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

by

Samantha M. Cook[1], Thomas F. Döring[2,3], Andrew W, Ferguson[1], Janet L. Martin[1], Matthew P. Skellern[1], Lesley E. Smart[1], Nigel P. Watts[1], Sue J. Welham[1,4], Christine Woodcock[1] and John A. Pickett[3]

with Industrial project partners:

Eileen Bardsley[5], Jo Bowman[6], Sean Burns[7], Matthew Clarke[8], Jackie Davies[9], Carl Gibbard[10], Andreas Johnen[11], Richard Jennaway[12], Richard Meredith[5], Darren Murray[4], Mark Nightingale[13], Nigel Padbury[7], Colin Patrick[12], Julia-Sophie von Richthofen[11], Peter Taylor[14], Michael Tait[15] and Peter Werner[10]

and Project officers from our funding bodies:

Jemilah Bailey (FFG, Defra)[16], George Rothschild (HSE-CRD)[17], James Holmes, Caroline Nicholls & Jenna Watts (AHDB-HGCA)[18]

[1]Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ; [2] Imperial College London Exhibition Road, London, SW7 2AZ; [3]Elm Farm, Hamstead Marshall, Newbury, Berkshire, RG20 0HR; [4]VSN International, 5 The Waterhouse, Waterhouse St., Hemel Hempstead, HP1 1ES; [5]Bayer CropScience, Cambridge Science Park, Milton Road, Cambridge, CB4 0WB; [6]Limagrain UK, Rothwell, Market Rasen, Lincolnshire, LN7 6DT [7]Syngenta Seeds, 30 Priestley Road, Surrey Research Park, Guildford, GU2 7YH; [8]Monsanto UK, Building 2030, Cambourne Business Park, Cambourne, Cambridge, CB23 6DW; [9]Oecos, 11a High Street, Kimpton, Hitchin, Hertfordshire, SG4 8RA; [10]KWS UK Ltd, 56 Church Street, Thriplow, Royston, Hertfordshire, SG8 7RE; [11]proPlant GmbH, Albrecht-Thaer Straße 34, 48147 Münster, Germany; [12]Saaten-Union UK, Rosalie Field Station, Bradley Road, Cowlinge, Newmarket, Suffolk, CB8 9HU; [13]Elsoms Seeds Ltd, Pinchbeck Road, Spalding, Lincolnshire, PE11 1QG; [14]Association of Independent Crop Consultants Limited (AICC), Agriculture Place, East Meon, Petersfield, Hampshire GU32 1PN; [15]Syngenta Crop Protection UK, CPC 4, Capital Park, Fulbourn, Cambridge, CB21 5XE; [16]Food and Farming Group, Department for food, farming and rural affairs, Nobel House, 17 Smith Square, London, SW1P 3JR; [17]Health & Safety Executive - Chemical Regulation Directorate, Mallard House Kings Pool, 3 Peasholme Green, YORK, YO1 7PX; [18]Agriculture and Horticulture Development Board – Home Grown Cereals Authority, Stoneleigh Park Kenilworth, Warwickshire, CV8 2TL

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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)

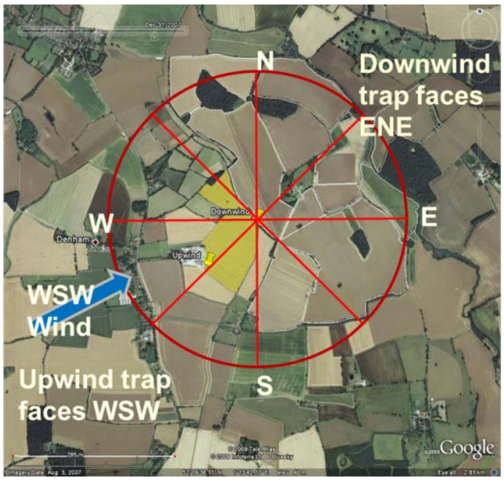
We ran a pollen beetle monitoring study in each of the 4 years of the project (2008-2011). In each year, winter OSR fields were selected on Rothamsted Farm, Woburn Farm and on as many other farms as possible across the UK. At each site, two yellow sticky traps were placed on different sides of the field; 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

