and 'other non-targets' were counted and recorded.

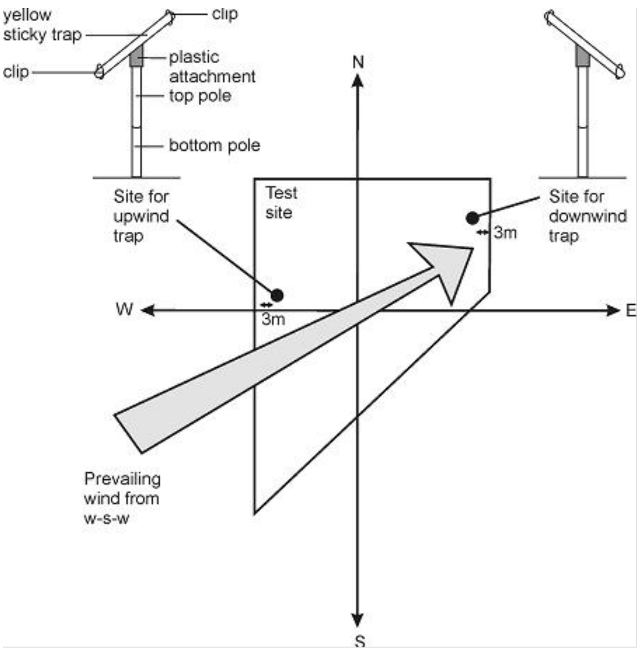


Figure 13. Trap assembly and positioning on field sites in the pollen beetle monitoring study. Each site assumed a west-south west prevailing wind. Potential sites for upwind and downwind traps are marked and the orientation of the traps (facing out of the crop) shown.

In order to help establish a relationship between trap catch and position of the trap with respect to the prevailing wind direction and surrounding landscape features (Monitoring Experiment aim no. 2 above; and see section 3.2.4), volunteers were also asked to provide information on their site including the co-ordinates of the field (if known), a map indicating the positions of the upwind and downwind traps on the study field, and information on the surrounding landscape within a 1km radius of each trap including positions of OSR crops in both the current and previous year.

Statistical analysis: correlation of the numbers of pollen beetles on the traps with the numbers on plants in the crop

Data from traps and plants in the crop were log transformed ($\log_{10}(x+1)$) and analysed by calculating the Pearson's correlation coefficient using GenStat (14th edition, VSN International, 2011). The following correlations were calculated: between pollen beetle numbers on traps vs. numbers on plants in the crop; between upwind traps vs. upwind numbers in the crop; between downwind traps vs. downwind numbers in the crop. We also calculated correlations between pollen beetle numbers in upwind vs. downwind traps; and between numbers on plants in the crop on upwind vs. downwind. For the correlation analyses the sites with very low counts (mean trap count of <5) were excluded. Analyses were also restricted to data recorded from crops at the damage susceptible stage (between GS 50-59).

Results & Discussion

Pollen beetle monitoring study

As a result of HGCA and AICC meetings, pieces in the farming press (Abel, 2010; ADAS, 2010; Case, 2010, 2011; Cook & Ferguson, 2007; Henly, 2010, 2011) and a little arm twisting, the number of volunteers increased in each year of the study; in 2008, 17 sites participated, in 2009 there were 27 sites, in 2010, 57 sites and in 2011, 77 sites - from all over the major OSR-growing regions of England and Scotland (Figure 14). The enthusiasm shown and willingness of these very busy people to freely give up their time towards this study is evidence of the scale of the pollen beetle problem in their view, and their desire to have alternative management tools such as a monitoring trap at their disposal.

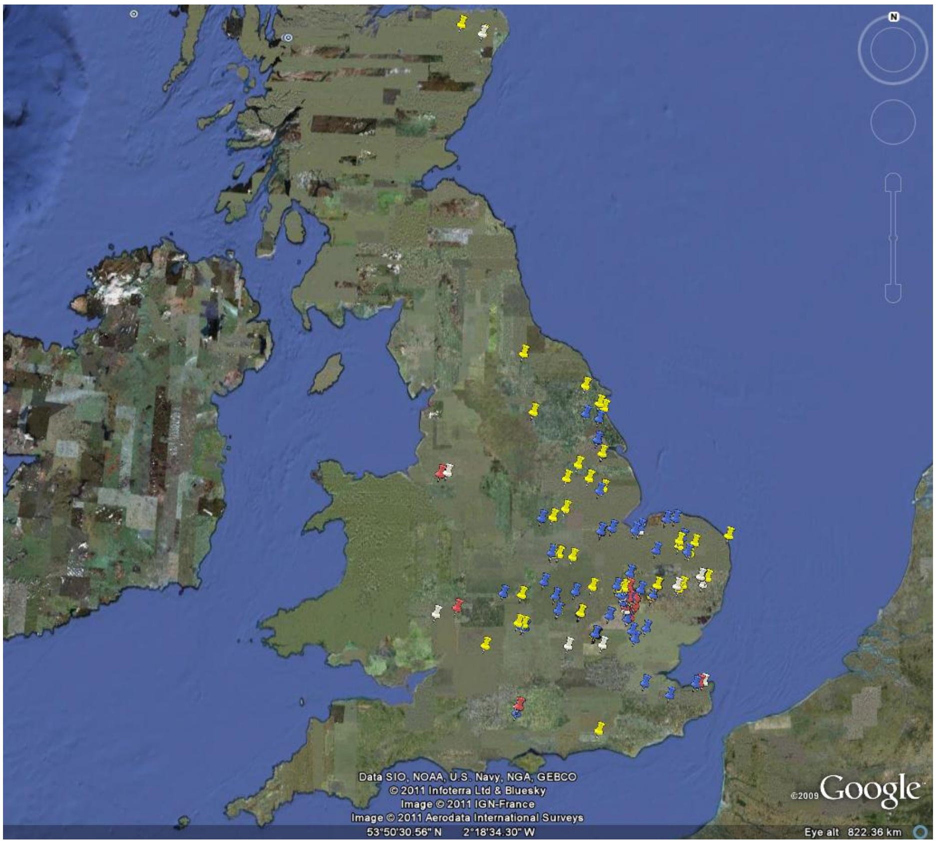


Figure 14. Positions of the oilseed rape sites participating in the pollen beetle monitoring study 2008-2011 [2008 (white), 2009 (red), 2010 (blue) and 2011 (yellow)]. Names and counties of each volunteer are given in the Acknowledgements section (3.11)

Over the duration of the study a total number of 155,727 pollen beetles were caught on traps. As expected, the total number caught each year increased as the number of sites participating in the study increased, but the mean number of beetles caught per trap also increased dramatically from years 1-4 of the study (Table 2). To some extent this may represent selection of sites that had good (i.e. large) trap catches for participation in following years. However, it is also likely that these data represent increasing size of the pollen beetle infestations from one year to the next. Data collected by FERA on the abundance of pollen beetles in crops across England & Wales is published on the CropMonitor website for 2005 and 2008 http://www.cropmonitor.co.uk/wosr/surveys/wosr.cfm but otherwise there is little information on the size of pollen beetle populations from one year to the next and this may warrant further investigation.

As beetles are known to fly upwind to colonize OSR fields (Williams *et al.,* 2007) we expected to catch more beetles in the traps placed downwind than upwind on the field sites. However, we found little evidence to support this hypothesis (Table 2) (but see section 3.2.4 which explored this in more detail, and found that the hypothesis cannot be rejected if wind direction is accounted for).

Table 2. Number of pollen beetles caught on yellow sticky traps in oilseed rape crops in a pollen beetle monitoring study 2008-2011

Year	Total number of pollen beetles caught	Mean (±SE) number of beetles caught per trap	Mean (±SE) number of beetles caught per trap - upwind	Mean (±SE) number of beetles caught per trap - downwind
2008	3,142	8.12 (0.82)	7.54 (1.32)	7.24 (1.30)
2009	16,344	18.85 (1.74)	15.64 (2.01)	15.96 (3.40)
2010	60,301	29.46 (2.08)	20.61 (3.04)	25.00 (3.61)
2011	75,670	40.49 (2.49)	45.76 (5.05)	28.76 (3.11)

Statistical analysis: correlation of the numbers of beetles on the traps with the numbers on plants in the crop

There was evidence for a correlation between the numbers of beetles trapped in the upwind and downwind traps and a strong positive correlation between the numbers of beetles per plant in the upwind and downwind crop scouting transects. However, there was no significant correlation between the trap catch and numbers on plants in the crop transects (Table 3).

Table 3. Pearson's correlation coefficients between pollen beetle numbers caught on traps (traps) and the mean number per plant derived from plant scouting from 10 plants along a 50 m transect from the crop edge towards the centre (transects)

Correlation	R	n
Total trap catch vs. total in transects	0.2249	280
Upwind traps vs. upwind transects	0.2423	280
Downwind traps vs. downwind transects	0.2484	280
Upwind vs. downwind traps	0.5609	280
Upwind vs. downwind transects	0.8044	280

Summary & conclusions

Unfortunately there was no simple correlation between the number of beetles caught in the traps and the number of beetles present on plants in the crop. We are therefore unable to calibrate trap catch to a given action threshold expressed as the number of beetles per plant using a simple linear relationship. There may be other factors that could help to explain the variance in the data, such as landscape factors and/or meteorological effects (see section 3.2.4) and work conducted in the Extension to this project (see Appendix C) will attempt to model these effects to improve calibration efforts. It should also be noted that the results presented here are based on numbers of beetles caught on a simple yellow sticky trap and not the prototype trap with a bait developed in Objective 1 of the project, which was shown to increase trap effectiveness (see Section 3.2). There may be value in repeating calibration experiments using the commercial traps. Furthermore, there may be great value in further work to calibrate the trap catch with actual *crop damage*, rather than numbers of beetles in the crop as a more direct action threshold to prevent crop loss. This will be investigated in the Extension to this project (see Appendix C).

In the meantime, it is important to point out that the monitoring trap still has value for pollen beetle management. The trap can be used at the start of the season (early March) to detect the start of immigration; if there are none on the trap there will be none in the crop, and there is no need to treat with insecticide. It may also be used to focus monitoring on crops (which is time consuming); as a rough rule of thumb if there are c.10 beetles on the trap, it is probably worthwhile monitoring the plants in the crop. It may also be used to detect peaks of immigration, but these will be relative to previous trap catches on the site, and completion of immigration, when the numbers on the traps do not increase, or begin to decrease.

3.2.4. Develop models to determine the best trap position

Introduction

We know from previous work that pollen beetles migrate to OSR crops upwind (Williams *et al.,* 2007) and generally colonize the crop from one direction, starting at the crop edge (Williams & Ferguson, 2010) resulting in an uneven distribution of beetles throughout the crop during its damage-susceptible stage (Ferguson *et al.,* 2003a,b). This poses a problem for crop scouting methods and for the positioning of monitoring traps, as unless several transects are performed or more than one trap placed on different sides of the field, values based on one sample position only could run the risk of under-estimating the pest population. However, in the interests of costs, it is preferable for growers to minimize sampling effort. A better understanding of the immigration behaviour of pollen beetles into OSR crops could help growers and crop consultants to know where best to place a monitoring trap or perform a crop scouting transect if only one sample is to be used to determine whether or not action thresholds have been breached or not. Such knowledge would also help to inform on where best to place trap crops (see section 3.5) or help to identify fields that may be at particular risk of pollen beetles.

We hypothesise that pollen beetle immigration into a given field will be influenced by meteorological conditions such as wind direction and temperature, and environmental features such as woodlands or hedgerows (where pollen beetles may hibernate) (Williams, 2010), the presence of OSR crops in the previous year (if they hibernate close to previous crops) and the presence of OSR crops in the current year (may increase attraction to a given field if block-cropped with other OSR if it is perceived by beetles to be a ‘super-stimulus’, or conversely this may have a ‘dilution effect’ resulting in fewer beetles on a given field than if that field was the only OSR crop in the near-locality).

We attempted to model the effect on pollen beetle trap catch of meteorological conditions and landscape features using data on the trap catch of pollen beetles from the pollen beetle Monitoring study (see section 3.2.3), meteorological data from the Environmental Change Network and UK Meteorological Office, and landscape information derived from information collected during the Monitoring study. We found strong evidence that meteorological conditions (temperature, wind direction and speed and daytime rainfall) and some evidence that landscape features (area of residential gardens, length of hedgerow and length of treeline) affect trap catch.

Materials & Methods

Digital mapping of environmental features surrounding sticky trap sites and the extraction of area and length data

In order to provide data to help determine the influence of landscape factors on trap catches of pollen beetles, relevant landscape features surrounding were digitally mapped within a 1km-radius around each trap using Google Earth. GIS software was then used to extract information on the areas or lengths of these features from within eight directional segments of a 1km circular buffer area mapped surrounding each trap.

Trap locations (upwind and downwind) were initially found using either coordinates or maps provided by the volunteers hosting field sites, and were marked using place-marker ‘points’ in Google Earth (Figure 15). Mapping was then carried out within a radius of approximately 1.1 km of each trap point (a slightly larger radius than that of the buffer area was used to ensure that the mapped area was of sufficient size for data extraction). The features to be mapped were chosen on the basis of their potential to provide overwintering habitats for the beetles, or were important as sites for feeding and reproduction (i.e. OSR crops). Linear features (hedgerows and lines of trees) were marked by drawing a line, or ‘path’ along them. Non-linear features (woodlands, residential gardens and OSR fields) were mapped by drawing ‘polygons’ around their perimeters, enclosing them. The features were usually clearly visible from the most recent Google Earth satellite photographs, but if they were not, images taken at earlier dates could be viewed to support the presence or absence of a particular feature. OSR fields within the area around each trap were mapped both for the trapping year, and for the previous year, using information provided by the site hosts. Once digitization was complete, the points, paths and polygons were converted into 'shapefile' format for use in ArcGIS.

Background maps, or 'basemaps' for the areas of interest were obtained from the EDINA OS Digimap service, and imported into the GIS software. The trap locations and the associated mapped landscape features were added and superimposed over the relevant basemap, ensuring that compatible geographical projections were used for data from different sources. At this point it was possible to visually check the correct alignment of the digitized data and the basemap.

A custom template for the 1 km-radius buffer was created using a spread sheet designed to plot the perimeter and segments of the buffer for any inputted pair of coordinates. The coordinates were read off for the trap location in ArcGIS, and then used within the spread sheet to plot the template. The template was then imported into ArcGIS, and a visual check made to ensure that it was centred on the desired trap location. The template was then used within ArcGIS as a buffer to extract the area and length data of individual features from within each of the eight segments. The segments were 45 degrees wide and centred on NNE, ENE, ESE, SSE, SSW, WSW, WNW and NNW bearings. The final ArcGIS output was a table of area and length data for the fragments of landscape features located within each of the directional segments around a trap. A visual check of the GIS map was performed on each occasion to confirm that the data extraction had been successful.

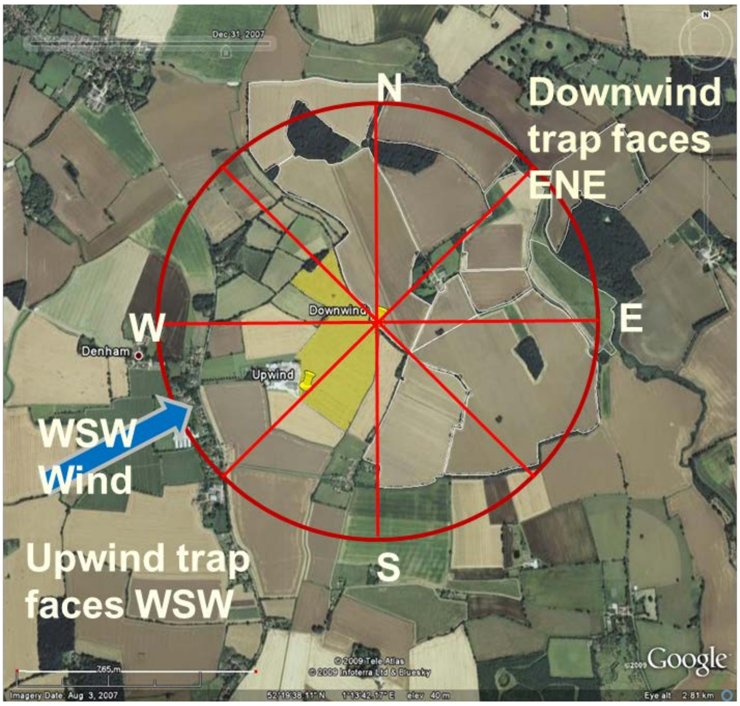


Figure 15 Mapping environmental features surrounding the pollen beetle traps. Areas of woodlands, residential gardens, oilseed rape crops in the current year or previous year and the length of tree-lines and hedges were mapped (see white lines) within a 1km radius of each trap (surround of downwind trap shown) and calculated for each of 8 segments

Weather data

Hourly weather data (temperature, wind speed and direction, rainfall) for Rothamsted and Woburn farms was obtained from the UK Environmental Change Network (www.ecn.ac.uk). Daily weather data (minimum and maximum temperature, daytime rainfall, wind speed and direction at 1200) were obtained from the UK Meteorological Office 'Daily Sites' data set for the weather stations closest to each field. Daily weather variables were calculated for Rothamsted and Woburn to match the variables obtained for the other sites. Wind directions were identified with the segments used to define to landscape sectors.

The temperature variables were then transformed into a quantity thought more likely to relate to insect behavior. Accumulated temperature for each day (day-degrees above 10°C) was derived from min and max temperature per day using a saw-tooth approximation. The daily minimum temperature was assumed to occur at 5am; the daily maximum was assumed to occur at 3pm; with interpolation by straight lines between these points. The accumulated temperature was calculated as the integral of this saw-tooth function during the period 0600-1800 (daylight hours) when temperature > 10°C. The baseline temperature of 10°C was used as no trap catches were observed unless the maximum temperature exceeded this value.

Modelling

Since meteorological variables, particularly temperature, were known to strongly affect pollen beetle catch within crops (Ferguson *et al.*, in press) it is necessary to adjust for these variables when trying to detect the effect of landscape. We expect that temperature, rainfall and wind speed might affect the number of beetles coming into the crop, and that wind direction might affect the direction from which beetles enter the crop, with beetles tending to fly upwind towards the crop. We also hypothesize that landscape features may affect the numbers of pollen beetles entering the crop – we assume that beetles fly reasonably directly towards the crop, and so landscape features in the 3 landscape segments facing each trap were used as explanatory variables for that trap.

The first step in the modelling process is to build a model of daily counts for trapped beetles; these numbers can then be accumulated across the trapping period. This model was implemented as a GLMM (generalized linear mixed model, Breslow & Clayton, 1993) with a composite link function (Thompson & Baker, 1981) used to implement the accumulation step. Random effects were used to define the structure of the data set as traps and days within fields, and this ensures that the correct denominator degrees of freedom are used in F tests for testing fixed terms. An initial model was fitted using weather variables only, written as

$$\log(\mu_{ijk})=c+\alpha T_{ik}+\beta_{v(ik)} + \gamma W_{ik}+ \delta_{u(ijk)}$$

where:

μ_{ijk} is the expected number of beetles in field i, on a trap in quadrant j, on day k

c is an overall constant

T_{ik} is the accumulated temperature (day-degrees) for field i on day k

β_v are a set of factor effects (v=2,3,4) for daytime rainfall (R_{ik}) in field I on day k. The index v is classified as 2 for $0.01 < R_{ik} \leq 1$, 3 for $1 < R_{ik} \leq 2.5$, and 4 for $2.5 < R_{ik}$.

W_{ik} is the wind speed at 12:00 in field i on day k

δ_u is a set of factor effects (u=2,3,4) for the discrepancy between the segment faced by the trap and the downwind segment from which beetles are expected to arrive (flying upwind). The index u is equal to the discrepancy in direction (measured as segments) with u=1 for no discrepancy.

The unknown parameters to be estimated in this model are c, α, β_v for v=2,3,4, γ and δ_u for u=2,3,4. This model uses first-level-zero parameterization, so the overall constant includes the effect of zero rainfall ($R_{ik}\leq 0.01$) and no discrepancy between the trap and wind direction. All explanatory variables were standardized (to zero mean and unity standard deviation) before analysis. The distribution of the trap counts was assumed to be negative binomial, to allow for spatial clustering (heterogeneity) that had been observed previously.

This model was extended by adding random terms for field, trap and day variation. Quadratic terms for the weather variables temperature, rainfall and wind speed were added to allow for curvature in these relationships. Landscape variables (areas of woodland, residential gardens and OSR crops in the current and previous year, lengths of treeline and hedgerow) were then added into the model, also using a quadratic form in order to detect curvature. This gave the full model which was then simplified using backwards selection, dropping the variable with the least significant marginal F-test ($p>0.1$) at each step.

Results & Discussion

Thirty fields were selected for modelling. These fields each had good landscape data provided by site hosts and several positive trap catches within the green bud period. These 30 fields encompassed 12 sites across four years (2008-2011) with 616 trap catches in total (108 in 2008, 210 in 2009, 150 in 2010 and 148 in 2011). For these sites, the minimum trap catch was zero, with maximum catch = 1368; median catch = 10 and mean catch = 55.27.

Summary statistics for landscape variables are given in Table 4. A large range of values is present for each of the variables and in most cases, the distribution of values is skewed (mean > median).