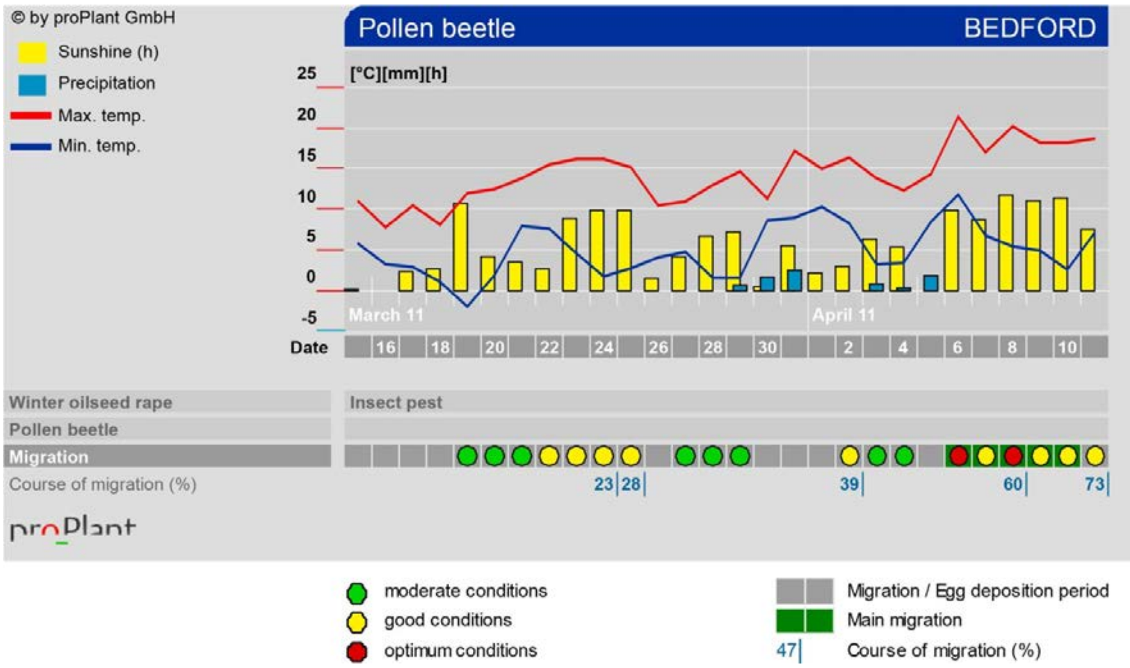
Advice on pollen beetle management is currently available to UK growers through the CropMonitor™ website http://www.cropmonitor.co.uk/ (hereafter referred to as 'current advice'). The period of risk from pollen beetles to OSR is defined in current advice in the UK as 'green-to-yellow bud stage' (BBCH 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

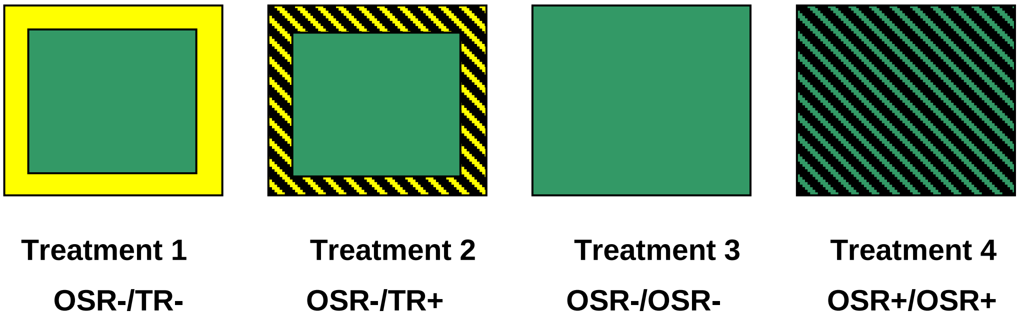
The relationships between pollen beetle numbers in TR borders during the bud phase (GS 50-59) against the numbers in the OSR centres of the same fields 1 week and 2 weeks later were examined.

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.



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 1st 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

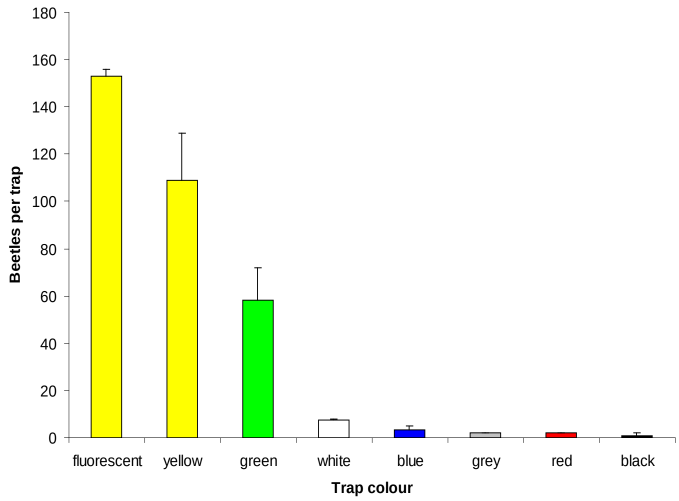
2.3.1. Develop a monitoring trap for pollen beetles (Objective 1, Task A)

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.



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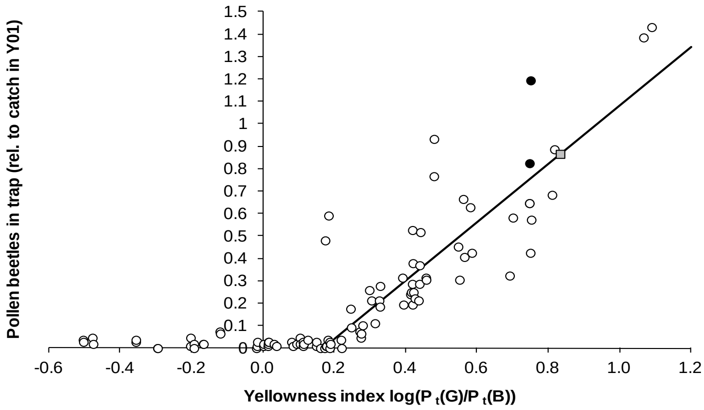
Summary Figure 5. Mean (± SE) number of trapped pollen beetles caught in selected trap colours in the field trapping experiment. The "yellow" trap was used as the reference trap (Y01).



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

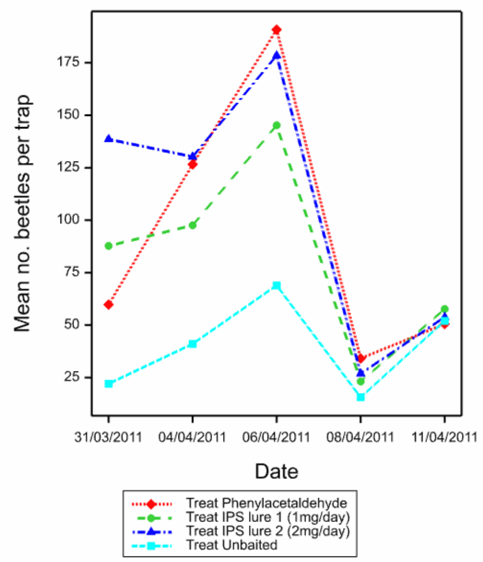
Optimise pollen beetle catch and minimize beneficial catch by investigating colour x odour interactions The different coloured sticky traps tested were much less effective at capturing pollen beetles than the yellow trap but they also caught more parasitoids. The addition of a lure increased pollen beetle 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).

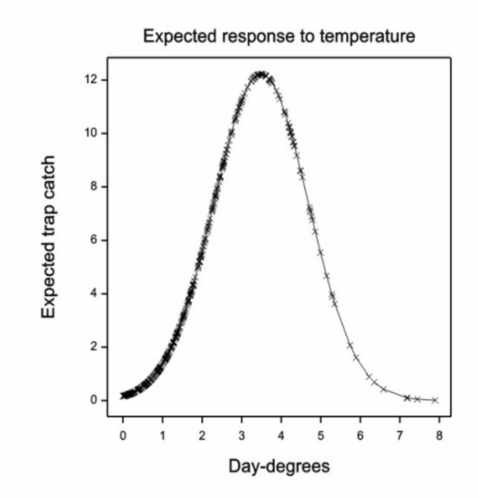
Summary Table 2. Number of pollen beetles caught on yellow sticky traps in oilseed rape crops in a pollen beetle trapping study 2008-2011

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)

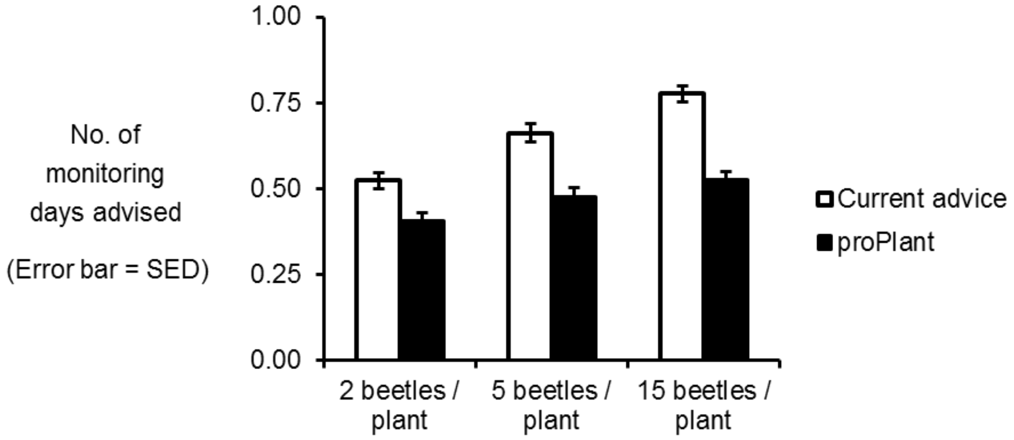
In total data from 44 sites were used in the comparisons. Although the 15 beetle threshold was breached at only one site, the 2 and 5 beetle thresholds were breached at 82% and 43% of sites, respectively, providing a good test of the performance of each DSS.