Table 4. Summary statistics for landscape variables for traps included in analysis

	Area (m^2)				Length (m)	
Summary statistic	Wood	Garden	OSR crop current year	OSR crop previous year	Hedge	Treeline
Minimum	0	0	21	0	0	0
Mean	135337	157789	88306	51678	3139	8846
Median	99452	50743	31449	28698	3006	534
Maximum	628402	955574	822312	600601	9376	3210

The final model contained terms for several meteorological variables: accumulated temperature (quadratic), wind speed (linear), daytime rainfall (as a factor) and discrepancy between wind and trap direction (as a factor). Several landscape variables were also retained in the model: area of residential gardens (linear), length of hedgerow (linear) and length of treeline (linear). Parameter estimates and their SEs are shown with t-statistics in Table 5. Clearly temperature, wind speed and direction are the dominant explanatory variables. The response to temperature (back-transformed onto the natural scale) is shown in Figure 16; beetle numbers increase as temperatures increase from 0 to 3.5 day-degrees (corresponding to a constant temperature of 13.5°C) and then decrease as temperatures increase further. Sedivy & Kocourek (1994) also reported that mass flight could occur at temperatures >13.5°C and recently Ferguson *et al*. (in press) found pollen beetle flight within a plot of OSR at 12°C. Beetle numbers decrease as wind speed increases, and as the amount of rainfall increases. Beetle numbers also decrease for a 3-segment discrepancy between trap and wind direction but then increase for a 4-segment discrepancy. This may reflect wind influence on beetle flight direction: beetles may fly upwind towards a crop, or be carried downwind towards it.

Beetle numbers increased as the area of residential gardens increased, as the length of treeline increased and as the length of hedgerow decreased, but these effects were much smaller than those for the meteorological variables.

Table 5 Estimated fixed effect from fitted generalized linear mixed model. Temperature, windspeed, area and length variables all standardized. Linear and quadratic terms fitted as orthogonal polynomials

Term	Estimate	SE	t
Constant	0.3065	1.2245	0.25
Accumulated temperature (linear)	1.1433	0.1305	8.76
Accumulated temperature (quadratic)	-0.7558	0.1325	-5.71
Windspeed	-1.4306	0.1412	-10.13
Rainfall 0.01-1mm	-0.7020	0.3769	-1.86
Rainfall 1-2.5mm	-1.2056	0.6763	-1.78
Rainfall >2.5mm	-2.2864	1.1410	-2.00
2 segment discrepancy in wind direction	-0.2584	0.1355	-1.91
3 segment discrepancy in wind direction	-1.0132	0.1494	-6.78
4 segment discrepancy in wind direction	-0.4845	0.1820	-2.66
Area of residential gardens	0.1676	0.0870	1.93
Length of hedgerow	-0.2540	0.0919	-2.76
Length of treeline	0.1767	0.0930	1.90

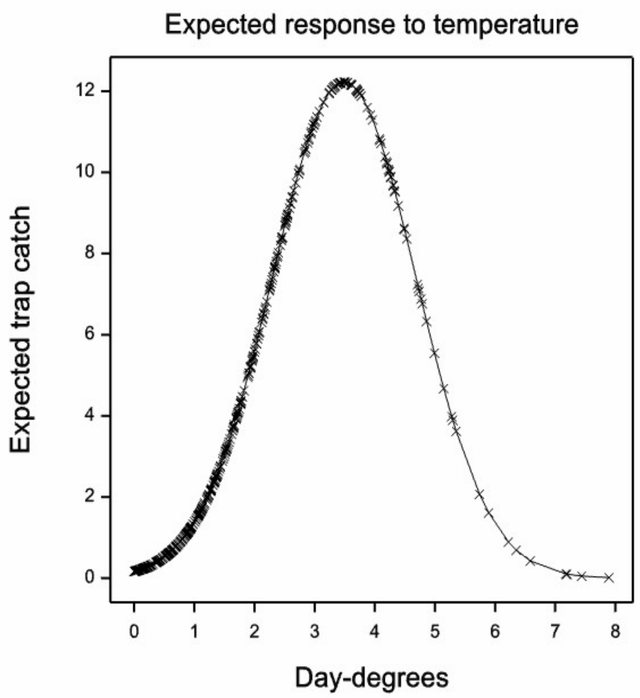


Figure 16. Expected trap catch of pollen beetles in response to accumulated temperature (day-degrees above 10°C) for no rainfall and other explanatory variables at their mean values.

As for all regression models, this model is based on observed correlations between the explanatory variables and the response, and may not reflect any causal mechanism. Given this caveat, these results are biologically interpretable in terms of causation with respect to the weather variables. The correlation with increased treeline could be interpreted as suggesting that pollen beetles may overwinter in treeline in preference to hedgerow, but this hypothesis would require further testing.

Summary & Conclusions

We have found that trap catches are strongly affected by weather conditions and weakly affected by landscape features. The effect of temperature suggests that there is no need to trap when the maximum temperature is below 10°C. The effect of wind direction suggests that traps should be placed on the down-wind side of a crop. However, variation in wind direction means that this position may vary between sample dates.

3.3. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle (Objective 1, Task B)

3.3.1. Introduction

A decision support system (DSS) that accurately identifies the period of risk by modelling pollen beetle population dynamics could focus monitoring (crop scouting and use of monitoring traps), making it less onerous. This could increase take-up of decision support systems and IPM tactics as a whole, and lead to reductions in unnecessary insecticide treatments to oilseed rape (OSR).

Advice on pollen beetle management is currently available to UK growers through the CropMonitor™ website www.cropmonitor.co.uk. CropMonitor™ is a collaboration between 10 organisations, including government agencies, levy bodies and industry. It provides up-to-date measurements of crop pest and disease activity in arable crops across England and acts as portal for access to a wide range of information on pests and pest risk assessment. Advice is compiled by Farming Online www.farming.co.uk from reports received from members of the Association of Independent Crop Consultants www.aicc.org.uk. Advice obtainable through the CropMonitor™ website is hereafter referred to as 'current advice'. The period of risk from pollen beetles to OSR is defined in current advice in the UK as 'green-to-yellow bud stage' (BBCH growth stage 51-59; Lancashire 1991) and it is advised that 'backward crops are most at risk'. Monitoring effort can be further focussed using current advice in the UK that states that 'pollen beetles fly at temperatures of 15°C or above'. However a simple temperature threshold is unlikely to take account of all significant factors governing the timing of immigration, and crop scouting every time the temperatures exceed 15°C is onerous, if not impractical for most growers and crop consultants. Improved DSS are needed.

'proPlant expert' http://www.proplantexpert.com/ (hereafter referred to as 'proPlant') is a web-based DSS developed in Germany that alerts the user to the start of pest immigration and its progress. Its forecasts are based on phenological models developed from historical pest data and a sophisticated use of weather variables (Johnen *et al*., 2010). The proPlant model for pollen beetles is parameterised by daily records of air temperature, rainfall, sunshine and wind speed, automatically downloaded from local meteorological stations. It provides local three-day forecasts of pest immigration risk that indicate whether monitoring is needed. proPlant is widely used commercially for OSR in Germany, Austria, the Czech Republic, France and Sweden. Users of this DSS in Germany apply less insecticides against spring pests than those not using the system (Johnen *et al.*, 2006).

The performance of proPlant was tested for pollen beetles in UK conditions and compared with current advice in relation to pollen beetle management in the UK. We assessed the accuracy with which the two DSS's identified immigration risk by reference to data from four years of field observations and compared the monitoring effort each recommended.

3.3.2. Materials and methods

Field observations

For this study 44 OSR crops that were intensively sampled in the Pollen beetle Monitoring study for pollen beetle phenology (see section 3.2.3) were chosen (2, 10 , 12 and 20 fields in 2008, 2009, 2010 and 2011, respectively). At these fields pollen beetles were sampled both by scouting on plants and by sticky traps. Samples were taken approximately twice-weekly during the green-to-yellow bud stage of the crop. Observations following any spring insecticide applications were excluded from the analysis as pollen beetle mortality following treatment would influence counts on plants in the transects and the reliability of detecting further immigration. The mean number of pollen beetles per plant was calculated for each field site on each sample date and compared to the standard spray thresholds of two, five and 15 beetles per plant for normal crops, backward crops and varietal associations, respectively (Oakley, 2003). It was not possible to sample crops daily so it was assumed that any threshold breach took place on the sampling date on which it was observed. This conservative assumption is independent of either DSS and the weather data on which they are based and any delay in the recognition of a threshold breach is likely to affect the performance assessment of each DSS equally.The timing of growth stages 51 and 59, which delimit the period of plant vulnerability to pollen beetle damage, were estimated by interpolation from growth stage data recorded on the twice-weekly sample dates, taking into account the progression of growth stages at other sites in the same year.

Weather data

Weather data were obtained from UK Met Office or farmer-operated meteorological stations within 1-80 km (average 16 km) of each sampled field. The proPlant phenological model requires daily measurements of minimum and maximum air temperature (°C), average air temperature (°C), rainfall (mm), sunshine (h) and average wind speed (m/s).

proPlant expert Decision Support System

proPlant expert provides forecasts for the day the system is consulted and the following two days. proPlant output gives a graphical display of weather data (max and min temperature, sunshine hours and rainfall) together with an ‘immigration’ bar on which forecasts are given of the start, peaks and end of immigration (Figure 17). The immigration bar also indicates the daily level of risk of immigration with a traffic-light system of coloured dots (green = immigration possible, yellow = good conditions for immigration and red = optimal conditions for immigration; here presented in grayscale, Figure 17).

The version of the proPlant model used in this UK study was the same as that used in all European countries where it is marketed. In 2011 the model was adjusted globally, extending the period to completion of immigration to give a better fit to observed data from Germany. Also in 2011, the model was refined to allow the user to tailor the model to local conditions of wind exposure, using a simple choice of two settings, open to wind or not. Finally, the graphical display of proPlant output was modified to indicate the days on which monitoring is advised. Monitoring days are indicated by vertical lines beneath the immigration bar (Figure 17). The monitoring indicator is accompanied by a figure giving an estimate of the percentage of the population of beetles that is predicted to have migrated from overwintering sites. This information is intended to allow the user to estimate the potential magnitude of any further immigration, relative to the size of beetle populations already in the crop.

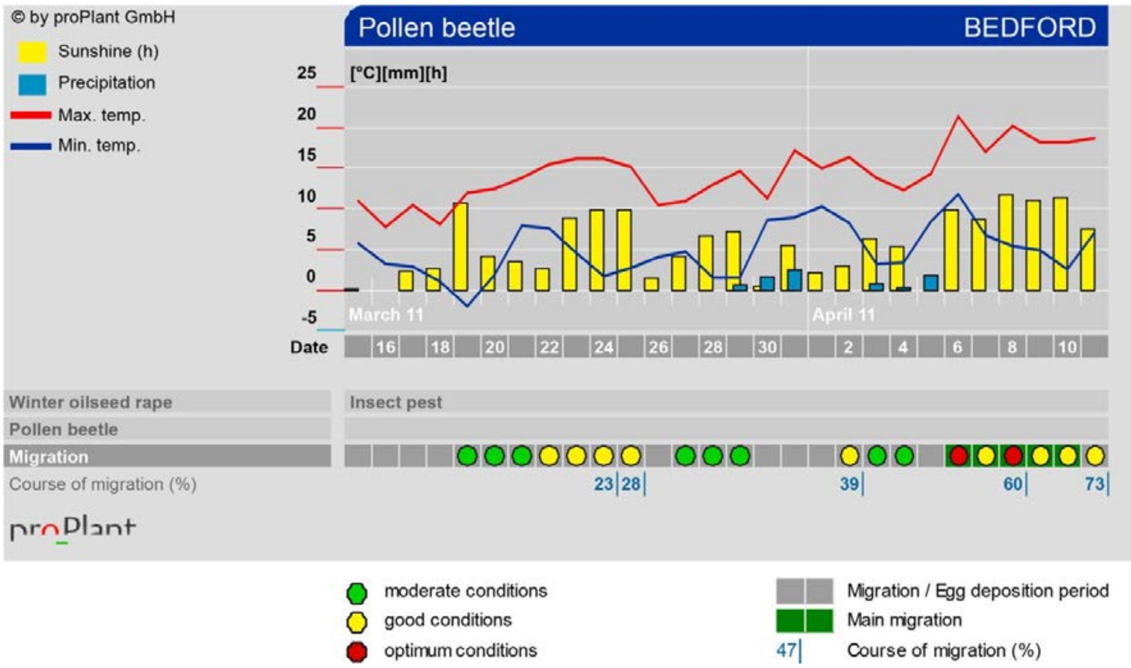


Figure 17. Example of proPlant output for the Bedford weather station 2011.

Criteria for assessment and comparison of DSS's

For both DSS', standard UK recommendations on spray thresholds and the susceptibility of crops to damage were followed. Advice derived from the two DSS' was compared in relation to the phenology of pollen beetles in the field from the Monitoring experiment and any breaches of the three thresholds (two, five and 15 beetles per plant). For each site and for each DSS, the dataset used was delimited by the period between the start of growth stage 51 and day on which the breach of threshold would be detected, had the advice of the DSS been followed. If no threshold breach was detected, the dataset was taken from the whole period delimited by growth stages 51 and 59.

Most assessments and comparisons of DSS' were made *a posteriori*, using known pollen beetle phenology and known weather data. To check the validity of this approach, an analysis of the performance of the two DSS' in real-time in 2011 was also made. proPlant uses weather forecasts to model future risk and therefore to forecast sampling days. Current advice states that beetles fly above 15°C so the risk of immigration can again be assessed from the weather forecast. Weather data from the UK Met Office Bedford site were used to provide daily three-day forecasts of weather parameters using the German Weather Service forecast model from 2 March to 21 April 2011. These data were used to provide three-day proPlant prognoses and forecasts of maximum temperature. Using this data, the performance of the each DSS in real time was assessed in relation to field monitoring data from nine sites within 50km of Bedford. This approach provides a more rigorous test of both DSS' as it takes into account the uncertainty inherent in weather forecasts.

DSS performance measures

Four performance measures were compared for current advice and for proPlant:

i) Number of days when consultation of the DSS was required

For current advice, all days during the susceptible plant growth stage (51-59) were designated as 'consultation days', i.e. days when the weather forecast should be consulted as to whether the temperature was likely to reach 15°C. proPlant was first consulted on the day that the crop reached growth stage 51. Thereafter, proPlant was consulted every either third day or on any day when a dot (of any colour) had been indicated by the previous consultation, whichever was more frequent. If proPlant indicated that immigration was complete, the last consultation was made on the following day, otherwise consultations stopped after growth stage 59.

ii) Number of monitoring days recommended

Monitoring is recommended by current advice on all days with a maximum temperature ≥15°C during growth stages 51-59. proPlant advises that monitoring is necessary only on days when the model indicates yellow or red dots (risk of significant immigration) during growth stages 51-59. Monitoring should start on the day with the first yellow or red dot. Thereafter, if a contiguous series of such days occurs, proPlant advises that monitoring is needed only every third day and the last day in the series.

iii) No. of breaches of threshold detected by the recommended monitoring

It was assumed that a breach of threshold would be detected by the first monitoring day to be advised by each DSS on or after the date when experimental sampling had shown the threshold (2, 5 or 15 beetles/plant) to have been breached.

iv) Relative timeliness of detection of threshold breaches

The number of days difference (if any) between current advice and proPlant in prompting the detection of threshold breaches was calculated.

Measures of immigration risk

Two measures of immigration risk were also compared between DSS'. The accuracy with which the start of pollen beetle immigration was indicated by each DSS was assessed by comparing the phenology of pollen beetle numbers on sticky traps with the first dates that the DSS' forecasted immigration risk (temperature ≥15°C for current advice and the first dot of any colour for proPlant). The number of days each DSS forecasted significant risk of pollen beetle immigration prior to each threshold breach (or until the end of growth stage 59) was also compared (all days with maximum temperature ≥15 °C for current advice and all days with yellow or red dots for proPlant expert).

Predictive accuracy of proPlant and current advice

The accuracy of current advice in forecasting pollen beetle immigration due to temperatures exceeding 15°C was assessed by comparing real-time three-day temperature forecasts (for days 0, +1 and +2) at the Bedford weather station in 2011 with the temperatures actually recorded. Similarly, the accuracy of proPlant three-day forecasts of significant immigration (yellow or red dots) at Bedford in 2011 was tested by comparison with the risk levels determined from the model *a posteriori* using recorded weather data.

Statistical analysis

The data were transformed ($\log_{10}(n + 1)$. The number of consultation days advised, the number of monitoring days advised and number of days of immigration risk prior to each threshold breach was analysed using a bivariate mixed model accounting for variation between the sites (GenStat, Version 14, VSN International 2011).

3.3.3. Results

The dataset

The number of sites with sufficient intensity of sampling for inclusion in the DSS comparison increased in each year of the study, providing a total of 44 (Table 6). Although the 15 beetle threshold was breached at only one site, the 2 and 5 beetle thresholds were breached at 82% and 43% of sites, respectively, providing a good test of the performance of each DSS. The average distance between the sampling site and the nearest weather station was 16 km with a mode of 1 km and a range of 1-80 km. The average duration of the DSS comparison at each site was 17 days, this period being limited by the duration of the green-yellow bud stage, the date that sampling commenced and the date of any insecticide application (after which no data was accepted for use in this comparison). The interval between field samples was 3.7 days, reflecting the selection of sites where sampling was approximately twice weekly.

Table 6. Summary of the dataset used for the DSS comparison

Year	No. sites used	Mean no. km to weather station (range)	Mean no. days of DSS comparison (range)	Mean no. days sample interval (range)	% sites insecticide applied
2008	2	9 (1-17)	22 (21-23)	3.8 (3-6)	0
2009	10	1	19 (8-33)	3.7 (1-7)	20
2010	12	15 (1-48)	21 (10-31)	3.8 (2-7)	25
2011	20	26 (1-80)	13 (5-19)	3.7 (2-7)	60
All years	44	16 (1-80)	17 (5-33)	3.7 (1-7)	39

Relative performance of the DSS':

Prompting appropriate monitoring

The performance of both current advice and proPlant in prompting monitoring that would lead to recognition of threshold breaches was very good. All threshold breaches at the 5 and 15 beetle thresholds would have been recognised using either DSS, as would almost all breaches of the 2 beetle thresholds. The analysis suggested that the 2 beetle threshold would have been unrecognised by one or both DSS' at three sites in 2010. At one site the apparent failure of both DSS' was probably an artefact of the sampling regime. The threshold breach was detected by experimental sampling on 12 April, a day when maximum temperature did not reach 15°C and when sampling was recommended by neither DSS; no further sampling was recommended before the crop began to flower. Had sampling been done every day (impractical) or in accordance with either DSS (risking experimental bias), experimental sampling would almost certainly have detected the threshold breach on 10 April, as would sampling according to the recommendations of either DSS. At two sites at Woburn, proPlant failed to detect the breach of the 2 beetle threshold. Here, proPlant estimated that immigration was complete by 23 April, although transect counts of beetles on plants in fact continued to rise thereafter. In 2011, the proPlant pollen beetle model was globally adjusted in response to data from Germany to extend the model's estimation of the period of immigration.

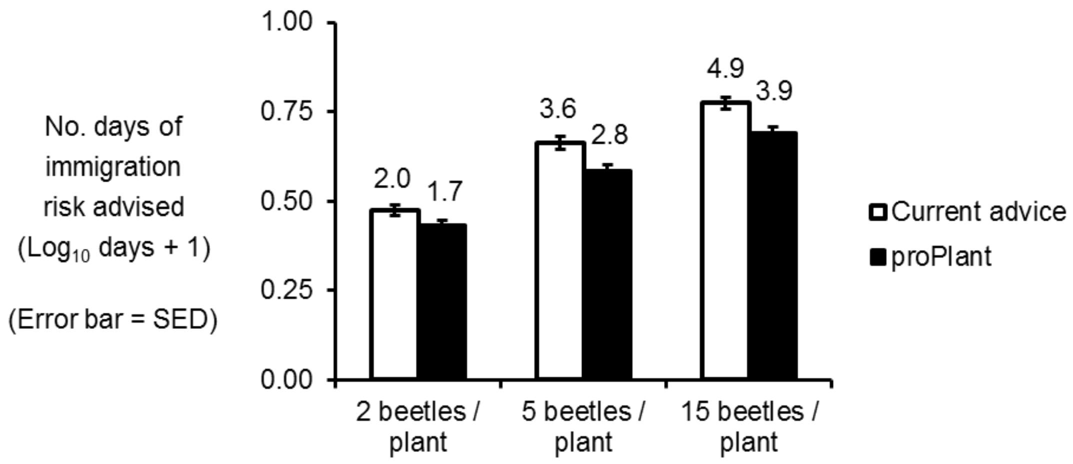


Figure 18. Forecasted days of good immigration conditions up to breaches of different Thresholds (back-transformed means are given above each bar)

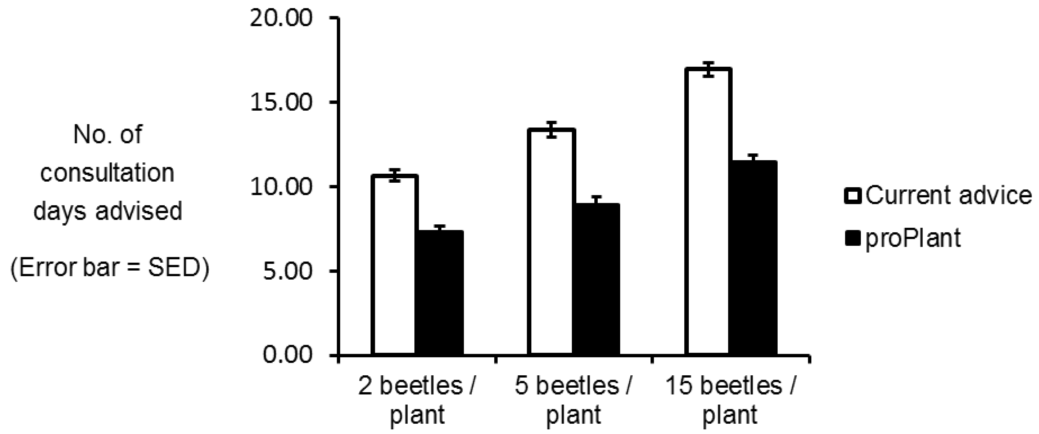


Figure 19. No. consultation days recommended up to the date that a threshold breach would be detected

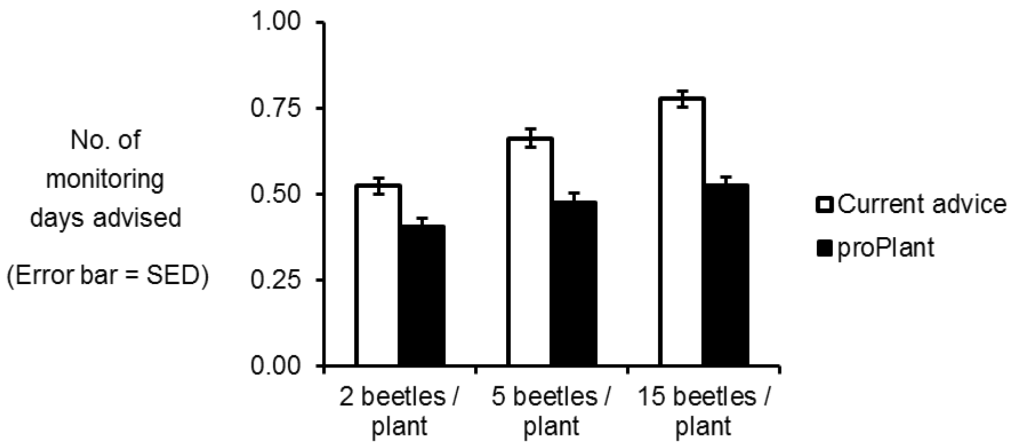


Figure 20. Number of monitoring days recommended up to the date that a threshold breach would be detected

Number of days of immigration risk, DSS consultation and monitoring

At every threshold level, proPlant consistently advised fewer days of good immigration conditions (14-21%; Figure 18), fewer days of DSS consultation (31-33%; Figure 19) and fewer pollen beetle monitoring days (34-53%; Figure 20) than did current advice.

Timeliness of threshold breach detection

On average the use of proPlant led to a delay in threshold breach detection of less than a day compared to using current advice (Figure 21).

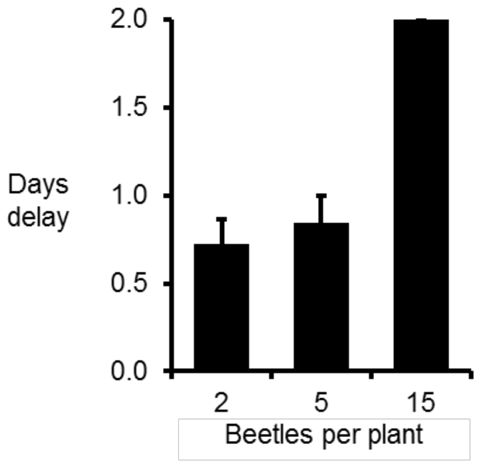


Figure 21 Relative delay in recognition of breached thresholds by proPlant compared to current advice (note that the 15 beetle threshold was breached at only one site).

Forecast of the start of immigration

proPlant consistently preceded or accompanied the first recorded immigration of beetles to experimental fields with a risk warning in the form of a green dot. By contrast the first immigration was only preceded by temperatures of ≥15°C on 57% of occasions and by red or yellow dots (proPlant) on 40% of occasions.

Accuracy of forecasts of the risk of pollen beetle immigration

proPlant responded appropriately to different weather conditions early in each year. For example, the greatest temperature difference in the early spring was between 2008 and 2011 (Figure 22). In 2011, proPlant accurately forecasted an earlier start to immigration, earlier peaks and greater percent of immigration in this period in 2011 (Figure 22). The main immigration period fell within the period 1-20 April each year, when the temperature was more variable between years. This period was markedly warmer in 2011 than in 2010. Nevertheless, proPlant accurately predicted the period when infestation increased in each year and prompted monitoring on critical dates.

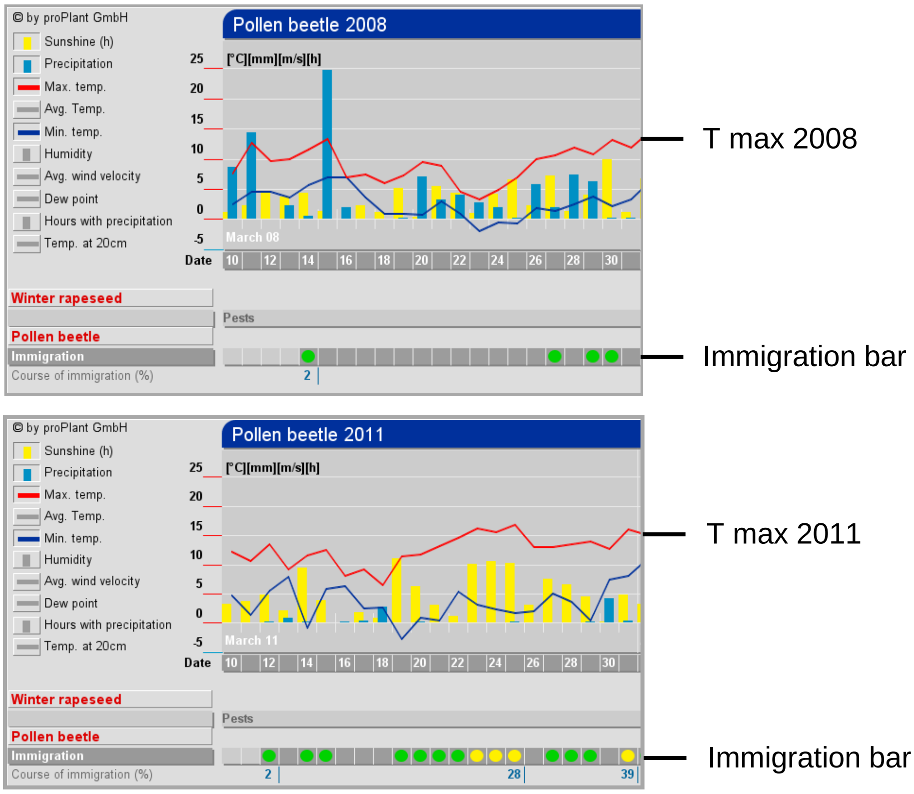


Figure 22 proPlant output for 10-31 March 2008 and 2011, indicating the daily maximum temperature (upper line) and immigration predictions.

As expected, the accuracy of forecasts declined the further they predicted into the future. In relation to current advice, 7.3% of weather forecasts predicted wrongly that the air temperature would exceed 15°C on the day that the forecast was issued or wrongly predicted that it would not. This rose to 15.4% for the forecast for two days ahead. The levels of inaccuracy of proPlant forecasts were also greatest for two days ahead but were remarkably similar to those for the temperature forecast alone (Table 7). There was no consistent tendency to either under-estimate or over-estimate the risk of immigration but employing current advice would have led to some over-estimation of risk for the day of the weather forecast and both DSS' tended to under-estimate the risk for two days ahead.

Validating a posteriori *DSS comparisons*

When using both DSS in real-time at nine sites in 2011, the reduction in monitoring effort if using proPlant was 52% and 65% relative to current advice at the two most commonly used thresholds (5 and 15 beetles per plant, respectively; Figure 23). These reductions were almost exactly the same as when comparing the two DSS using *a posteriori* weather data at the same sites, validating the approach of the main study.

Table 7 Percent accuracy of prediction of good pollen beetle immigration conditions using forecasted temperature (current advice) or using proPlant.

	Current advice: forecast of maximum temperature ≥15°C			proPlant: forecast of good migration conditions (yellow or red dot)		
	day 0	day +1	day +2	day 0	day +1	day +2
% predictions inaccurate	7.3	10.0	15.4	7.3	7.5	12.8
% predictions over-estimate	7.3	7.5	5.1	2.4	2.5	0.0
% predictions under-estimate	0.0	2.5	10.3	4.9	5.0	12.8
n	41	40	39	41	40	39

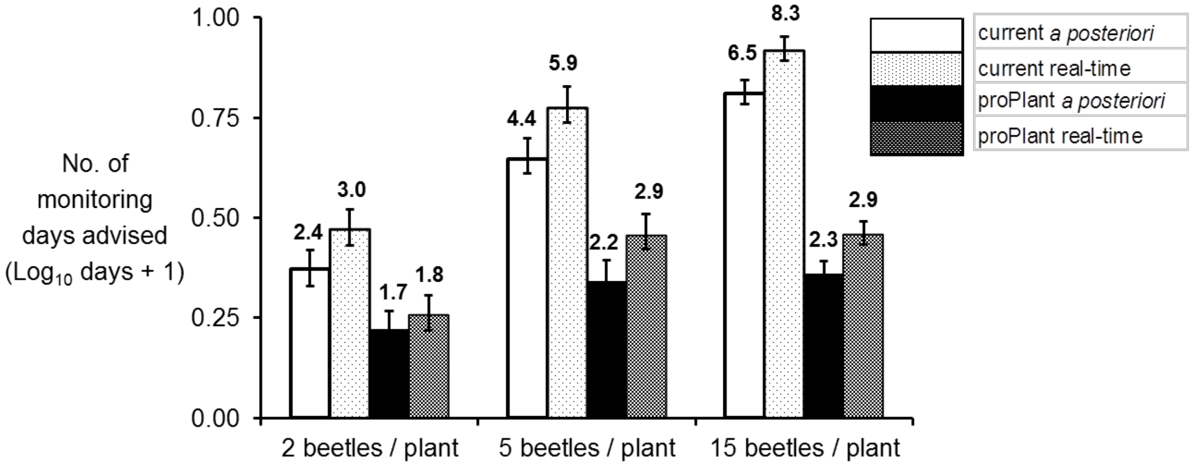


Figure 23 Comparison of number of monitoring days recommended when using DSS's in real-time and *a posteriori* (Error bar = SED; back-transformed means given above each bar).

3.3.4. Discussion

Both DSS' performed reassuringly well in prompting monitoring that would detect breaches of spray thresholds for pollen beetles in OSR. However the remarkable reductions provided by proPlant in the need for DSS consultation (30%) and for pollen beetle monitoring (34-53%) in comparison with current advice are potentially of great significance to time-pressured growers and crop consultants. These benefits are achieved without loss of effectiveness in detecting breaches of threshold, and with an average delay in threshold breach detection of less than a day. This small delay is due to less frequent monitoring during contiguous days of immigration. It seems likely that this would be accompanied by little additional risk to yield, given the compensatory ability of the crop, and would probably be outweighed by the benefit of using the DSS.

Markedly different winter and spring conditions in different years over the four years of this study did not affect the accuracy of the proPlant model which predicted pollen beetle immigrations into OSR crops in England and Scotland remarkably well. The greater sophistication of proPlant’s use of weather data is probably responsible for its ability to give earlier warning of pollen beetle activity than current UK advice. Its data-rich phenological model provides reduced estimates of immigration days, taking into account, for example, days that may be warm enough for flight but too windy or too wet. Although close proximity of source of weather data to the associated rape field is desirable, acceptably accurate proPlant prognoses were derived even when using data from a weather station 50 km distant.

As expected, the accuracy of forecasts declined the further they predicted into the future for both DSS. It is reassuring that the levels of inaccuracy of proPlant forecasts were remarkably similar to those for the temperature forecast alone. Modern weather forecasting models achieve high degrees of accuracy in predicting temperature, the basis of the pollen beetle immigration risk prediction on current advice. The proPlant model appears to introduce no more inaccuracy to its prognoses than is inherent in the weather forecast data used to parameterise its model.

Most assessments and comparisons of DSS’s presented here were made *a posteriori*, using known weather data and known pollen beetle phenology. The validity of this approach was confirmed by the real-time study in 2011 where reductions in monitoring effort matched those found *a posteriori.* Mixed modeling (REML) analysis will improve this validation in the Extension work to this project (see Appendix C).

During the course of the project, two adjustments to proPlant were made to improve accuracy and fit to local conditions. The first modification allowed the user to tailor the model to local wind exposure and the second delayed the progress and extended the period of immigration. It was not possible to validate proPlant’s estimate of the end of immigration in the UK because the crop flowers earlier in relation to immigration than in continental Europe, but the model predicted the progress of immigration well. No special adjustment was necessary to adapt proPlant to the UK, despite the more maritime, less continental climate than Germany where it was developed.

It should be emphasised that, although proPlant provides an estimate of the percent completion of immigration, it does not give an estimate of the level of infestation. As when using current UK advice, the decision as to whether to treat the crop with insecticide is made by the farmer or his adviser, with reference local thresholds and the results of the monitoring prompted by the DSS.

Our findings suggest that proPlant expert reliably models pollen beetle phenology in the UK and that its introduction to the UK would reduce the monitoring time, effort and cost required to assess pollen beetle infestations according to thresholds. This could in turn increase DSS uptake by farmers, leading to better targeting of insecticides, reductions in insecticide use and costs and less risk of insecticide resistance. In spring 2012, Bayer CropScience ran a trial version of proPlant on their website as part of their Stewardship activities. This is a clear mark of the success of this LINK project which played a significant role in leading to this trial. A small impact assessment of the effects of the proPlant maps on the 2012 season will be made in an Extension of this project (see Appendix C).

3.4. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape (Objective 1, Task C)

Sentinel plants are usually used as bio-indicators of environmental pollution (e.g.Felsot *et al.*, 1996; Beeby & Richmond, 2003) or as early warning systems to detect invasive species (e.g. Britton *et al.*, 2010). This project assessed the potential of using such plants in risk assessment for crop protection. The turnip rape (TR) plants in the trap crop must develop faster and flower a few weeks before the oilseed rape (OSR) crop for the system to work (Cook *et al.*, 2006b). This early flowering character offers two scenarios for the potential use of TR as a sentinel plant for risk assessment in OSR: (1) predictive: the number of pollen beetles on the TR at its green-yellow bud stage could be used to predict future infestation levels of the OSR crop when it reaches its susceptible growth stage; (2) real-time monitoring: sentinel plants of flowering TR could be used as ‘living monitoring traps’ at the damage-susceptible stage of OSR to estimate the level of infestation in the OSR crop. Use of the trap crop in this way may offer additional benefits and further improve its value to growers.

3.4.1. Sentinel turnip rape plants for risk prediction in oilseed rape crops

Introduction

We investigated the possibility that the mean number of pollen beetles on the TR plants during their green-yellow bud stage could be used to predict future infestation levels of the OSR crop when it reached a similar growth stage (green-yellow bud i.e. the damage-susceptible stage). We found evidence of a correlation between the numbers of beetles on TR plants at the bud stage with the numbers present in OSR crops one week later, suggesting some merit in this approach to risk assessment.

Materials & Methods

Simple linear regression was used to investigate the relationship between the TR border and the OSR plants in the centres of the same fields. Two different approaches of treating growth stage information were investigated. The first explored the relationship between pollen beetle numbers in TR borders during the bud phase (GS 50-59) against the numbers in the centres of the same fields 1 week later and 2 weeks later (regardless of the OSR growth stage, but assuming OSR is 1or 2 weeks behind in its development compared with TR). The second approach examined the relationship between OSR and TR at specific growth stages, using the data from the first dates at which a given growth stage (e.g. 51) was reached in TR and OSR.

For both approaches, data were used from the Trap crop experiment (Section 3.5), extracted from Treatment 1 (in which plots of OSR had a TR trap crop which was not treated with insecticide; OSR-/TR-) and Treatment 2 (in which plots of OSR had a TR trap crop which was sprayed for pollen beetle (OSR-/TR+); in this case data were used up until the point where the TR was sprayed). For each analysis data from experiments done in 2009-2011 were combined. The mean number of beetles within borders and centres for each field were calculated and then data were transformed using $\log_{10}(x+1)$.

Results & Discussion

Relationship between pollen beetle numbers on plants in TR borders during the bud phase (GS 50-59) against the numbers in the OSR centres of the same fields 1 week later and 2 weeks later
Analysis of the number of beetles on plants in the TR border and on OSR plants one week later gave a significant regression slope ($F_{1,38}$ = 17.68; P<0.001; adjusted R^2=30.0; n=40) (Figure 24). However, there was no significant relationship between 2 weeks later ($F_{1,36}$ = 2.88; P = 0.1; R^2=4.8; n=38). These results must be treated with some caution as the data contained some influential observations and growth stages were often recorded as ranges so this also complicated the analysis and introduced additional variation. This variation will be explored and the model improved in the Extension to this project (see Appendix C).

Relationship between pollen beetle numbers in TR borders at a given growth stage and OSR in the centres of the same fields when it reaches the same growth stage
The relationship between the number of beetles on TR plants in the trap crop when at a certain growth stage and on OSR plants when they reached the same growth stage was inconsistent between growth stages; at GS 50, 51, 57 and 59 a significant relationship was found (P<0.05; Table 8) but for GS 52, 53 and 55 the relationship was not significant (P>0.05; Table 8). These results must be treated with some caution as the analysis is based on only a few observations

(n=12) and the data contained some influential observations, particularly in 2011. Growth stages were often recorded as ranges and this also complicated the analysis and introduced additional variation. This variation will be explored and the model improved in the Extension to this project (see Appendix C).

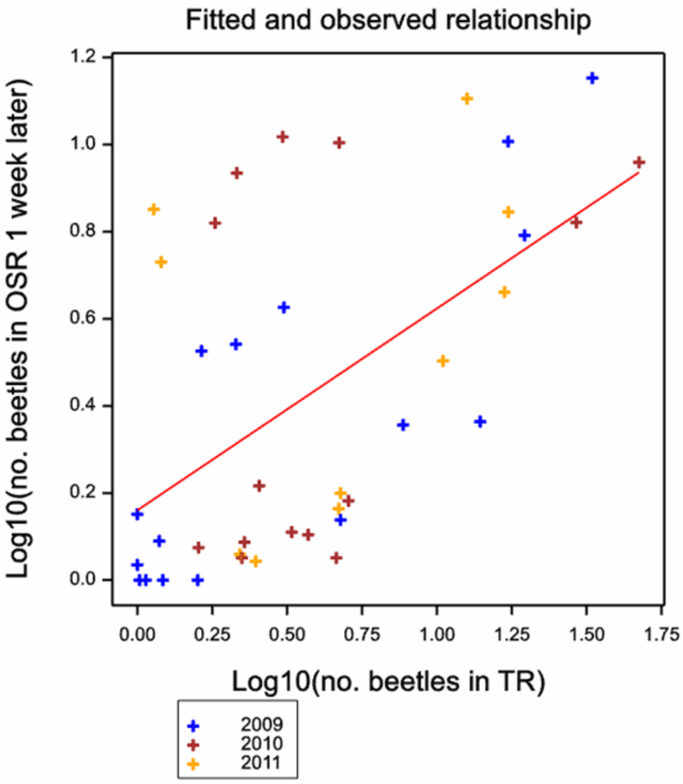


Figure 24 Fitted regression line and observed values showing the relationship between the mean number of pollen beetles in turnip rape trap crop plants at the green-yellow bud stage and the mean number of beetles on oilseed rape plants in the same field 1 week later (2009-2011). Regression line Y= log (mean pollen beetles in OSR centre +1) = 0.16 + 0.46 x log (mean number of pollen beetles in TR border).

Summary & Conclusion

Turnip rape plants in trap crops at the bud stage could act as early warning sentinel plants for risk assessment to alert growers to potentially large populations of pollen beetles in the OSR crop one week later. However, the relationship is probably not robust enough to be of practical value at present. More data are needed to improve the confidence in the analysis, specifically more frequent and more intensive sampling with more accurate recording of growth stages would give more observations for each growth stage.

Table 8 Results for linear regression analyses between the mean number of pollen beetles on turnip rape plants at a given growth stage and the number on oilseed rape plants when they reached the same growth stage.

Growth stage	Adjusted R^2	$F_{1,10}$	P	n
50	50.69	12.307	0.0056	12
51	71.28	28.295	0.0003	12
52	*	0.731	0.4124	12
53	13.53	2.721	0.1300	12
55	*	0.702	0.4216	12
57	28.35	5.352	0.0433	12
59	53.94	13.882	0.0039	12

* R^2 variable could not be estimated

3.4.2. Sentinel turnip rape plants as 'living monitoring traps' for threshold detection in oilseed rape

Introduction

We investigated the hypothesis that the mean number of pollen beetles on flowering TR plants growing in the trap crop border can be used to estimate the mean number of beetles per plant in the OSR crop during its susceptible green-yellow bud stage in order to facilitate action threshold detection. This would save the need for time consuming plant scouting transects for monitoring, and could also save costs by eliminating the need for a commercial monitoring trap.

Materials & Methods

Simple linear regression was used to investigate the relationship between the numbers of pollen beetles on OSR plants in the centres GS 50-59 with the numbers on TR plants in the trap crop at the same time. The data were used from the Trap crop experiment (Section 3.5) exactly as described in Section 3.4.3 above. As in 3.4.3, the mean number of beetles per plant on plants in the trap crop borders and on OSR plants in the crop centres for each field were calculated and then data were transformed using $\log_{10}(x+1)$.

Results & Discussion

There was a positive correlation between the mean number of beetles on plants in the OSR crop with the number on TR plants in the trap crop ($F_{1,31}$ = 41.37, P <0.001, adjusted R^2 = 55.8) (Figure

25). This indicates that it may be possible to use the TR trap crop as a 'living monitoring trap'. According to the regression model, an action threshold of 2 beetles on OSR plants in the main crop would be identified when approximately 7 beetles are found in the TR. A threshold of 5 beetles in the main crop would be identified by a mean number of 34 beetles in the TR. The data collected did not allow the model to accurately predict beyond 5 beetles/plant in the main crop, so a figure for the 15 beetles/plant threshold cannot be predicted at this stage. It must be noted however, that like 3.4.1, there were influential observations in the 2011 data and more data are required to improve the model before we can be confident enough to recommend this as an approach to growers. We aim to improve the model as part of the work in the Extension to this project (see Appendix C).