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.

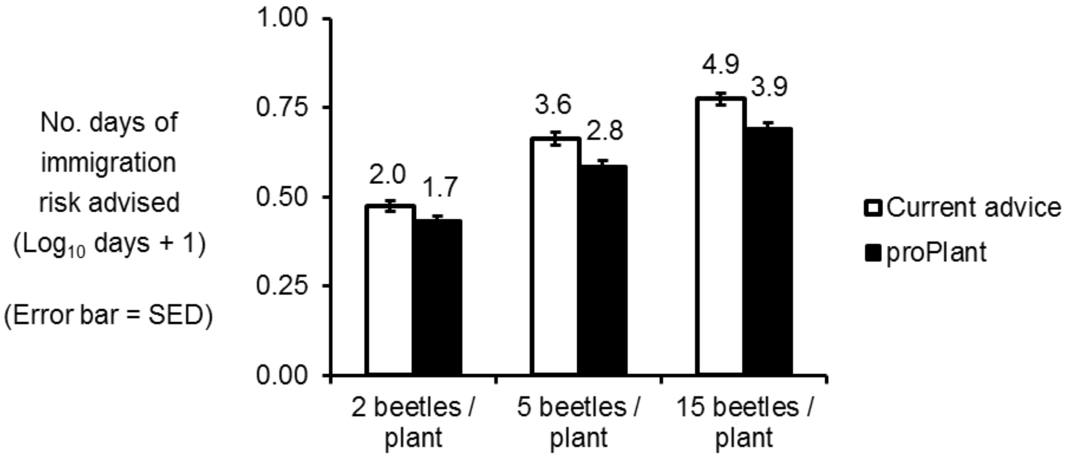
Number of breaches in threshold detected The performance of both current advice and proPlant in prompting monitoring that would lead to recognition of threshold breaches was very good. All threshold breaches at the 5 and 15 beetle thresholds would have been recognised using either DSS, as would almost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

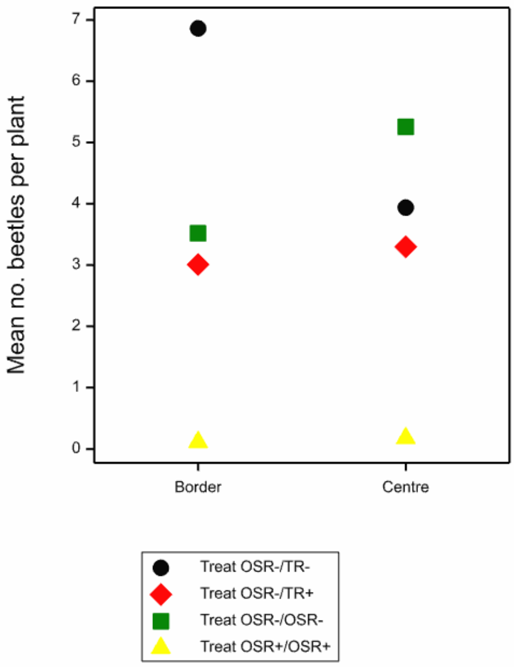
It must be noted for both scenarios that there were influential observations in the 2011 data and more data are required to improve the models before we can be confident enough to recommend these approaches for risk assessment to growers.

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

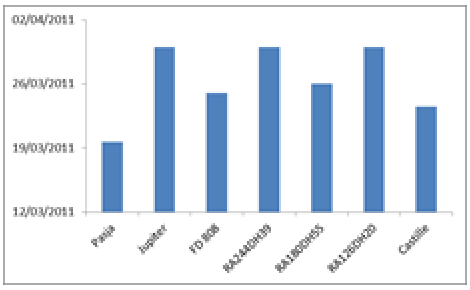
2.3.6. Initiate a programme to develop a practical and efficient trap cropping strategy for winter oilseed rape (Objective 3, Tasks F&G)

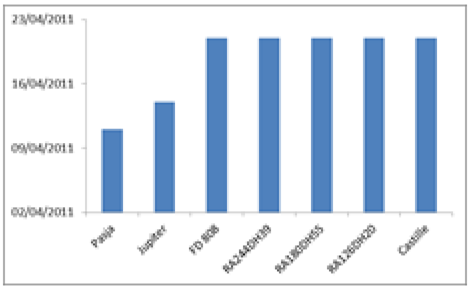
Field assessment of early flowering oilseed rape lines

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).

A. Average date plots reached Growth Stage 51

B. Average date plots reached Growth Stage 60





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.