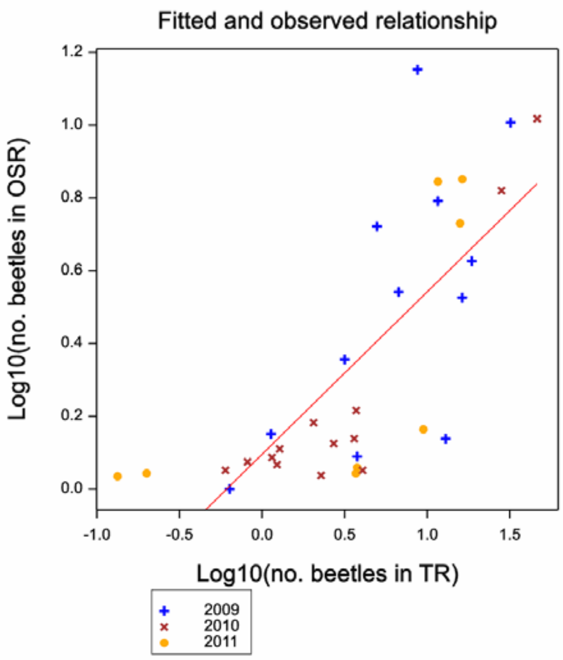


Figure 25 Fitted regression line and observed values showing the relationship between the mean number of pollen beetles on turnip rape plants in a trap crop and the mean number of beetles on oilseed rape plants in the main crop when it is at the damage-susceptible green-yellow bud stage (GS 50-59) Regression line Y= log (mean pollen beetles in OSR centre +1) = 0.096 + 0.45 x log (mean number of pollen beetles in TR border).

Summary & Conclusion

Turnip rape plants in trap crops could act as 'living monitoring traps' to facilitate pollen beetle monitoring in associated OSR crops. As the number of beetles in the OSR crop was correlated with the number on trap crop plants, it should be possible for growers to sample the trap crop plants (in the border of the crop where they are easily accessible) instead of doing a transect into the field of OSR. This would save time and would also negate the need (and cost) of commercial plastic monitoring traps, giving growers that use trap crops an additional benefit. However, the relationship is probably not robust enough to be of practical value at present. More data are needed to improve the confidence in the analysis before this approach could be recommended to growers.

3.5. Evaluate on a field scale the potential of a turnip rape trap crop for reducing the abundance of pollen beetles in oilseed rape crops (Objective 2, Task D)

3.5.1. Introduction

Trap crops are plant stands deployed to attract, intercept and retain insect pests thereby reducing damage to the main crop (Cook *et al*., 2007a). Use of trap crops can reduce the area that needs to be treated with insecticides, and can potentially eliminate the need for insecticide use altogether. Trap crops exploit the host-plant location processes of pests and comprise highly attractive host plants of a growth stage, cultivar or species preferred by the target pest, and are usually planted in close proximity to the main crop to be protected. They have been used successfully in a variety of cropping systems (Hokkanen, 1991; Cook *et al.,* 2007a, Shelton & Badenes-Perez, 2006) but are not currently available for OSR. Previous work in Defra-funded studies PI0340, PS2107 and PS2113 identified turnip rape (*Brassica rapa*) (TR) as an effective trap crop for pollen beetles in spring OSR because it is early flowering (flowers ~3 weeks earlier than spring OSR); exploiting the colour attraction of pollen beetles to yellow; see also section 3.2.1). It also has a more attractive odour at the bud stage, due to increased levels of phenylacetaldehyde and indole (Cook *et al*., 2006b). The trap crop therefore retains beetles until the OSR is past its damage-susceptible phase (Cook et al., 2006b). A trap crop planted as a border surrounding the main crop was selected following modelling studies (Potting *et al.*, 2005) and reduced numbers of pollen beetles to below threshold levels (Cook *et al.*, 2004). Work is currently underway to transfer the model to a winter OSR cropping system more relevant to UK agriculture, and it shows potential for control of flea beetle (*Psylliodes chrysocephala*) (Barari *et al.*, 2005) and pollen beetle (Defra PS2113). However, these studies have been conducted on small plots (30 x 30 m) and the tactic needed to be tested on a more realistic field scale.

We evaluated, in a replicated field scale experiment conducted over three years, the potential of a turnip rape trap crop planted as a border around the main OSR crop for reducing the abundance of pollen beetles in the OSR crop in comparison with untreated crops without a trap crop. We also compared the effect of spraying the turnip rape trap crops with insecticide and compared trap cropping treatments with a scenario of prophylactic insecticide treatment on OSR crops. We found that the trap crop performance was inconsistent; the tactic reduced pollen beetle populations in some fields in some years but overall the population of pollen beetles in the main OSR crop was not different from fields with no trap crop.

3.5.2. Materials & Methods

Field experiment set up

A replicated experiment was done on two farms (Rothamsted Experimental Farm, Hertfordshire and Woburn Experimental Farm, Bedfordshire) over three years (2009-2011). In each year, four treatments were established on each site; each treatment was grown as a 1 ha plot in a separate field with a minimum of 500m between each treatment and any other OSR fields. Treatments were: 1. OSR-/TR-: oilseed rape with a turnip rape trap crop border (both untreated); 2. OSR-/TR+: oilseed rape (untreated) with a turnip rape trap crop border treated with a pyrethroid insecticide (Hallmark with Zeon Technology - lambda-cyhalothrin- at 75ml/ha) at green-yellow bud stage for pollen beetle and at early flowering for seed weevil (regardless of pest population); 3. OSR-/OSR-: oilseed rape with no trap crop (i.e. with an OSR border; all untreated); 4. OSR+/OSR+: oilseed rape with no trap crop, all insecticide treated as above (Figure 26). In each year winter OSR cv. Astrid was used (sown at 6.8kg/ha with approx. 120 seeds/m^2). For treatments with a trap crop, Pasja (a hybrid cross between a forage turnip and forage rape) was used as a model ‘turnip rape’, as this was found to be the earliest flowering turnip TR type in previous experiments done in Defra project PS2113 and flowering differential between the main crops and the trap crop is crucial to function of the trap crop (Cook *et al.,* 2007b). The Pasja turnip rape trap crop (hereafter referred to as the TR trap crop) was sown at 3.3Kg/ha with approx. 100 seeds/m^2) as a 9 m border around the main OSR crop and therefore represented approximately 10% of the area of the whole plot. Both OSR and the trap crop were autumn-sown on the same day.

Assessments

Adult pest infestation and presence of natural enemies (parasitoids) and other beneficial insects in the borders and the OSR main crop were assessed at 36 spatially referenced points in a 6x6 grid pattern throughout the field (Figure 27). At each point, the main racemes of 3 plants were sampled using the beating method (Williams *et al.*, 2003). In each year assessments took place every 3-4 days, starting when the temperature first reached 10ºC after March 1st and continued until mid-flowering of the winter OSR crop (BCCH GS 63). On each assessment date the growth stage of the OSR and TR plants was recorded for each treatment using the BBCH scale (Lancashire *et al.*, 1991). At the end of the experiment in each year, seed yields were taken; samples of seed harvested from 4 'cuts' (2 m wide by 10m long) were taken from the OSR centres of each treatment and 4 cuts from the borders, one from each side of the plot (either OSR or TR; TR yields were taken earlier than those for OSR at the optimum time). Yield (t/ha) was calculated.

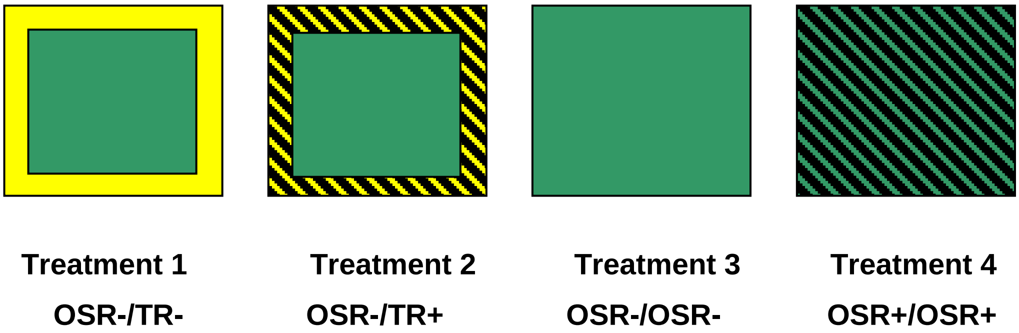


Figure 26 Diagrammatic representation of treatments in the trap crop field experiment. 1. OSR-/TR- oilseed rape with a turnip rape trap crop border (both untreated); 2. OSR-/TR+ oilseed rape (untreated) with a turnip rape trap crop border treated with an insecticide at its green-yellow bud stage for pollen beetle; 3. OSR-/OSR- oilseed rape with no trap crop (i.e. with an OSR border; all untreated); 4. OSR+/OSR+ oilseed rape with no trap crop, all treated with insecticide at green-yellow bud stage.

Data analysis

Distribution and abundance of pollen beetles

The data were analysed using a mixed model analysis (REML) where the data were combined over the three years (2009,2010 & 2011) and two sites (Rothamsted and Woburn). To combine the data three sampling occasions were used: 1. the sample before any spray was applied; 2. the sample after the TR spray had been applied to treatment 2 OSR-/TR+ but before an OSR spray; and 3. the sample after the OSR spray had been applied to treatment 4 OSR+/OSR+. An analysis was performed on each of the three sampling occasions in a mixed model that accounted for the different sources of variation: variation associated with years, sites, fields, samples and individual plants. To assess treatment differences the mixed model included terms for the position of the sample (plot border or centre) and the trap cropping treatment combination used in the field. Where overall differences were found LSD values were used to examine individual comparisons.

Shade plots

The mean number of beetles for the three plants sampled at each of the 36 spatially explicit sampling points was calculated and the data transformed ($\log_{10}$ n+1) and plotted as a shade plot on a 6x6 grid using GenStat for each of the treatments on each of the sampling assessments.

Yield

The yield data were analysed using a mixed model analysis (REML). The data were combined over the three years (2009, 2010 & 2011) and two sites (Rothamsted and Woburn) in a mixed model that accounted for the difference sources of variation: variation associated with years, sites, fields, position within fields and samples. Three contrasts were formed to test for an overall difference between border and centre yield, differences between yields for treatments positioned within the borders, and differences between yields for treatments positioned within the centres of the fields.

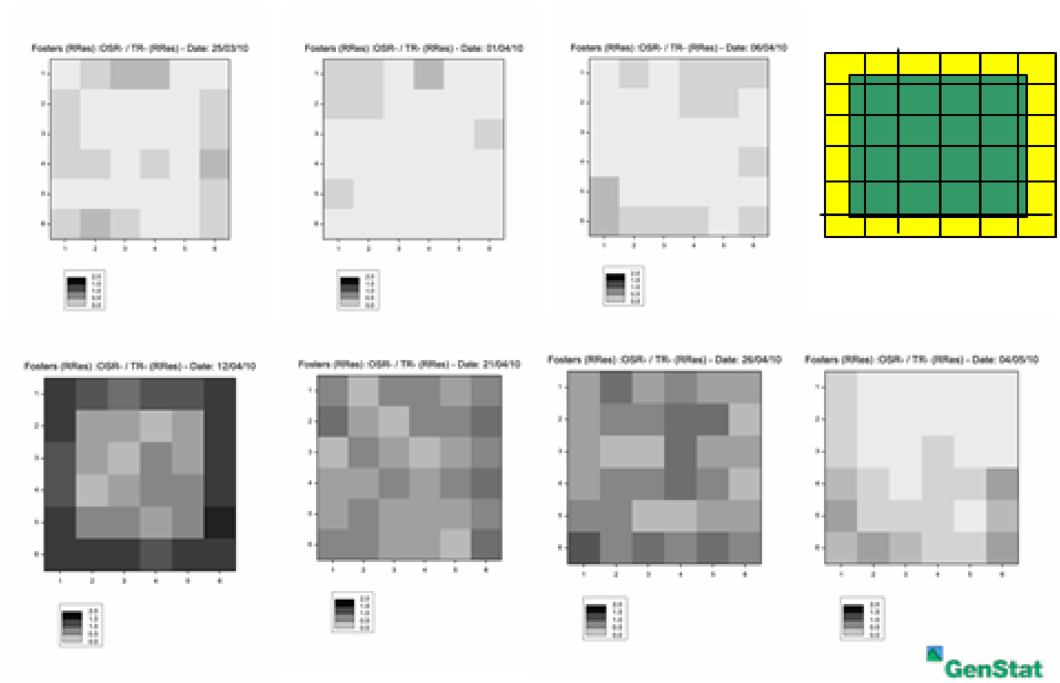
3.5.3. Results & Discussion

Pollen beetle distribution and abundance

As the number of beetles on plots was sampled on a grid pattern across the whole plot, by plotting the abundance of beetles combined with their distribution across the plot as a shade plot makes it possible to easily visualize the effects of the treatments on pollen beetles and how this changes through time. Figure 27 shows an example of these data for a plot with a trap crop (Treatment 1 OSR-/TR-) and without a trap crop (Treatment 3 OSR-/OSR-). From these it can be seen how beetles start to colonize the plots mainly from the edge and often from one particular direction. This supports earlier studies that suggest that pollen beetles colonize the crop from the edge (Williams & Ferguson, 2010). The effect of the trap crop is clear as beetles tend to heavily colonize these plants (suggesting they are remaining there after arrival) whereas without a trap crop they colonize the field more evenly. This is similar to distribution and abundance patterns observed in spring trap cropping systems (Cook *et al.,* 2004).

However, from this example (Figure 27) it is not clear that the trap crop reduced the number of beetles in the OSR centre of the plot compared with the plot without the trap crop, but this did occur on some fields in some years. The effect of TR trap crop was inconsistent across years. We believe this is attributed mainly to growth stage differential; in plots where the trap crop strategy worked, there was a greater differential between the growth stages of the trap crop and the main crop (c. 2 weeks). Growth stages were only c. 1-week apart in some cases where the strategy did not work. Early-flowering cultivars of TR which flower consistently 2-3 weeks earlier are needed for the strategy to be more reliable.

A in plot with TR trap crop (OSR-/TR-)



B in plot with no TR trap crop (OSR-/OSR-)

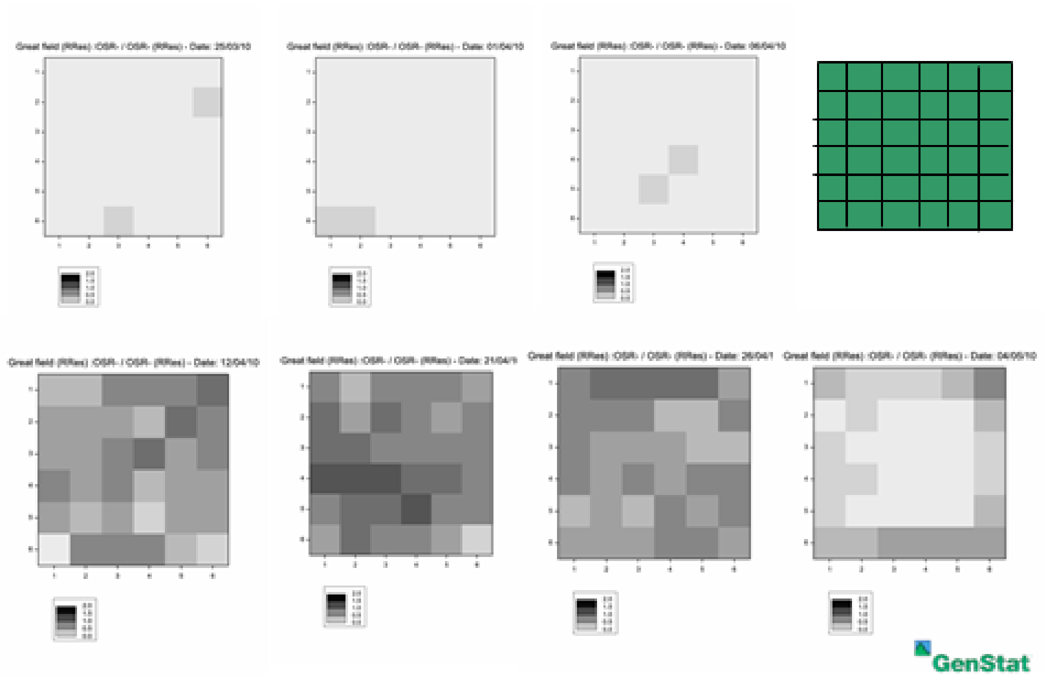


Figure 27 Shade plots showing the distribution and abundance of pollen beetles in a plot with a trap crop (A) and a plot without a trap crop (B). Figure A shows Treatment 1, an oilseed rape plot with a trap crop, both unsprayed (OSR-/TR-) on Fosters field, Rothamsted Farm on 7 dates at weekly intervals between 25/3/10-4/5/10. Figure B shows Treatment 3, an oilseed rape plot without a trap crop, i.e. with an OSR border, both unsprayed (OSR-/OSR-) on Great Field field, Rothamsted Farm on 7 dates at weekly intervals between 25/3/10-4/5/10. In both A &B the top right square shows the sample positions done within a 6x6 grid across the plot.

Although results were inconsistent between years, there was not enough statistical power to analyse differences between treatments for each year separately. We therefore combined data from all three years in the overall analysis (as intended in the original experimental design). One field at Woburn (Horsepool) (treatment 4 OSR+/OSR+) in 2009 was removed from the analysis due to very low observations.

At the start of the experiment before any of the insecticide treatments were applied the data from plots with trap crops were combined (1. OSR/TR- and 2. OSR/TR+) and those without TR trap crops were combined (3. OSR-/OSR- and 4. OSR+/OSR+). The number of pollen beetles in plots differed according to treatment and position ($F_{1,760}$ = 233.26, P<0.001). The number of beetles on plants in the TR trap crop in the border was significantly greater than the numbers on OSR plants in the plot borders ($LSD_{95\%}$=0.1812) (Figure 28A, left hand side). This supports our previous findings in a spring OSR system, that TR plants are more attractive than OSR plants and therefore have good potential as trap crop plants for OSR crops (Cook *et al.* 2006b 2007b). The numbers of beetles on plants in the OSR crop centres were fewer on treatments with a trap crop than without, but the difference was not significant ($LSD_{95\%}$ = 0.1824) (Figure 28A, right hand side).

When the plants in the trap crop borders came into green-yellow bud they were sprayed with insecticide on Treatment 2 OSR-TR+ plots. The number of pollen beetles in plots differed according to treatment and position ($F_{2,760}$ = 286.93, P<0.001). As the Rothamsted beetle populations had been tested each year for their pyrethroid insecticide resistance status and were found to be susceptible, spraying had the expected effect of significantly reducing the mean number of beetles per plant on these treatments compared with the untreated TR plants (1. OSR-/TR-) ($LSD_{95\%}$ = 0.2131) (Figure 28B, left hand side). Spraying the trap crop border (2. OSR-/TR+) had no significant effect on the numbers of beetles per plant in the OSR crop in the centre in comparison with the untreated trap crop (1. OSR-/TR-) ($LSD_{95\%}$ = 0.2787) (Figure 28B, right hand side). Populations on the OSR centre plants were still lower in treatments with a trap crop (1. OSR/TR- and 2. OSR/TR+) than without (Combined treatments 3. OSR-/OSR- and 4. OSR+/OSR+) but not significantly (contrast $t_{15.06}$ = 1.74; P=0,103) (Figure 28B, left hand side).

At the damage-susceptible stage of the main OSR crop, the crop in Treatment 4 OSR+/OSR+ was treated with insecticide. As expected, numbers in both the borders and centres of this plot were drastically reduced (Figure 28C). The numbers of pollen beetles on TR plants in the border that had been sprayed (2. OSR-/TR+) were quickly recolonized. Unsprayed TR plants in the trap crop (1. OSR/TR-) were significantly more infested than unsprayed OSR plants in the border (3. OSR-/OSR-) ($LSD_{95\%}$ = 0.2202) (Figure 28 C left hand side), again demonstrating the increased attractiveness of TR plants over OSR plants at their damage susceptible stage and supporting their potential as trap crop plants. In the OSR plot centres there were more beetles on OSR plots without the trap crop (3. OSR-/OSR-) than on plots with trap crops (1. OSR-/TR- and 2 OSR-/TR+) (contrast $t_{13.63}$ =1.38; P=0,189), but the difference was not significant.

Our results suggest that having a trap crop is slightly better than not having one in terms of reducing populations of beetles to below spray threshold levels. In *some cases*, the population of beetles in plots with trap crops were reduced to below the 5 beetle/plant spray threshold compared with plots without a trap crop (Figure 28C) and would have therefore saved the cost of an insecticide application if this action threshold was used. However, alternatives to insecticides usually carry some risk of failure, and many growers find this risk acceptable. However, we admit to feeling disappointed that we could not demonstrate a lower risk of failure of this strategy in our experiment. Further work to identify the reasons for the failures of the strategy in our experiment is necessary. Given the economics of the trap cropping strategy (see Section 3.6) the most promising way of delivering the benefits of a trap crop to growers may be through crop margin management (i.e. using flowering margins containing Brassicas to act as trap crops). This possibility is being addressed in Defra-funded project IF0139, and will require further work in addition to enable delivery to growers.

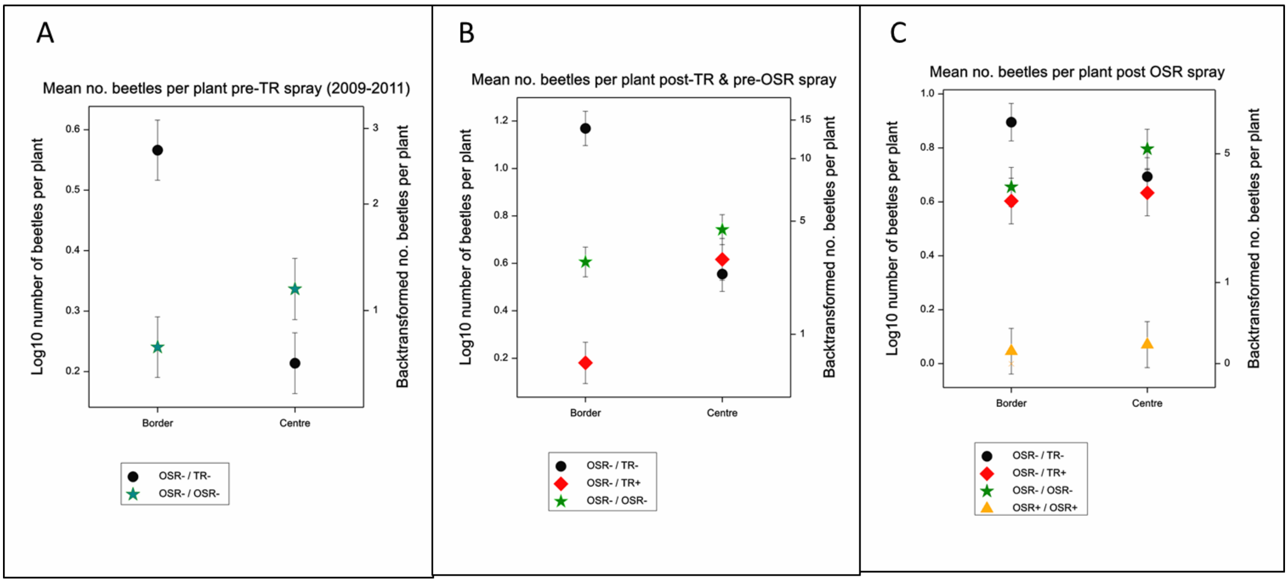


Figure 28 Mean (±SE) number of pollen beetles per plant in the borders and centres of plots with the following four treatments 1. OSR-/TR- oilseed rape with a turnip rape trap crop border (both untreated); 2. OSR-/TR+ oilseed rape (untreated) with a turnip rape trap crop border treated with an insecticide at its green-yellow bud stage for pollen beetle 3. OSR-/OSR- oilseed rape with no trap crop (i.e. with an OSR border; all untreated) 4. OSR+/OSR+ oilseed rape with no trap crop, all treated with insecticide at green-yellow bud stage at key time points of the trap crop experiment: before any insecticide applications (A); following the treatment to the turnip rape trap crop border in Treatment 2 (OSR-/TR+) and following the insecticide application to the centre and border of Treatment 4 (OSR+/OSR+).

Yield

In the first year of the experiment (2009) one treatment, (3. OSR-/OSR-), on White horse field at Woburn failed to establish and the other three treatments had very poor establishment and the resulting crop was extremely thin, so this site was excluded from the yield analysis. In 2011 another field site at Woburn, Stackyard (1 OSR-/TR-) was also very thin and this too was excluded from the analysis. The treatments had no significant effect on the yield of the OSR main crop in the plot centres ($F_{3,15.3} = 0.41$, $p=0.746$) (Table 9). The yield in the plot borders did differ significantly between treatments ($F_{3,18.5} = 31.69$, $p < 0.001$). This was due to the plant effect, with the yield of borders with TR yielding less than the borders with OSR (LSD value for TR vs OSR both sprayed = 1.0139 and LSD for TR vs OSR both unsprayed = 0.8706); yield in OSR borders did not significantly differ (LSD value 0.9349) and yield in TR borders did not significantly differ (LSD value 0.9820) (Table 9). These results were not unexpected as yield differences are rarely shown in insecticide studies and it is known that the yield of TR is less than OSR. The yield data were used in the cost:benefit analysis to assess the cost effectiveness of the trap cropping tactic (section 3.6) and section 3.7 addresses the search for an OSR cultivar to replace the TR component of this system.

Table 9 Mean (±SE) yield (t/ha) from 4 treatments in a trap crop experiment for the plot centres (main oilseed rape crop) and the borders (either turnip rape for treatments 1 and 2 or oilseed rape in treatments 3 and 4) . Treatments were: 1. OSR-/TR- oilseed rape with a turnip rape trap crop border (both untreated); 2. OSR-/TR+ oilseed rape (untreated) with a turnip rape trap crop border treated with an insecticide at its green-yellow bud stage for pollen beetle 3. OSR-/OSR- oilseed rape with no trap crop (i.e. with a OSR border; all untreated); 4. OSR+/OSR+ oilseed rape with no trap crop.

Treatment: Position	1. OSR-/TR-	2 OSR-/TR+	3 OSR-/OSR-	4 OSR+/OSR+
Centres	4.143 (0.32)	4.461 (0.35)	4.389 (0.29)	4.019 (0.35)
Borders	1.908 (0.32)	1.872 (0.35)	3.853 (0.29)	3.603 (0.35)

3.6. Assess the cost effectiveness of the trap cropping tactic (Objective 2, Task E)

3.6.1. Introduction

The trap cropping tactic can reduce pollen beetle populations on plants in the main oilseed rape (OSR) crop centres, often to below spray thresholds. For organic growers it offers the only realistic solution at present towards effective pest control; as well as pollen beetle, it has also been shown to be effective at reducing population levels of cabbage stem flea beetle (*Psylliodes* *chrysocephala*) (Barari *et al*., 2005) and possibly cabbage seed weevil (*Ceutorhynchs assimilis*) (Cook *et al.,* 2004, 2006) in OSR crops. But does trap cropping represent a viable option for conventional growers? In March 2008 when this project started, the only alternative to the pyprethroid group of insecticides was the neonicitinoids. Now, in 2012, there are also the inoxacarb and pymetrozine groups. So, can trap cropping ever be more than the last resort in the unlikely situation that resistance spreads to *all* other active ingredients or that EU legislation revokes *all* the current products available? We conducted a small cost:benefit analysis in which we assessed the cost effectiveness of the trap cropping tactic in terms of the reduction in area sprayed and the financial cost in comparison with insecticide-treated crops.

3.6.2. Materials & Methods

Approach

This analysis compared the relative costs and benefits of a number of different trap cropping and insecticide use scenarios for the control of pollen beetles. The core of the analysis was based on the treatments investigated in the Trap cropping experiment (Section 3.5), namely oilseed rape (OSR) with an unsprayed turnip rape (TR) trap crop border (OSR-/TR-), oilseed rape with a turnip rape trap crop border sprayed with a pyrethroid insecticide (to the border only; OSR-/TR+), oilseed rape unsprayed (OSR-/OSR-) and insecticide-treated oilseed rape (OSR+/OSR+). Other options investigated include OSR treated with a more expensive insecticide (i.e. a neonicotinoid, indoxacarb or pymetrozine; for this study the neonicitinoid Biscaya was selected at random as an example for this purpose), and TR trap crop options where the trap crop is harvested or destroyed. This option was considered as the possibility existed that the extra costs associated with drilling and harvesting a turnip rape border may outweigh the value of the yield of the turnip rape proportion of the crop.

Gross margins, defined as total output (yield x price) less variable costs (costs which vary directly in proportion to the enterprise, e.g. seed, fertiliser, pesticides) can be useful in making comparisons between different enterprises or when trying to determine the effects of making adjustments to the levels of inputs, for example, to a particular enterprise. Gross margins, however, do not take into account fixed costs, for example machinery, labour and general overheads. Due to the nature of the different trap cropping options compared here, adjustments were made to both variable costs (for example the costs or savings of using or omitting an insecticide application) and to a proportion of the fixed costs which can be attributed to a particular operation, such as spraying or harvesting. The proportion of fixed costs attributable to these operations will vary drastically from farm to farm, but for these purposes, the ‘Farmer’s average cost per ha’ for machinery operations as quoted in Nix (2012) were used to enable comparisons to be made between trap cropping and insecticide options. Where the figures for farmer's average cost were unavailable, average contractor rates for the operation are used instead.

Calculation of margins

For the purpose of these comparisons, a gross margin for each option was initially calculated. The costs of the field operations (for a typical schedule of operations involved in growing an OSR crop from primary cultivations through to harvest) were taken from this figure, giving a 'margin less costs of field operations' figure. This was used for each scenario for comparative purposes (but would not represent a profit or loss until further fixed costs, such as buildings, interest and rent were considered). Figure 29 shows an example of the calculation for the OSR-/OSR- treatment, along with notes on calculations and sources of data.

Conventional oilseed rape, no insecticide for pollen OSR-OSR-

	OSR centre	OSR 10% border	Combined yield	Notes
Yield (t/ha)	4.389	3.853	4.3354	90% contribution (to total yield) from centre, 10% contribution from border, own values
Crop price (£/t)	£ 355.00			Average spot price, Farmers weekly, 16th May 2012
Gross output £/ha	£ 1,539.07			Combined yield x price
Variable costs (£/ha):				Variable costs from Nix, 2012
Seed	£ 52.00			
Fertiliser	£ 254.00			
Sprays excluding cost of pollen beetle control	£ 131.71			Nix states £136 for sprays (this figure is £136 minus cost of typical pyrethroid @ £4.29 per ha)
Pollen Beetle control spray	£ -			
Total Variable costs	£ **437.71**			
Gross margin	£ **1,101.36**			Gross output - variable costs
Costs associated with operations (£/ha)				
Plough	£ 57.00			Nix 2012, farmer's average cost, medium land (values for heavy and light averaged)
Combination Drill	£ 51.00			Nix 2012, farmer's average cost
Roll	£ 15.00			Nix 2012, farmer's average cost
Slug pellets broadcast	£ 11.10			Nix 2012, contractor's average cost (not specified for farmers)
Autumn weed control / fungicide spray	£ 12.00			Nix 2012, farmer's average cost
Autumn fertiliser broadcast	£ 9.00			Nix 2012, farmer's average cost
Feb fertiliser broadcast	£ 9.00			Nix 2012, farmer's average cost
Mar fertiliser broadcast	£ 9.00			Nix 2012, farmer's average cost
Spring weed control / fungicide spray	£ 12.00			Nix 2012, farmer's average cost
April insecticide (PB control)	£ -			Assume no tank mix
May Insecticide (SW, PM) / fungicide	£ 12.00			Nix 2012, farmer's average cost
July / August dessicant	£ 12.00			Nix 2012, farmer's average cost
Combine	£ 83.00			Nix 2012, farmer's average cost
Grain cart	£ 12.54			Nix 2012, adjusted contractor's average cost (not specified for farmers). hour for carting
Total field operation costs	£ **304.64**			
Margin less costs of field operations	£ **796.72**			

Figure 29 Calculation of the 'margin less costs of field operations' figure for an untreated oilseed rape crop (OSR-/OSR-).

Margin calculations were performed using yields achieved for the different treatments in the trap cropping experiment (see section 3.5, Table 9). Yield measurement samples were taken from the border area of each plot (irrespective of whether or not the plot had a TR border), and also from the centres. Throughout the analysis, it is assumed that a border TR as in Treatments 1 and 2 and effectively OSR in treatments 3 and 4) represents 10% of the total area of the plot. The 'combined yield' value shown in Figure 29 assumes that a 10% contribution to total yield will be made at the level achieved in the border, and a 90% contribution will be made at the yield achieved in the centre. The combined yield value was used in the gross margin calculation. A price of £355 per tonne (spot price, 18th May 2012; source Farmer's weekly) was assumed in making initial calculations.

Standardisation of margin values

During the analysis, it became apparent that variation in the yields achieved in the experimental plots may be masking the effects on the margin of the cost differences associated with each scenario. To answer the question of how the differences in costs associated with each option would affect the margin at a standard yield and price, margins were calculated at a standardised yield (OSR) of 3.5 t/ha and standardised price of £350/t using the costs (variable + operations) associated with each scenario. For TR treatments we used the following logic to calculate a standard yield that accounted for yield reduction in TR border (or lack of any yield at all in OSR-/TR+(un-harvested trt); we took our average TR yield (1.89 t/ha) and adjusted down to account for the fact that the standard OSR yield (3.5 t/ha) is lower than our average (4.3.t/ha) i.e. TR yield was adjusted proportionally by 3.5/4.3 = 0.184 to give a standard yield of 1.54 t/ha.

Increase in yield required to offset the extra costs of each scenario

With yield variation eliminated, costs alone could be looked at and the increase in yield (in the plot centres, based the standard OSR price) required to offset the extra costs of each scenario (adding in borders, sprays etc) compared with the baseline control (the OSR-/OSR- treatment) were calculated and converted into a percentage. This was simple for the treatments with no TR because the increase in yield is over whole area of plot, but another calculation was needed to transfer the overall yield increases onto the centres only in the case of scenarios involving TR borders. The yield needed for centres only was calculated as =(unadjusted yield -(proportion of trap crop area x standard TR yield)/proportion of crop centre) [i.e., =(unadjusted yield -(0.1 x 1.54))/0.9)].

3.6.3. Results & Discussion

Combined yields for scenarios including TR trap crops were less than those for OSR as the yield of this species is less than that for OSR (Table 10). The standard OSR crop with no treatments (OSR-/OSR-) was obviously among the lowest scenarios in terms of costs but the lowest was actually the un-harvested, untreated TR trap crop option, followed by the un-harvested, treated trap crop option; due mainly to savings on the cost of seed plus combining. Even if the trap crop was harvested and sprayed, however, the TR options still had lower costs than the insecticide options when applied to the whole crop, due mainly to a 90% reduction in the costs of insecticide (Table 10).

The profit margin, when based on experimental results for yield was best for the untreated OSR standard (OSR-/OSR-) at £796 (Table 10). The next best option was the OSR with a treated TR trap crop (OSR-/TR+) at £740, considerably better than either of the options without trap crops where the whole crop is sprayed with insecticides. However we know from our field experiment results that the yield of the OSR plot centres did not differ *significantly* between treatments (see Section 3.5), so margins based on experimental results may be a little misleading. When standardised net margins are considered (at a standard yield of 3.5t/ha and a price of £350/t) the standard OSR treatment still comes out on top at £482 (Table 10) but the next best margin is for the OSR option without a trap crop with a pyrethroid spray. Either way, it is clear that if a trap crop is sown, it is worthwhile harvesting it; margins for both OSR-/TR- and OSR-/TR+ options were greater when the TR was harvested than without (Table 10).

Table 10 Summary of the combined yield per plot, costs and margin for different crop management scenarios with and without trap crops and with and without insecticide applications

Scenario	Combined yield (t/ha) based on experimental results	Costs £ (variable + field operations)	Margin less costs of field operations £ (based on experimental results)	Standardised net margin £ @ 3.5 t/ha and £350/t
OSR-/OSR-	4.335	742.35	796.72	482.45
OSR+/OSR+ (Pyrethroid)	3.977	758.64	653.34	466.36
OSR+/OSR+ (e.g. Neonicotinoid)	3.977[1]	769.12	642.86	455.85
OSR-/TR-	3.920	748.73	642.70	407.67[2]
OSR-/TR- (un-harvested)	3.729	735.17	588.52	367.33[2]
OSR-/TR+	4.202	751.56	740.19	404.85[2]
OSR-/TR+ (un-harvested)	4.015	738.00	687.30	364.51[2]

[1] assumed no difference in yield when sprayed with a pyrethroid versus a non-pyrethroid (neonicotinoid, indoxacarb or pymetrozine)

[2] Standardised margin adjusted for TR yield loss

With standardized yields, we can calculate the increases in yield (at a given price) that are required to offset the additional costs of each cropping scenario compared to the OSR standard (OSR-/OSR-) which had the greatest margin. A c.1.5% increase in yield is required to offset the costs associated with treating the crop with cheap pyrethroids; this rises to c.2.25% when the more expensive alternatives to pyrethroids are used (Table 11). An increase of c.7% in yield would be needed for the best trap cropping scenario to offset the costs associated with harvesting. This represents only an approximate 4.5% increase in yield needed over and above what many growers are happily accepting when they spray prophylactically with a non-pyrethroid.

Table 11. Increase in yield required to offset the extra costs of each cropping scenario

Scenario	Yield (t/ha) required to Match OSR-/OSR- Standard margin	Centre yield increase needed (t/ha)	% increase needed to better OSR-/OSR- (t/ha)
OSR-/OSR-	3.50	-	-
OSR+/OSR+ (pyrethroid)	3.55	-	1.43
OSR+/OSR+ (e.g. neonicotinoid)	3.58	-	2.29
OSR-/TR-	3.52	3.74	6.86
OSR-/TR- (un-harvested)	3.48	3.87	10.57
OSR-/TR+	3.53	3.75	7.14
OSR-/TR+ (un-harvested)	3.49	3.88	10.86

Summary & Conclusion

Our analysis indicates that the best strategy is to have an OSR crop and spray only when necessary according to threshold (returning a net margin of £482/ha, note this does not include the cost of advice or monitoring aids). If insecticides are used the margin will be reduced to £466 if pyrethroids are used and to £455 if another insecticide class is used. The net margin for a strategy with a trap crop to reduce beetles to below spray threshold is £407. The margin calculations do not include to cost of advice in spraying to threshold, but nor do they include benefits of trap cropping (such as use of the trap crop as a monitoring trap (see section 3.4.2)) or benefits from biocontrol when the crop is not sprayed. A more refined cost:benefit analysis is required to account for these factors, and a value of the damage caused by pollen beetles is also needed to determine the economic consequences of spraying according to different thresholds.

3.7. Initiate a programme to develop a practical and efficient trap cropping strategy for winter oilseed rape (Objective 3, Tasks F&G)

3.7.1. Introduction

The trap cropping strategy tested as part of this project (Section 3.5) is based on a winter turnip rape (TR) trap crop planted as a border to the winter oilseed rape (OSR) crop. Both the TR and OSR can be sown at the same time but the TR ripens earlier and does not yield as well (see Section 3.5). To improve practicality and maximize yield from the area cropped, higher yielding and later ripening cultivars of TR or highly attractive early-flowering cultivars of OSR are needed to replace the TR component of the strategy. Ultimately, a trap cropping tactic based on two cultivars of OSR could comprise one highly attractive cultivar as the trap crop and one highly unattractive cultivar as the main crop. Together with the Project partners involved in plant breeding, we screened experimental lines for useful germplasm or potential lines and field tested the most promising in a small plot field trial.

3.7.2. Materials & Methods

Approach

The approach to finding useful germplasm or improved cultivars for the trap cropping strategy started with discussions during project meetings in the first year. A ‘wish’ list was drawn up of the varietal characteristics that are of most interest so that the breeders could look for promising lines from their records and in current field trials:

1. Time to flowering (early for potential trap crop; late for improved main crop)
2. Leaf/bud colour (light yellow-green for trap crop; dark blue-green for improved main crop)
3. Flower colour (yellow for potential trap crop; apetalous, not yellow or ‘light’ yellow for improved main crop
4. Infloresence size (many, large and dense for potential trap crop; few, small and widely spaced for improved main crop

Two visits by Rothamsted Project staff members were made to field trial sites being run by KWS (1/4/2009) and Elsoms Seeds (13/5/2009). The KWS site was of interest as strips of winter TR cv. Buko were sown at two edges and in the centre of a field of winter OSR cv. Epure. This site was sampled to assess the performance of TR cv Buko as a potential trap crop. Buko was clearly more attractive than the OSR plants on the day of our visit and therefore shows good potential for use as a trap crop. We also found evidence to support the theory that beetles fly upwind to field sites (Section 3.2.4) (Methods and Results presented in Appendix B). The Elsoms trials site was of interest as it comprised many trial lines of OSR that we could observe for interesting phenological variation. It was evident from this visit that there was very little phenological variation in any of the characteristics on the wish list other than flowering time. Following these visits, the breeders advised that as little research effort is given to breeding new lines of winter TR it would be more fruitful to focus on finding an OSR line to do the job of the TR plant, rather than to spend effort trying to improve TR lines. Also it was felt that there was little value in identifying late flowering OSR lines as a main crop as 'growers will grow what they want to grow as a main crop, based on their local conditions, yield etc.', The agreed approach was therefore to focus effort on identifying early flowering lines of OSR that could be used in place of early flowering TR in a trap cropping strategy. This line should ideally fit in with any OSR cv selected by growers as their main crop. Seed from early flowering lines identified as a result of the Elsoms visit was bulked-up and provided by Elsoms for small plot trials on Rothamsted farm in the final year of the project to assess the potential of these lines in comparison with TR. In addition, lines present in the OREGIN trial were screened for potentially useful early flowering characters.

Assessment on the OREGIN demonstration plot trials 2010

The Oilseed Rape Genetic Improvement Network project (OREGIN) www.oregin.info has assembled key genetic resources to enable researchers and breeders to explore the relevant gene-pool for enhanced traits to incorporate into breeding programmes. This includes establishing diversity fixed foundation sets for B. napus (*Bna*DFFS). The set of founder lines within the *Bna*DFFS was compiled to represent a structured sampling of the genetic diversity across the global *B. napus* genepool, and to encompass winter and spring OSR, swedes, and fodder, forage and salad kales. OREGIN established small-scale demonstration trials in 2009/10 and 2010/11 to gather baseline information on plant performance and properties of the *Bna*DFFS Hopkins *et al.,* (2010-2011). In year 1 of the trial, the diversity demonstration trial comprised 48 winter OSR varieties, 8 winter kales, 4 winter swedes, and 1 synthetic line. Two replicates of each type were grown for each treatment (low and high N) in a randomized block design. We assessed the flowering periodicity to identify early flowering lines and pollen beetle infestation to identify potential lines that are highly preferred or less preferred than others.

The plots were observed weekly and the start of flowering (defined as the date when 25% of the plot had reached GS60) and end of flowering (defined as the date when 95% of the plot had no more flowers) was recorded. At the green bud stage a single Vortis suction sample was taken from each plot and the number of pollen beetles and parasitoids recorded.

Field assessment of early flowering oilseed rape lines

The four early-flowering experimental lines supplied by Elsoms FD 808, RA244DH39, RA180DH55 and RA126DH20 were tested in a small field plot experiment in Rothamsted in the final year of the experiment (2011) in comparison with winter turnip rape cv. Jupiter, Pasja (the hybrid cross between a forage turnip and forage rape used used as a model early flowering ‘turnip rape’ in Experiments in Section 3.5), and a standard winter OSR cultivar, Castille. Plots (3m long x 1.8m wide) were autumn sown at the same time at 120 seeds/m^2. Three replicates were established in separate blocks. Plots were assessed weekly and the date that they reached green bud GS51, (defined as the date when 25% of the plot had buds visible from above), when they started flowering GS 60 (defined as the date when 25% of the plants in the plot had some flowers) and when they finished flowering (defined as the date when 95% of the plants on the plot had no flowers).

3.7.3. Results & Discussion

Assessment on the OREGIN demonstration plot trials 2010

The full dataset from these assessments is recorded on the OREGIN database. There was a wide variation in the start of flowering between the lines ($F_{60,140}$ = 78.42; P<001) . (Figure 30) Several plots were heavily damaged by pigeons; as this would affect flowering so these plots were excluded from the analysis. In general, pollen beetles were most abundant on the early-flowering lines (Figure 30), but note that pigeon damaged plots were not accounted for in this analysis. There were several lines (Ningyou 7, Huashuang 5, 102 and B-104-2 that flowered early and may be worth considering further in future studies as these also had high numbers of beetles; however, no cultivars of OSR flowered earlier than any of the swedes or fodder brassicas tested in the study, and so are not of further interest in this study in terms of development of a trap crop. There were several lines that had relatively low numbers of beetles in comparison with others of similar flowering time (Huashuang 5, Eyou changjia, TN172, Hansen x Gaspard DH line, Royal Darmor, Slovenska Krajova and Palu); these could be of interest for future studies to identify less preferred OSR cultivars (but caution must be applied as this could be due to pigeon damage). Nitrogen significantly affected the start of flowering $F_{60,140}$ = 2.01; P<001 with flowering appearing to be slightly earlier on the high-N compared to the low-N treatment. There was no significant effect of the two nitrogen treatments (low and high) on pollen beetle infestation ($F_{60,140}$ = 1.13; P=0.279).

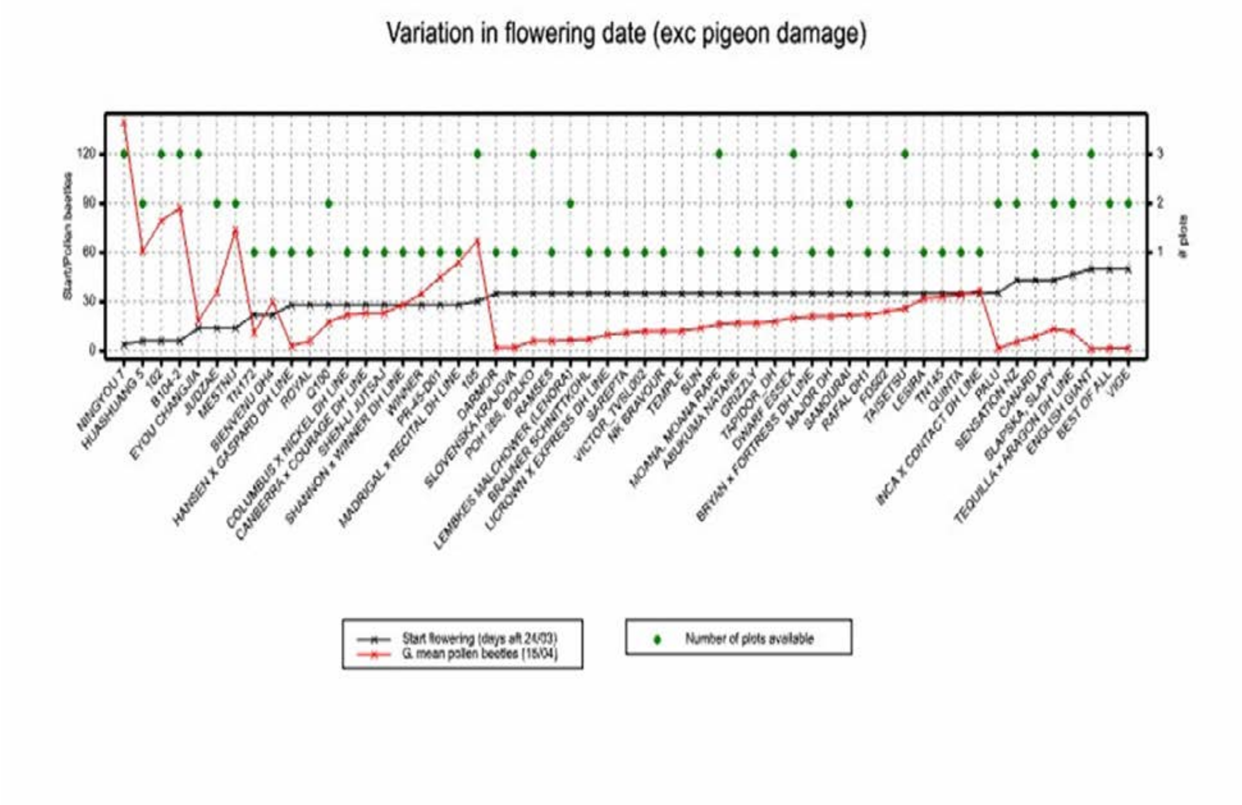


Figure 30 Average number of pollen beetles per plot in the OREGIN *Brassica napus* diversity fixed foundation sets demonstration trial 2010 (red line, left hand axis), Start of flowering time as number of days after 24/3/2010 when assessments began (black line) and number of plots (out of a possible 4) the analysis is based on (green dots).

Field assessment of early flowering oilseed rape lines

The experimental OSR lines got off to a promising start, with all four lines reaching green bud GS60 before the standard OSR cv Casille (Figure 31A). However, these lines did not start flowering earlier than the standard OSR cv Castille, and were considerably later than Pasja and TR cv. Jupiter (Figure 31B). Pasja finished flowering first, followed TR cv. Jupiter, Elsoms RA180DH55 then Castille; FD 808, RA244DH39, and RA126DH20 all finished flowering last. The success of the trap cropping strategy depends on having a good distinction between the flowering time between the trap crop and the main crop. It is therefore unlikely that any of these cultivars would be effective as trap crop plants.

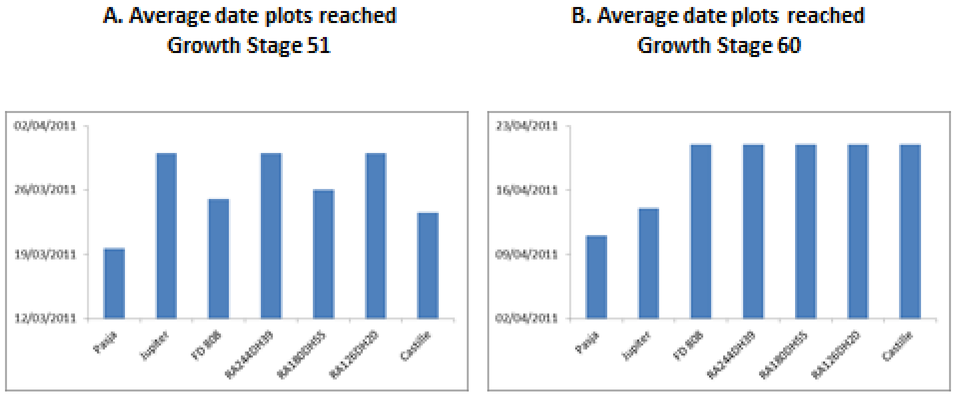


Figure 31 Average date plots of Pasja, winter turnip rape cv. Jupiter, Elsoms winter oilseed rape experimental lines FD 808, RA244DH39, RA180DH55 and RA126DH20 and winter oilseed rape cv Castille reached the green bud stage (GS 51) (A) and started flowering (GS 60) (B) in a replicated field plot trial.

Summary & Conclusions

We focused on identifying early flowering lines of OSR that would function as trap plants to replace the less practical TR element of the trap cropping tactic. We screened lines in the OREGIN experiments and those from our breeding partners but were unable to find a suitable winter OSR genotype for this purpose. Early-flowering brassicas were identified and these could be incorporated into OSR breeding programmes in the future together with lines that were less preferred by pollen beetles to develop new cultivars for the trap crops of the future. However, in the meantime, the strategy will have to remain based on early-flowering TR types as trap crop plants.

3.8. Propose an IPM strategy for controlling pollen beetles in winter oilseed rape based on the combination of the most effective elements tested in this project (Objective 3, Task H)

As a result of this study, an IPM strategy for pollen beetles is proposed to facilitate the judicious use of insecticides; it is based on the use of decision support systems to forecast immigration risk, monitoring methods to enable the use of action thresholds and alternative crop management (trap crops) to reduce the number of sprays needed. This IPM strategy can be used by growers as good practice and its use could also gain points awarded under the Defra Entry Level Stewardship (ELS) Scheme - Option EM4 ‘Develop a crop protection management plan’. The ELS scheme is aimed at promoting best environmental practice and EM4 should include ‘making full use of biological, cultural and chemical methods on the farm and inspection of crops for pest problems’. The IPM strategy proposed here could also be of use to policy makers to contribute towards National Action Plans (section on ‘Adoption of IPM techniques’) required under the EU Sustainable use of pesticides Directive (2009/128).

Damage-susceptible growth stage of the crop

Pollen beetles feed and oviposit in the buds of OSR. Yield loss due to pollen beetles is largely through feeding damage as the beetles chew large holes into the bud and feed on the pollen from the developing anthers within, often damaging the ovary in the process, leading to bud abscission. However, when the crop starts to flower, beetles feed on pollen from the open flowers (it is easier than chewing holes in buds!) and by this stage the plant has well developed lateral shoots and so is well able to compensate for any damage caused. **The accepted damage susceptible stage of the crop is therefore the green-yellow bud stage only (BBCH GS 50-59). Insecticide applications for pollen beetles should not be applied after GS 60.**

Action thresholds

Insecticides should only be applied if the crop is within its damage-susceptible growth stage *and* action thresholds have been breached. For many years the accepted HGCA action thresholds were: 2 beetles/plant for varietal associations, 5 beetles/ plant for backward crops and 15 beetles/ plant for otherwise good crops (e.g. Oakley, 2003; HGCA, 2010). However, varietal associations are no longer widely grown and results of a recent HGCA-funded study proposed a threshold scheme in which pollen beetle threshold is negatively related to plants/m^2 (Ellis & Berry, 2011). This scheme is based on the number of flowers than can be lost by plants and still produce maximum yield and takes into account the compensatory ability of the crop; thus the threshold for thin crops is greater than that for a thick crop. **As a rule of thumb, new action thresholds are c.30 beetles/plant for thin crops (<20 plants/m^2), 20 beetles/plant for optimal crops with 40 plants/m^2 and c. 10 beetles/plant for thick crops with >60 plants/m^2. There is no distinction between spring and winter sown crops.** Although this system requires further validation, the new thresholds have been adopted and published by AHDB-HGCA (HGCA 2012).

Risk & forecasting risk of pollen beetle immigration

Monitoring of the size of pollen beetle populations in the crop is needed to enable detection of any breaches of action thresholds, but it is very time consuming to do properly. The crop can be at its damage-susceptible stage for several weeks and the period of immigration of the pollen beetle to OSR crops can also stretch over 3-4 weeks.

As a rule of thumb, the crop is at a lower risk due to pollen beetle immigration when temperatures <10°C, when there are strong winds and if it is raining or has rained in the past 12h as beetles do not fly until temperatures reach c.13°C, and the other factors were each shown to negatively affect pollen beetle populations in the crop in our experiments. **The crop is at greatest risk when temperatures >15°C**.

Decision support systems (DSS) that provide risk assessments of pollen beetle immigration should be used to minimize monitoring effort and focus it to when it is most needed. Current advice on the CropMonitor website www.cropmonitor.co.uk advises monitoring beetle populations when the crop is at the green-yellow bud stage and the temperature is >15°C. However, proPlant www.proplant.de is a decision support system that uses a phenological model of pollen beetle immigration and local meteorological data to predict the start, peaks and end of pollen beetle immigration. It produces forecasts of immigration risk and advises monitoring days for up to 2 days in advance using a traffic-light system of coloured dots (green = immigration possible, yellow = good conditions for immigration and red = optimal conditions for immigration. It can reduce monitoring effort by up to 50% in comparison to following the advice on CropMonitor. **As a result of this Project, the proPlant forecasting tool is freely available on the Bayer CropScience website** http://www.bayercropscience.co.uk/ (confirmed for at least the 2012 & 2013 seasons). The site shows a series of maps of the UK showing for each area start, risk and % completion of immigration predicted. The start of migration maps are particularly useful for academics and those involved in field trials of plant protection products against pollen beetle. For growers and crop consultants they can give an indication of when the system needs to be consulted more frequently in readiness to detect large peaks of immigration that could result in breaches of the action threshold. Hovering the mouse over the coloured dot given for the area of interest will return the exact % completion of immigration. **The maps showing immigration risk for the next 2 days**

and % completion of migration should be used to help decide whether or not plant monitoring is necessary. Use of these maps has great potential to save unnecessary 'insurance' insecticide applications. For example, if monitoring had taken place and returned a mean number of say, 8 beetles/plant, a spray might have been applied if conditions were good as 'tomorrow there may be 15 beetles'. The use of the forecast may give growers and crop consultants the confidence to hold off a spray if poor conditions are predicted for immigration over the next few days. Similarly in this situation if consultation of the % completion of migration map returned 100%, a spray would not be necessary at any point in the future, even if the crop is within the damage susceptible stage as further increases in the pollen beetle population would not be expected.

proPlant is a decision *support* tool, not a decision *making* tool. The proPlant phenological model is built using numbers of beetles on plants in the crop, and is designed to prompt population monitoring in the crop after which a decision is made as to whether to spray or not. However, the system could also be used in conjunction with commercially available monitoring traps. In this case, traps should be placed in the crop as soon as possible after proPlant forecasts the start of migration, and monitoring trapping can cease after immigration is predicted to be complete.

Detection of action thresholds (population monitoring)

The recommended method for population monitoring of pollen beetles is from plant sampling in the crop and is based on the beating method; the main raceme of the plant is beaten firmly two or three times against the base of a tray (ideally white with a deep lip). This dislodges the beetles and they can then be easily counted. A white tray helps the black beetles to be easily visible and the deep lip helps to prevent them becoming lost before counting is complete (CropMonitor, Oilseed rape pests encyclopaedia:Pest sampling methods). Breathing out over the raceme also helps to dislodge the beetles. Action thresholds are expressed as a *mean* number of pollen beetles per plant. **At least 10 plants for sampling should be selected at random, taken along a transect of at least 30 m, starting at the headland and heading towards the crop centre (HGCA 2012). Plants should not be sampled in the headland alone as pollen beetles are often more abundant at the crop edge,** and this will not reflect the average across the field. Ideally four transects should be performed on each side of the crop, as beetles are not evenly distributed across the field and often come into the crop from one main direction. If only one transect is performed the mean could be an under-estimate if the wrong side is selected. However **if there is only time to do 1 transect, it should be done on the down-wind side of the crop according to the wind direction at the time of sampling,** as beetles fly upwind towards the crop.

A baited monitoring trap for pollen beetles has been developed as part of this Project and will be commercially available in 2013 from Oecos www.oecos.co.uk. The monitoring trap comprises a yellow sticky card angled at 45° to the vertical and is baited with phenylacetaldehyde, a floral volatile produced naturally by several plant species. **Unfortunately at present the monitoring trap cannot be used to determine action thresholds in the crop and should not replace the monitoring of plants directly in the crop.** There was no correlation between the number of beetles caught in the traps and the number of beetles present on plants in the crop and so we were unable to calibrate trap catch to a given action threshold expressed as the number of beetles per plant using a simple linear relationship. **However, the monitoring trap still has value for risk assessment, especially if used in conjunction with decision support systems.** If the traps are set out in early March they can detect the start of immigration (and verify at a local level any DSS forecasts); if there are none on the trap there will be none in the crop, and there is no need to spray! The trap may also be used to focus time-consuming plant monitoring in crops; as a *rough* rule of thumb if there are c.10 pollen beetles on the trap, it is probably worthwhile monitoring the plants in the crop. It may also be used to detect peaks of immigration (and therefore risk), but peaks will only be detected relative to previous trap catches on the site (again the trap can be used to verify forecasts of immigration peaks issued by DSS). Completion of immigration can be detected (or DSS forecasts verified), when the numbers on the traps do not increase further, or begin to decrease (~May). **Ideally one monitoring trap should be placed on each side of the field but if only one per field is used it should be placed downwind of the prevailing wind on the site**, and users should be aware that trap catch will vary as the actual wind direction may change between sample dates. **Monitoring traps should be used during the green-yellow bud stage of the crop only and should then be removed.** The lure is designed to last c.30 days, which should be sufficient to cover the intended period of use of the trap. After this time the lure will become less attractive and the crop itself begins to compete with the trap. If traps are not removed promptly as flowering starts, they may become swamped and difficult to retrieve as the crop grows taller.

Alternative crop management (trap cropping)

Turnip rape (TR) flowers earlier than oilseed rape (OSR) and is more attractive to pollen beetles. A TR trap crop comprising c.10% of the area of the field planted as a border around the edge of the main OSR crop can be used to reduce the population of pollen beetles to below spray thresholds. However, given the economics of this management option (a net margin of £407 compared to £482 if an OSR crop is sprayed according to threshold and remains untreated) it is likely that this option will only be of interest to organic growers, especially if the action threshold used is high (10-30 beetles according to HGCA, 2012 rather than 5 for a backward crops according to HGCA, 2010).

If this crop management option is to be used for management of pollen beetles, it is essential that **the flowering differential between the trap crop and the main crop should be maximized; the earliest flowering cultivar of TR possible should be selected as the trap crop (e.g. Buko) and the latest flowering OSR cv possible should be selected as the main crop.** Both the trap cop and the main crop can be planted on the same day; do not plant the OSR crop before the TR trap crop. Crop management can then proceed as normal until harvest. **We do not recommend spraying the trap crop for pollen beetle. We recommend that the trap crop should be harvested at the optimal time.** Although this represents another farm operation, this prevents seed shed leading to volunteer problems later and economically, the returns are worthwhile (net margin is reduced to £367 for management option where the trap crop is destroyed).

Insecticide resistance management

Repeated use of the same insecticidal active ingredient or active ingredients with the same mode of action can lead to the development of insecticide resistance. To help prevent this insecticide resistance management is important. Each class of insecticide has been classified and assigned a mode of action (MoA) group by the Insecticide Resistance Action Committee (IRAC, 2012) http://www.irac-online.org/wp-content/uploads/MoA-classification.pdf Alternations, sequences, or rotations of compounds with different MoA groups in a pest management strategy will help to ensure that selection for resistance to compounds in any one MoA group is minimized. Currently there are insecticides from four chemical groups registered for pollen beetle control Pyrethroids, Noenicotinoids, Indoxacarb and Pymetrozine. Each of these has been classified into a different MoA group: 3A (sodium channel modulators), 4A (nicotinic acetylcholine receptor antagonists), 9B (selective homopteran feeding blockers) and 22A (voltage-dependent sodium channel blockers), respectively (IRAC, 2012). Growers should therefore consider rotating use of these such that successive generations of the pollen beetle are not treated with or exposed to compounds from the same group within the insecticide regime used over the life time of the crop.

3.9. General Discussion/Conclusions and implications

3.9.1. Develop a reliable monitoring trap for pollen beetles to enable easy and effective detection of threshold levels of these pests (Objective 1,Task A)

A monitoring trap for pollen beetles would help growers and crop consultants to more easily and accurately identify when pollen beetle immigration has started and when spray thresholds have been breached. This would save time and money and help to prevent unnecessary insecticide applications.

Investigate responses of pollen beetles to colour to optimize trap colour

- Our results indicate that pollen beetles have three types of photo-receptors, a green, a blue and a UV receptor. In this respect they are similar to other flower-visiting insects studied so far such as honey bees.
- In our field studies we showed that pollen beetles are attracted to yellow colours, but are most attracted to fluorescent yellow (with UV reflectance). Such traps would be optimal for use as a pollen beetle monitoring trap in order to maximize trap catch.
- We developed a colour choice model which showed that the beetles use a green vs. blue colour opponent mechanism in their colour choice, which explains their preference for yellow (a 'super green' signal).
- The colour choice model could have applications in the development of other integrated pest management approaches that exploit the colour-guided host finding behaviours of the pollen beetle. For example it could be used to predict the relative attractiveness of new trap materials for potential monitoring traps without the need to perform time consuming and costly field experiments. It could also be used in the development of new crop cultivars which are of a more attractive colour to beetles (for trap crops) or less attractive colours (for 'resistant' main crops.

Identify and develop semiochemical baits for a monitoring trap with minimum catch of non-targets

- Our experiments indicated that a yellow sticky trap had the highest pollen beetle:non-target parasitoid proportion compared with other coloured traps. Baiting the trap with host plant volatiles further increased this proportion. We conclude that a baited trap will therefore help to maximize target catch and make counting target pollen beetles less difficult by reducing the non-target catch

- We identified several new compounds from OSR plants *in situ* that are electrophysiologically active (i.e. detected) in pollen beetles. This information will help us to better understand the host-plant interactions between the crop and the pollen beetle. Some of these compounds attracted significantly fewer beetles than the unbaited controls and could provide leads in the development of 'resistant' crop cultivars
- Low release rates of phenylacetaldehyde, a non-toxic, floral volatile commonly found in several plant species, consistently attracted significantly higher numbers of pollen beetles than the unbaited controls in trapping experiments.
- Commercially available trap mounts and lure dispensers performed as well as our experimental materials. The Oecos carrot fly trap mount and the IPS phenylacetaldehyde lure (low release rate, 1 mg/day) were selected for the final trap design.
- **We are delighted that a monitoring trap for pollen beetle will be made commercially available for the 2013 season by Oecos www.oecos.co.uk as a direct result of this project.**

Calibrate trap catch with numbers of beetles per plant in oilseed rape crops

- A pollen beetle Monitoring study was performed during the project (2008-11) to provide data to help calibrate the monitoring trap, help determine the best position for the trap (see below) and to help test improved decision support systems (see 3.9.2). Volunteers from across England and Scotland volunteered to host sites for this study. Data were collected from a total of 178 sites. The enthusiasm shown and willingness of these very busy people to freely give up their time towards this study is evidence of the scale of the pollen beetle problem in their view, and their desire to have alternative management tools such as a monitoring trap at their disposal.
- There was evidence for a correlation between the numbers of beetles trapped in the upwind and downwind traps and a strong positive correlation between the numbers of beetles per plant in the upwind and downwind crop scouting transects.
- Unfortunately there was no significant correlation between the trap catch and numbers on plants in the crop transects. We are therefore unable to calibrate trap catch to a given action threshold expressed as the number of beetles per plant using a simple linear relationship. There may be other factors that could help to explain the variance in the data, such as landscape factors and/or meteorological effects (see below) and future will attempt to model these effects to improve calibration efforts (Appendix C).

- The uncalibrated monitoring trap still has value as part of an integrated pest management strategy for pollen beetles. The traps can be used to detect the start of pollen beetle immigration on a field and could help to focus more time consuming plant monitoring effort to when it is most needed. Comparing relative trap catch on a site may indicate immigration peaks thus highlighting periods of risk, and when the trap catch levels off or begins to decrease this can indicate that immigration is coming to an end. The trap may be most useful when used in conjunction with decision support systems (see 3.9.2).
- Future work to calibrate trap catch to actual crop damage rather the number of beetles per plant may provide a more direct and accurate action threshold to prevent crop loss from pollen beetle (see Appendix C).
- An uncalibrated monitoring trap still has value for risk assessment in IPM for pollen beetle. It can be used to detect the start, peaks and completion of pollen beetle migration at a local level, and validate forecasts of these variables gained from decision support systems (see 3.9.2)

Develop models to determine the best trap position

- We found strong evidence that meteorological conditions (temperature, wind direction and speed and daytime rainfall) and some evidence that landscape features (area of residential gardens, length of hedgerow and length of treeline) affect trap catch
- Our model did not support the hypothesis that beetles overwinter in woodland, although they may overwinter in treelines in preference to hedgerows
- Our model supports previous work suggesting pollen beetles fly upwind towards crops and that they fly at c.13°C
- Monitoring traps (and by analogy, positions for plant scouting transects) are therefore best placed down-wind of the prevailing wind on a field site to maximize trap catch
- There is no need to trap when temperatures are ≤10°C
- More work is needed to define properly the flight threshold for pollen beetles and more importantly the relationship between weather variables and crop damage

3.9.2. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle (Objective 1, Task B)

- Better risk assessment and decision support could help to focus monitoring effort, but the best system available in the UK is advice on the CropMonitor website www.cropmonitor.co.uk. Monitoring is advised when the crop is at the green-yellow bud stage and the temperature is >15°C

- Growers and crop consultants on the Continent can use proPlant www.proplant.de, a decision support system that uses a phenological model of pollen beetle immigration and local meteorological data to predict risk of immigration. We tested the model under UK conditions using data from our pollen beetle monitoring study (3.9.1) and found that it accurately predicted the start of immigration, the main periods of risk and the end of immigration.
- We compared monitoring advice between the current advice system and proPlant. Both systems performed reassuringly well in prompting monitoring that would detect breaches of spray thresholds for pollen beetles in OSR. However there were considerable reductions provided by proPlant in the need for consultation of the system (30%) and advised monitoring days (34-53%) in comparison with current advice.
- Use of the proPlant system could therefore save growers and crop consultants time and money. It could help to reduce unnecessary insecticide applications by preventing insurance sprays when beetle numbers are *approaching* threshold, and by forecasting the end of migration, when sprays are not necessary even if the crop is still at the damage-susceptible stage.
- **We are delighted that as a result of work in this Project, a simplified version of the proPlant model which forecasts start of migration, risk of significant immigration in the next 2 days, and end of immigration was made freely available to growers and crop consultants via the Bayer CropScience website in the 2012 and 2013 seasons.** www.bayercropscience.co.uk
- It would be valuable to conduct an impact survey of the proPlant tool on the Bayer website and to test its predictions against actual data on pollen beetle immigration to give growers and consultants confidence in the tool, and to further improve uptake in the future (see Appendix C).

3.9.3. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape (Objective 1, Task C)

- The early flowering character of turnip rape (TR) trap crop plants offers two scenarios for the potential use of TR as a sentinel plant for risk assessment in oilseed rape (OSR): (1) predictive, (2) for real time monitoring
- Scenario 1 Predictive: We found some evidence that the number of pollen beetles on TR plants at the green-yellow bud stage were correlated with infestation levels of

the OSR crop one week later. Thus large infestations in TR at the green bud stage could act as an early warning of future risk in OSR. However, the relationship is probably not robust enough to be of practical value at present; more data are needed to improve the confidence in the analysis. We aim to improve the model as part of the work done in the Extension to this project (Appendix C).

- Scenario 2 Real-time monitoring: There was a positive correlation between the mean number of beetles on plants in the OSR crop at the damage-susceptible green-yellow bud stage with the number on flowering TR plants in the trap crop. It may therefore be possible to use the TR trap crop as a ‘living monitoring trap’. A mean of 7 and 34 beetles per TR plant would relate to an action threshold of 2 and 5 beetles/plant, respectively in the main OSR crop. Further work is needed to extend the model to be able to predict action thresholds relating to 15 beetles in the main crop and to improve confidence in the analysis (see Appendix C). However, this approach could provide added value for growers that use TR trap crops, negating the need for scouting transects to be performed in the main crop and the need to purchase plastic monitoring traps.

3.9.4. Evaluate on a field scale the potential of a turnip rape trap crop for reducing the abundance of pollen beetles in winter oilseed rape crops (Objective 2, Task D)

- Our previous work showed that spring turnip rape (TR) planted as a border to a spring oilseed rape (OSR) crop could reduce the populations of pollen beetles to below spray thresholds. We tested the strategy on a realistic field scale (1ha plots in individual fields) using winter cultivars on two sites over three years. We also examined the effect of spraying the trap crop and compared efficacy of trap cropping against prophylactic sprays on OSR.
- Winter TR plants in the border were more heavily infested than winter OSR plants in the border, suggesting that TR plants are more attractive.
- The effect of TR trap crop was inconsistent across years. In some replicates on some sites in some years the population of beetles in OSR plots with trap crops was significantly lower than in plots without trap crops. However, overall, although populations were lower in plots with trap crops than without, the difference was not significant. We believe this is attributed mainly to growth stage differential; in plots where the trap crop strategy worked, there was a greater differential between the growth stages of the trap crop and the main crop. Growth stages were only c. 1-week apart in some cases where the strategy did not work. Early-

flowering cultivars of TR which flower consistently 2-3 weeks earlier are needed for the strategy to be more reliable.

- Spraying the TR trap crop reduced the populations of beetles in the trap crop but did not affect the populations in the main crop; this approach is therefore not recommended.
- Populations of beetles were significantly lowest on the OSR treated prophylactically with insecticide.
- There was no significant difference in the yields between treatments
- Given the economics of the trap cropping strategy as it currently stands (see Section 3.9.8) it is likely that this option is most useful to organic growers. The most promising way of delivering the benefits of a trap crop to conventional growers may be through crop margin management (i.e. using flowering margins containing Brassicas to act as trap crops). This possibility is being addressed in Defra-funded project IF0139, and will require further work in addition to enable to delivery to growers.

3.9.5. Assess the cost effectiveness of the trap cropping tactic (Objective 2, Task E)

- We performed a simple cost:benefit analysis which explored the costs and net margin returns of different cropping scenarios, with and without trap crops and with and without insecticides
- Our analysis indicates that the best strategy is to have an OSR crop (without a trap crop) and either not treat it or only treat when necessary (returning a net margin of £482/ha if the crop is not sprayed; note this does not include the cost of advice or monitoring aids associated with determination of thresholds). If insecticides are used, the margin will be reduced to £466 if pyrethroids are used and to £455 if another insecticide class is used. The net margin for a strategy with a trap crop to reduce beetles to below spray threshold is £407.
- If trap crops are grown, they should be harvested; margins are reduced from £407 to £367 if the trap crop is destroyed.
- An increase in yield of 1.4% is needed if a pyrethroid insecticide is used to break even in comparison with margins returned from an untreated crop; this rises to 2.3% if the more expensive non-pyrethroid insecticide classes are used. A 6.9% increase in yield is necessary if a trap crop is grown for control of pollen beetle.
- To refine the cost:benefit analysis a figure for the yield loss caused by a given amount of pollen beetle damage is required; there is no *economic* threshold available. Future analyses should also take into account the costs of advice and monitoring to enable thresholds to be determined and the economic, environmental and political benefits of reduced insecticide use

3.9.6. Initiate a programme to develop a practical and efficient trap cropping strategy for winter oilseed rape (Objective 3, Tasks F&G)

- The trap cropping strategy tested as part of this project (Section 3.9.6) is based on a winter turnip rape (TR) trap crop planted as a border to the winter oilseed rape (OSR) crop. Both the TR and OSR can be sown at the same time but the TR ripens earlier and does not yield as well as OSR (see Section 3.5). To improve practicality and maximize yield from the area cropped, earlier-flowering, later-ripening and higher yielding cultivars of winter TR or highly attractive early-flowering cultivars of winter OSR are needed to replace the TR component of the strategy. We focused on identifying early flowering lines of OSR that could function as trap plants in the trap cropping tactic.
- We screened lines in the OREGIN 2010 demonstration trial www.oregin.info and those from our Project partners involved in plant breeding but were unable to find a suitable winter OSR genotype to suit our purpose.
- In the OREGIN trial, we identified some early-flowering brassicas, and these could be investigated further in the future together with lines that were less preferred by pollen beetles with the aim to develop new cultivars for trap crops of the future, based on highly attractive early flowering OSR cultivars as the trap crop and less attractive, pollen beetle 'resistant' cultivars as the main crop.

3.9.7. Propose an IPM strategy for controlling pollen beetles in winter oilseed rape based on the combination of the most effective elements tested in this project (Objective 3, Task H)

An IPM strategy for pollen beetles is proposed to facilitate the judicious use of insecticides; it is based on the use of decision support systems to forecast immigration risk, monitoring methods to enable the use of action thresholds and alternative crop management (trap crops) to reduce the number of sprays needed. It is intended for use by growers, crop consultants and policy makers.

- **The damage susceptible stage of the crop is the green-yellow bud stage only** (BBCH GS 50-59). Monitoring of pollen beetle populations should be concentrated within this period and any insecticide applications should not be applied after flowering has started.
- **Action thresholds should be used**. Insecticides should only be applied if the crop is within its damage-susceptible growth stage *and* action thresholds have been breached. For many years the accepted HGCA action thresholds were: 2 beetles/plant for varietal associations, 5 beetles/ plant for backward crops and 15 beetles/ plant for otherwise good crops (e.g. Oakley, 2003; HGCA, 2010). However, varietal associations are no longer

widely grown and results of a recent HGCA-funded study proposed a threshold scheme in which pollen beetle threshold is negatively related to plants/m^2 (Ellis & Berry, 2011). As a rule of thumb, new action thresholds are c.30 beetles/plant for thin crops (<20 plants/m^2), 20 beetles/plant for optimal crops with 40 plants/m^2 and c. 10 beetles/plant for thick crops with >60 plants/m^2. There is no distinction between spring and winter sown crops (HGCA 2012).

- **Risk of crop damage is related to pollen beetle immigration risk** As a rule of thumb, the crop is at a lower risk due to pollen beetle immigration when temperatures <10°C, when there are strong winds and if it is raining or has rained in the past 12h. The crop is at greatest risk when temperatures >15°C.
- **Forecasting risk of pollen beetle immigration** Decision support systems (DSS) that provide risk assessments of pollen beetle immigration should be used to minimize monitoring effort and focus it to when it is most needed**.** proPlant www.proplant.de is a decision support system that uses a phenological model of pollen beetle immigration and local meteorological data to predict the start, peaks and end of pollen beetle immigration. It produces forecasts of immigration risk and advises monitoring days for up to 2 days in advance .As a result of this Project, the proPlant forecasting tool is freely available on the Bayer CropScience website www.bayercropscience.co.uk The maps showing immigration risk for the next 2 days and % completion of migration should be used to help decide whether or not plant monitoring is necessary. Use of these maps has great potential to save unnecessary 'insurance' insecticide applications.
- proPlant is a decision *support* tool, not a decision *making* tool. The proPlant phenological model is built using numbers of beetles on plants in the crop, and is designed to prompt population monitoring in the crop after which a decision is made as to whether to spray or not.
- **Detection of action thresholds (population monitoring) The recommended method for population monitoring of pollen beetles is from plant sampling in the crop** and is based on the beating method; the main raceme of the plant is beaten firmly two or three times against the base of a tray. Action thresholds are expressed as a *mean* number of pollen beetles per plant. At least 10 plants for sampling should be selected at random, taken along a transect of at least 30 m, starting at the headland and heading towards the crop centre (HGCA 2012). Plants should not be sampled in the headland alone as pollen beetles are often more abundant at the crop edge, and this will not reflect the average across the field. Ideally four transects should be performed on each side of the crop, as beetles are not evenly distributed across the field and often come into the crop from one main direction. If only one transect is performed the mean could be an under-estimate if the wrong side is selected. However if there is only time to do 1 transect, it should be done

on the down-wind side of the crop according to the wind direction at the time of sampling, as beetles fly upwind towards the crop.

- **A baited monitoring trap for pollen beetles** has been developed as part of this project and will be commercially available in 2013 from Oecos www.oecos.co.uk. Unfortunately at present the monitoring trap cannot be used to determine action thresholds in the crop and should not replace the monitoring of plants directly in the crop. However, the uncalibrated monitoring trap still has value for risk assessment. They can be used to detect the start of immigration, peaks of immigration and end of immigration and be used to verify at a local level the forecasts provided by the DSS. Ideally one monitoring trap should be placed on each side of the field but if only one per field is used it should be placed downwind of the prevailing wind on the site, and users should be aware that trap catch will vary as the actual wind direction may change between sample dates. Monitoring traps should be used during the green-yellow bud stage of the crop only and should then be removed.
- **Alternative crop management (trap cropping)** A TR trap crop comprising c.10% of the area of the field planted as a border around the edge of the main OSR crop can be used to reduce the population of pollen beetles to below spray thresholds. The tactic in its current form will be of most interest to organic growers. It is essential that the flowering differential between the trap crop and the main crop should be maximized; the earliest flowering cultivar of TR possible should be selected as the trap crop (e.g. Buko) and the latest flowering OSR cv possible should be selected as the main crop. Both the trap crop and the main crop can be planted on the same day; do not plant the OSR crop before the TR trap crop. Crop management can then proceed as normal until harvest. We do not recommend spraying the trap crop for pollen beetle. We recommend that the trap crop should be harvested at the optimal time. Although this represents another farm operation, this prevents seed shed leading to volunteer problems later and economically, the returns are worthwhile compared with management options where the trap crop is destroyed.
- **Insecticide resistance management** Repeated use of the same insecticidal active ingredient or active ingredients with the same mode of action can lead to the development of insecticide resistance. Currently there are insecticides from four chemical sub groups registered for pollen beetle control Pyrethroids, Noenicotinoids, Indoxacarb and Pymetrozine. Growers should therefore consider rotating use of these such that successive generations of the pollen beetle are not treated with or exposed to compounds from the same group within the insecticide regime used over the life time of the crop.

3.9.8. General Discussion

The integrated pest management (IPM) strategy for pollen beetles we propose is based on the use of decision support systems (DSS) to forecast immigration risk and focus monitoring effort, improved monitoring methods to enable the use of action thresholds and alternative crop management (trap crops) to reduce the pest population. These three tactics represent the three major achievements of our project.

One of the major limitations to use of action thresholds is that proper monitoring of the populations is time consuming and has to be conducted over a prolonged period. Better risk assessment and decision support could help to focus monitoring effort. proPlant is a decision support system available in mainland Europe that uses a phenological model of pollen beetle immigration and local meteorological data to forecast the start and end of pollen beetle immigration into the crop and main periods of risk up to 2 days in advance and advises when to monitor. We tested the model under UK conditions using data from our pollen beetle monitoring study and compared monitoring advice given with the best current advice system on the CropMonitor website. Both systems performed reassuringly well in prompting monitoring that would detect breaches of spray thresholds for pollen beetles in OSR. However there were considerable reductions provided by proPlant in the need for consultation of the system (30%) and advised monitoring days (34-53%) in comparison with current advice. Use of the proPlant system could therefore save growers and crop consultants time and money. It could help to reduce unnecessary insecticide applications by preventing insurance sprays when beetle numbers are *approaching* threshold, and by forecasting the end of migration, when sprays are not necessary even if the crop is still at the damage-susceptible stage. We are delighted that as a result of work in this Project, a simplified version of the proPlant model which forecasts start of migration, risk of significant immigration in the next 2 days, and end of immigration is now freely available to growers and crop consultants in the UK via the Bayer CropScience website www.bayercropscience.co.uk.

Use of action thresholds is reliant on reliable and effective methods for monitoring populations of pollen beetles in the crop. Current crop monitoring methods involve time consuming plant samples from transects 30m into the crop. Unless several transects are performed results can be inaccurate as a measure across the whole field and can vary according to the position of the plants sampled and the time of day and weather conditions. A monitoring trap for pollen beetles would help growers and crop consultants to more easily and accurately identify when pollen beetle immigration has started and when spray thresholds have been breached. A baited monitoring trap for pollen beetles has been developed as part of this Project and from 2013 will be commercially available from Oecos www.oecos.co.uk. The monitoring trap comprises a yellow sticky card held at 45°, baited with phenylacetaldehyde, a floral volatile produced naturally by several plant species. Unfortunately at present the monitoring trap cannot be used to determine action thresholds in the crop**.** There was no correlation between the number of beetles caught in the traps and the number of beetles present on plants in the crop and so we were unable to calibrate trap catch to a given action threshold expressed as the number of beetles per plant using a simple linear relationship. However, the monitoring trap still has value for risk assessment, especially if used in conjunction with decision support systems.

Trap crops of turnip rape (TR) planted as a border to an oilseed rape (OSR) crop consistently reduced populations of pollen beetles to below spray thresholds in a spring OSR system in previous studies. We tested the strategy for a winter OSR cropping system on a realistic field scale over three years. We found evidence that the strategy worked well in some years, but not others. In years when the tactic did not work, the growth stage differential between the main crop and the trap crop was probably too short. To optimize efficacy, growers will be restricted to using the earliest of TR cultivars and the latest of OSR cultivars possible, and this tactic is probably practical and economically worthwhile only for organic growers.

We believe that use of these IPM tools will facilitate use of action thresholds and help encourage more growers and crop consultants to use spray thresholds. Use of the strategy or components of it will undoubtedly save growers time, money and prevent unnecessary insecticide sprays.

As well as practical IPM tools, our project has also considerably increased the knowledge base of pollen beetle physiology and it behavioural and chemical ecology. We have determined the spectral sensitivity of pollen beetles, identified putative green, blue and UV receptors and explained how their preference for yellow is physiologically determined. As well as being of great academic interest, this work has produced a colour choice model that can be used to assess the relative attractiveness of traps, plants or other materials for use in IPM strategies that exploit colour preference – without the need to run expensive field trials. We have identified several new volatile compounds not previously found in OSR plants and identified plant genotypes that may be useful in future plant breeding programmes to develop super attractive cultivars for trap plants or unattractive ‘resistant’ cultivars for improved main crops each of which exploit the host-location process of pollen beetles. Lastly, and perhaps most significantly, we have gained considerable additional knowledge on the immigration behaviour of pollen beetles into OSR crops. This knowledge has several future practical applications. Further analysis of our data will help to inform on better plant monitoring practices: are transects at least 30m long really needed? Can we not correlate numbers on plants in headlands with numbers in the crop to enabling sampling just from the crop edge? We have shown that pollen beetles fly at lower temperatures than previously thought (c. 13°C, rather than 15°C) and we have confirmed that they fly upwind towards crops. We have shown immigration is also affected by wind speed and rain. It is commonly understood that pollen beetles overwinter in woodland, but sites near to woodlands did not necessarily result in larger populations in the field. Further work may enable growers to predict the likely direction of immigration on a site so that insecticide applications are better targeted spatially (reducing area treated), monitoring transects and traps could be more accurately selected and sited and fields most at risk from pollen beetles identified, all given the surrounding landscape features.

We believe our project was a great success and we are proud of our achievements. We have worked together to develop an IPM strategy for pollen beetles in winter OSR that can be used as a framework by growers and crop consultants to manage pollen beetles with reduced insecticide inputs and the confidence to do so. This will prolong insecticide life by reducing selection for resistance, reduce environmental impacts and contribute towards the sustainability and profitability of OSR in the UK.

3.10. References

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Defra PS2107 2003-2006 A framework for the practical use of semiochemicals in field crops

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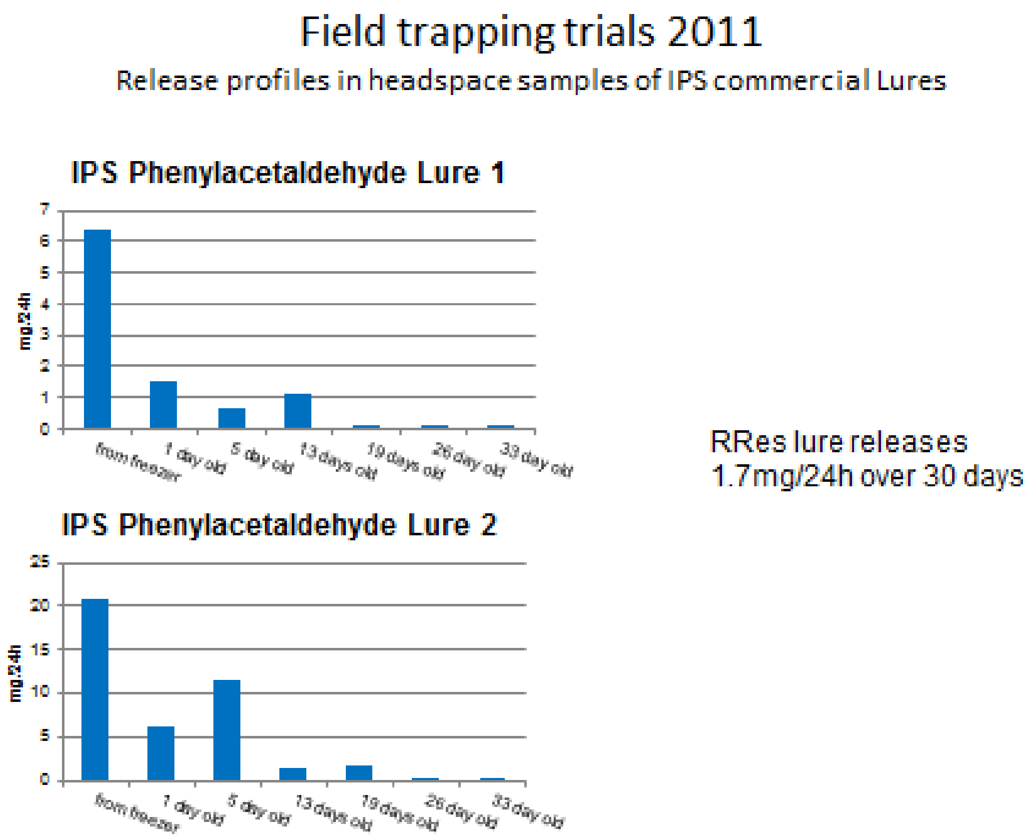
3.12. Appendices

3.12.1. Appendix A: Release rates of International Pheromone Systems commercial lure

Release rates were determined by weight loss over time of standard under standard conditions of temperature and wind speed. Several lures were tested and two, the phenylacetaldehyde low rate (Lure 1) and phenylacetaldehyde high ratete (Lure 2) gave values in the region of the Rothamsted experimental lure (1.7mg/24h over 30 days).



3.12.2. Appendix B KWS field trials visit: Assessment of the potential of winter turnip rape cv Buko to act as a trap crop to protect against pollen beetles in winter oilseed rape

Introduction

In Section 3.7 we worked towards the initiation of a programme to develop a practical and efficient trap cropping strategy for winter oilseed rape (OSR) (Objective 3, Tasks F&G). The trap cropping strategy tested as part of this project (Section 3.5) is based on a winter turnip rape (TR) trap crop planted as a border to the winter OSR crop. Both the TR and OSR can be sown at the same time but the TR ripens earlier and does not yield as well (see Section 3.5). To improve practicality and maximise yield from the area cropped, higher yielding and later ripening cultivars of TR were initially sought. A field trial site run by KWS was visited to assess the performance of TR cv Buko as a potential trap crop for OSR. Buko plants were clearly more attractive than the OSR plants on the day of our visit and therefore show good potential for use as a trap crop. We also found evidence to support the theory that beetles fly upwind to field sites.

Materials & Methods

A visit was made by Rothamsted Project staff members to a KWS field trial site in Cambridgeshire on 1/4/2009. The KWS site was of interest as 0.5m-wide strips of winter turnip rape cv. Buko were sown on two opposite edges and in the centre of a crop of winter oilseed rape cv Epure (Figure A 1). The TR plants were at early flowering (GS 61) and the OSR plants were at GS 50 with buds visible. We sampled along 8, 100m transects across the length of the field, at right-angles to the TR strips. On each transect, 3 plants were sampled at each of 45 sample points along the transect. The number of pollen beetles on each of the 45 sample points along the transects was totalled across the 8 transects (n=24) as pollen beetle numbers were low.

Results & Discussion

Clearly more beetles were found on TR plants (positions 1, 23 and 45 on the transects) than on OSR plants in the transects (Figure A2). This indicates that cv Buko would make a good potential trap crop as these plants are more attractive than those of OSR at the damage susceptible stage of the crop. There was some evidence that the function of the trap crop was acting at close range, because in general as the distance between a trap strip and OSR plants increased, so did the number of beetles on those plants (Figure A2; particularly between plants 24-44). There was also some evidence that beetles were immigrating to crops upwind as more beetles were found downwind of the WSW prevailing wind on the site than upwind (i.e compare decrease in numbers between TR 45, 23 and 1). Futher work is needed to investigate both these points.

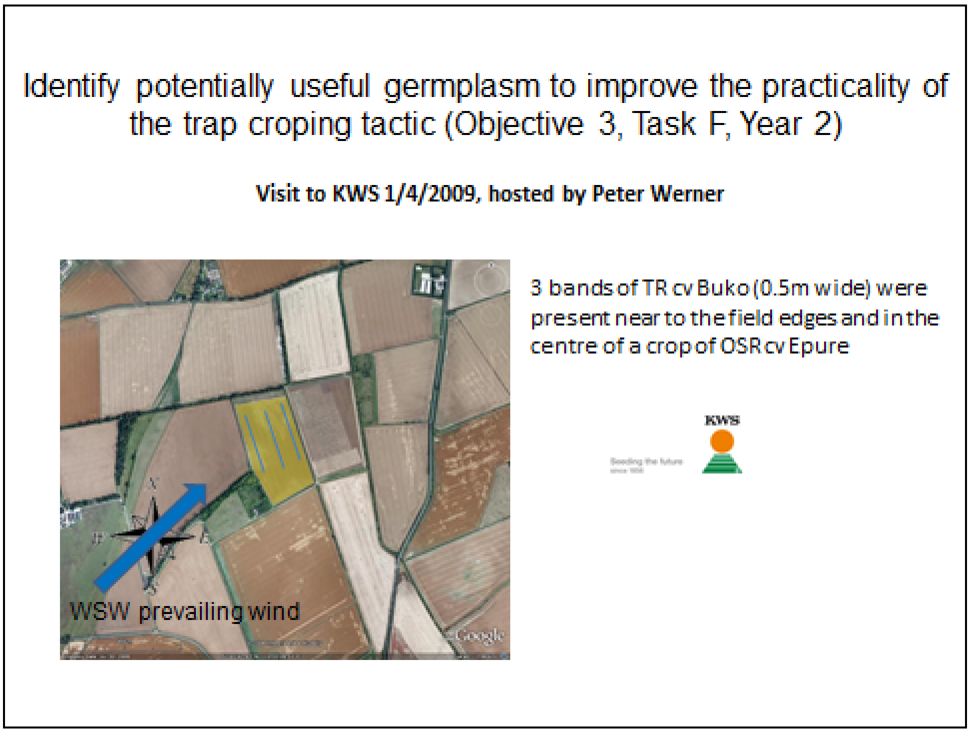


Figure A1 Lay-out of KWS field trial with trap crop strips shown as blue lines.

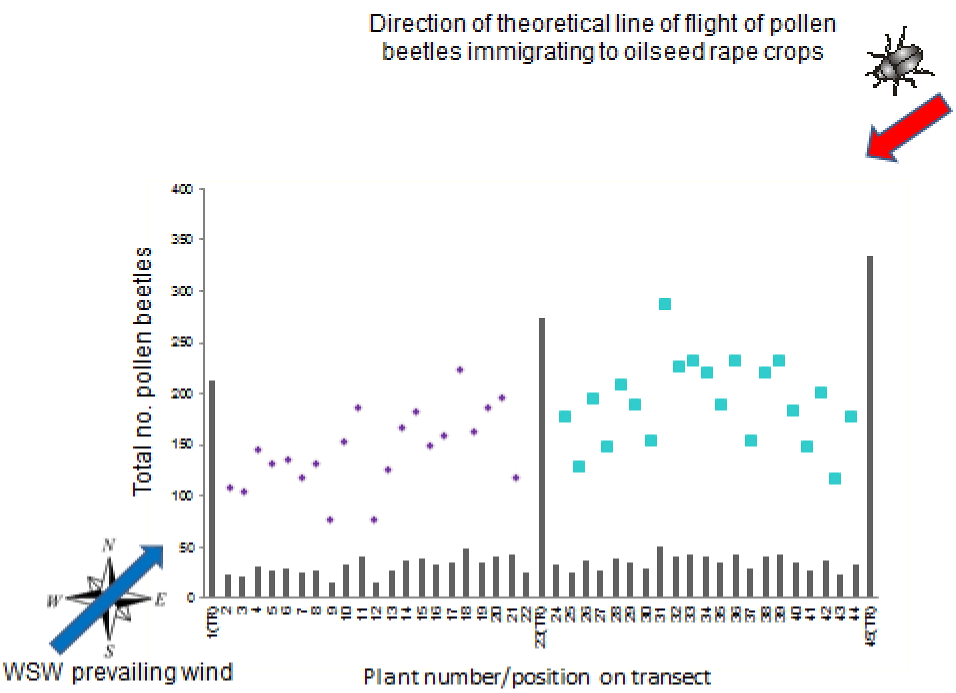


Figure A2 Total number of pollen beetles found on 45 positions sampled across 8, 100m transects (n=24). Turnip rape strips represent positions 1, 23 and 45. Dots and squares represent the oilseed rape data only on a scale of 0-60 beetles (clearer in the absence of large TR values).

3.12.3. Appendix C: LK09108 Extension - Development of an integrated pest management strategy for control of pollen beetles in winter oilseed rape: Improving monitoring, decision support and risk assessment

Background

LINK project LK09108 'Developing an integrated pest management strategy for pollen beetles in winter oilseed rape' aimed to develop an IPM strategy for pollen beetles in oilseed rape (OSR). The project was extremely successful in addressing the objectives. Further funding (£55,000) was made available from CRD and will add significant value to the outcomes by enabling some of the analyses to be fully completed and/or extended in an 11-month extension to the project. This extended work is backed by £24,240 in-kind support; it includes 10 days' time from Andreas Johnen, proPlant (at £720 /day = £8,640 contribution, including VAT) and a high level of support for this project from stakeholders:

- 15 farmers/crop consultants are giving their time in-kind to collect bud samples and run monitoring traps on a range of sites across the UK (2 hours/week each; 90 hours in total at £100/h = £9,000)
- HGCA, LEAF, Farming Online, Rothamsted Research Association & Procam Agronomy gave their time in-kind to help promote the study to find growers and crop consultants willing to participate in an impact assessment of the proPlant pollen beetle forecasting tool (2 hours each at £100/h = £1000)
- 14 farmers/crop consultants are giving their time in-kind to provide data for an impact assessment of proPlant pollen beetle forecasting tool (4 hours each at £100/h = £5,600)

Project duration 11 months: 21/03/12 - 28/02/2013

The results of the extension work will be reported as a supplementary report to the final report of LK09108

Aims

The aims of the extension funding are to work towards completion and/or extension of the following Objectives/Tasks from LK09108:

Objective 1 Task A. Develop a reliable monitoring trap for pollen beetles to enable easy and effective detection of threshold levels of these pests

Objective 1 Task B. Assess and improve the ability of existing decision support systems to identify risk periods for pollen beetle

Objective 1 Task C. Assess the potential of using turnip rape as a sentinel plant system for risk assessment in oilseed rape

The work will be conducted to address 18 new milestones within 3 workpackages:

Workpackage 1. Modelling to quantify monitoring methods for pollen beetle (LK09108 Objective 1, Task A)

Background & Approach

Currently, pollen beetle numbers in the crop are monitored by walking a transect into the crop and calculating the mean number of beetles/plant from a minimum of 10 plants (HGCA advice). This approach is time consuming and results are variable depending on the position and timing of the transect, as pollen beetles are unevenly distributed in the field and activity is affected by temperature. A monitoring trap will alert growers and crop consultants as to when migration is occurring but potentially could also more easily and accurately identify when spray thresholds have been breached than the current monitoring methods. In LK09108 we developed a monitoring trap for pollen beetles. However we were unable to calibrate the trap as there was no simple relationship between the number of beetles/trap and the number of beetles/plant in the crop (to relate trap catch to control thresholds of 5 or 15 beetles/plant).
We do, however, have additional data collected by a PhD student outside of the project. The student carried out transect counts on 4 sides of a field every hour for 12h over a 5 day period. A group of monitoring traps were also run on each side of the field, covering the 4 cardinal compass points; and these were changed hourly. Weather data (wind speed, direction and temperature) were collected on an hourly basis throughout the study. We will analyse these data (relating trap and transect counts to weather variables) to help to quantify the different sources of variation (trap or transect position, day and time of day) and to try to explain this variation using the weather variables. We can then use these relationships to test the hypothesis that transect counts are related to the cumulative influx of beetles into the crop – as measured by trap counts – modified by weather at the time of sampling. This analysis was beyond the scope of the original project and is based on understanding gained during the project. This work will improve our understanding of the relationship between trap catch and numbers of beetles in the crop and help to determine how to solve the problem of trap calibration without further extensive large-scale experimentation.

Objectives & Milestones

Objective 1 Quantify variability in trap and transect data (to enable full completion of LK09108 Objective 1, Task A)

Milestone 1 Analyse data from repeated trap and transect study (delivery by 28/9/12)

Milestone 2 Model trap and transect data (delivery by 31/12/12)

Milestone 3 Re-assess pollen beetle monitoring trap calibration in light of information from Milestones 1-2; Report on results, produce scientific papers and disseminate information as appropriate (delivery by 31/1/13)

Objective 2 Assessment of potential use of turnip rape plants to protect oilseed rape crops (to enable full completion of LK09108 Objective 1, Task C)

Milestone 4 Explore the variation in turnip rape trap cropping data and the potential of adding data from spring oilseed rape experiments done in PS2017 and PS2113 to improve correlations of numbers of beetles per plant on oilseed rape and turnip rape plants in winter oilseed rape systems (tested in LK09108) (delivery by 31/1/13)

Milestone 5 Report on results, produce scientific papers and disseminate information as appropriate (delivery by 28/2/13)

Workpackage 2. Extension of decision support system comparison

Background & Approach

Current advice available from HGCA and the CropMonitor website is that growers/ crop consultants should monitor their OSR crops during the damage-susceptible phase (green bud until start of flowering) and that pollen beetles fly at temperatures of 15°C or above. In practice, monitoring for this period would involve an unrealistic commitment of time as the damage-susceptible phase can often last 2-4 weeks and temperatures can often exceed 15°C in this period. This may contribute to unnecessary 'insurance' spraying against pollen beetles. For example, an isolated monitoring visit to the crop may indicate beetle populations at ~6 or 7 beetles/plant and a decision could then made to spray because 'tomorrow there may be more beetles…'. proPlant Expert is a decision support system used widely by growers, crop consultants and advisory bodies in six countries across mainland Europe. It is based on a phenological model of pollen beetle migration and, using weather data, it can forecast the start, peaks and end of pollen beetle migration.

In LK09108 we assessed pollen beetle phenology from trapping studies carried out on over 150 fields across the UK over a 4-year period. At the end of each season we obtained weather data for the most intensively sampled sites and compared *a posteriori* proPlant prognoses for migration with our trapping study results. We concluded that the system can accurately predict the start, peaks and end of beetle migration in the UK. Comparing current UK advice with proPlant advice, we showed that using proPlant could halve the monitoring days required to identify a breach in threshold. The proPlant system is being made available to UK growers free via the Bayer website for the 2012 and 2013 seasons (after which the service will be reviewed by Bayer).

During the final year of the project we conducted a trial in real-time, comparing the implementation of proPlant and current UK advice using 9 sites in the Bedford area, to validate our results using the *a posteriori* approach. A preliminary analysis of this has been done for the final report, but we aim to refine and extend our comparison of monitoring days needed using REML and to extend the analysis to new objectives, analysing the number of days of immigration risk forecasted by each decision support system and the number of days during the risk period that each system required forecasts to be consulted. A small impact assessment will also be conducted to evaluate how using the proPlant system in the 2012 season has influenced monitoring and spraying practices.

Objectives & Milestones

Objective 1 Extend decision support system comparison (to enable full completion of LK09108 Objective 1, Task B)

Milestone 6 Extend the comparison of monitoring days needed using REML (delivery by 31/1/12)

Milestone 7 Analysis of the number of days of immigration risk forecasted by each decision support system and the number of days during the risk period that each system required forecasts to be consulted using real-time data (delivery by 31/12/12)

Objective 2 Conduct impact assessment on proPlant expert map decision support system (to extend outcomes of LK09108 Objective 1, Task B)

Milestone 8 Conduct a small survey amongst farmers and advisers on their evaluation of proPlant expert map and its influence on their practice (delivery by 31/11/12)

Milestone 9 Report on results, write scientific papers and disseminate information as appropriate (delivery by 28/12/13)

Workpackage 3. Extending proPlant to forecast pollen beetle damage risk

Background & approach

This workpackage aims to better understand the relationship between damage in the crop, population size and temperature with the view to extend proPlant to forecast pollen beetle damage risk in the UK. An outcome of LK09108 was the identification of a major knowledge gap regarding how actual crop damage (feeding and oviposition damage to buds) relates to numbers of beetles in the crop (or on traps) and how this interacts with temperature. We believe there is now the opportunity to refine the output of the proPlant model to include not only forecasts of pollen beetle immigration but also forecasts of damage risk, potentially leading to further reductions in pesticide use. These objectives build on the success of the proPlant model for pollen beetles in the UK and the network of volunteer farmers' sampling sites built-up during LK09108.

There appears to be little differentiation between European populations of the pollen beetle, as the proPlant model does not require modification for the UK, yet the treatment threshold for the UK, at 15 beetles per plant, differs greatly from the 2-5 beetles per plant advised in the northern European mainland. We hypothesise this is related to the feeding rate of pollen beetles on plants; the cooler spring weather in the UK leading to lower feeding rates and less damage, and is also related to the speed of crop development which is again temperature-dependent. Temperature is a critical component of the proPlant model. We will investigate the potential for modifying the model to provide forecasts of damage risk as well as forecasts of immigration. This could be particularly important in the light of climate change and the potential for warmer UK springs.

Methods

Field work Pollen beetles in winter OSR will be sampled from green bud stage at ~10 sites in the UK, including one at Rothamsted until the start of flowering. Standard protocols developed for LK01908 will be used for sampling i.e. counts of beetles on yellow sticky traps and transect counts of insects on plants, with growth stage assessments of the crop for each transect. Samples of main racemes taken from transects will be taken to assess pollen beetle feeding damage and oviposition. Weather data for each sampling site will be obtained by proPlant. At the end of the season, the phenology of bud damage will be compared by proPlant with the phenology of pollen beetles and temperature to test the potential for modelling the risk of bud damage.

Laboratory experiments Replicated laboratory experiments will be conducted to investigate (i) the threshold temperature for flight and (ii) the effect of temperature on the rate of feeding and oviposition. A series of lab experiments will be done using beetles collected from the field, glass-house grown plants and small cages in controlled environment facilities.

Objectives & milestones

Objective 1 Better understand the relationship between temperature, population size and damage in the crop, with a view to extending proPlant to forecast pollen beetle damage risk (to extend outcomes of LK09108 Objective 1, Task B)

Milestone 10 Locate and run field work on ~10 sites across the UK (delivery by 30/3/12)

Milestone 11 Run trap sites at Rothamsted (delivery by 31/5/12)

Milestone 12 Count the number of pollen beetles per trap on traps returned from field work sites and enter data into database together with numbers of beetles per transect from field sites (delivery by 30/9/12)

Milestone 13 Assess feeding and oviposition damage on bud samples returned from field work sites and enter data into database (delivery by 31/8/12)

Milestone 14 Conduct lab experiments to determine temperature threshold for flight (delivery by 31/8/12)

Milestone 15 Conduct lab experiments to determine the effect of temperature on feeding and oviposition rates (delivery by 31/8/12)

Milestone 16 Collate field and laboratory data and forward to proPlant for modelling (delivery by 30/10/12)

Milestone 17 Initial modelling to assess the potential to forecast damage risk to oilseed rape crops from pollen beetles (delivery by 31/1/13)

Objective 2 Disseminate results on the relationship between temperature, population size and damage in the crop (to extend outcomes of LK09108 Objective 1, Task B)

Milestone 18 Report on results, write scientific papers and disseminate information as appropriate (delivery by 28/2/13).