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Re-evaluating thresholds for pollen beetle in oilseed rape

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Re-evaluating thresholds for pollen beetle in oilseed rape

by

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1. ABSTRACT

The aim of this project was to produce up-to-date thresholds for pollen beetle control by relating the potential for pest damage to the inherent tolerance of the crop to pest damage. The arrival of insecticide resistant pollen beetle in the UK makes it imperative that treatments are not applied unless really necessary to protect yield. The project hypothesises that oilseed rape crops produce significantly more flowers than required to produce the optimum pod number to maximise yield so there are excess flowers, which could be sacrificed to pollen beetle attack before yield is lost.

The research has resulted in a number of conclusions which have a significant impact on our understanding of the pest/host relationship between pollen beetle and oilseed rape:

- A single pollen beetle is capable of destroying an average of nine buds. This information was previously unknown and is pivotal in determining thresholds for the pest.
- Winter and spring rape crops produce a similar number of excess flowers suggesting no inherent difference in their tolerance to pollen beetle attack. This contradicts current understanding.
- There is no difference in the number of excess flowers between hybrid and conventional varieties contradicting the perceived wisdom that hybrid varieties are potentially more susceptible to pollen beetle damage
- Sparse crops have a greater tolerance to pollen beetle attack than more dense plantings. This result appears counter-intuitive but is supported by the fact that crops with fewer plants/m^2 had more excess flowers per plant
- Plant number and GAI (green area index) are potentially good indicators of excess flower number
- A dynamic threshold scheme is suggested in which the treatment threshold is no longer a single value for all crops. Instead it varies in relation to the number of excess flowers produced by different varieties in different seasons. This is an important change in the developmental approach to thresholds which has potential for application to other pest/crop interactions.

An experiment in which a range of beetle populations (0, 5, 10, 15, 20 and 50/plant) were confined on rape plants suggested that a single beetle on average is capable of destroying nine buds. Excess flower numbers (flower numbers minus pod numbers at harvest) were assessed in a range of hybrid and conventional spring and winter rape varieties sown at a range of seed rates (10 to 200 seeds/m^2). Spring oilseed rape crops produced a similar number of excess flowers to winter oilseed rape crops, which indicates that they are potentially equally tolerant of pollen beetle attack. This is a significant change from current advice that suggests that spring crops are inherently more susceptible to pollen beetles than winter crops. Hybrid, open pollinated and semi-dwarf varieties produced a similar number of excess flowers suggesting they are also potentially equally tolerant of pollen beetle attack, although there were significant differences between specific varieties e.g. Castille had relatively few excess flowers. Again this result contradicts the perceived wisdom which suggests that hybrid crops are more susceptible to pollen beetle because they are sown at lower seed rates than conventional varieties. Crops with fewer plants/m^2 had more excess flowers per plant than more dense crops, suggesting that thin or ‘backward’ crops may not be as susceptible to pollen beetle attack as initially thought. The project has demonstrated that it is possible to predict variation in the number of excess flowers per plant within a season from measurements of plants/m^2 or GAI (green area index) at green bud. Both parameters showed strong negative relationships with excess flowers per plant. However, there were large seasonal differences in excess flower number and further work is required to predict seasonal variation over a number of years. A conceptual pollen beetle threshold scheme has been proposed in which the pollen beetle control threshold is negatively related to plants/m^2. This implies that the threshold will change dependent upon the number of excess flowers which may be influenced by both variety and season. To move away from the concept of the threshold being a single value applicable to all cropping situations represents an important development in the evolution of pest control strategies.

Further work is required to validate the prediction scheme, particularly whether crops are less tolerant to losing buds from the main raceme compared with later formed buds.

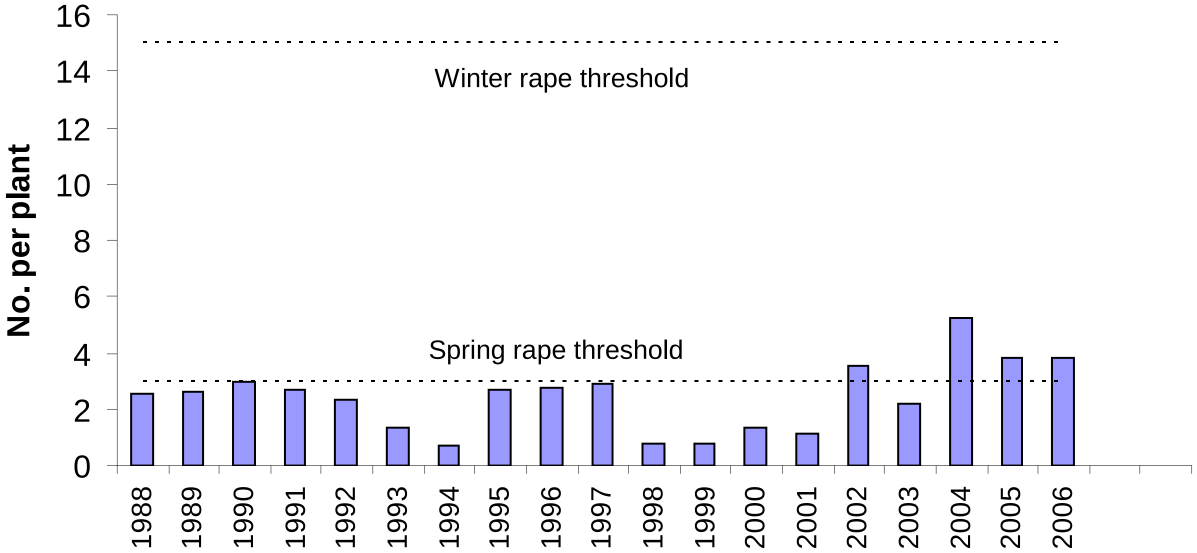
Only small differences were detected between pollen beetle numbers measured in the field margins compared with the field centre. There was a weak trend for more pollen beetles along the southern side of a field, but the effect was not consistent.

2. SUMMARY

2.1. Introduction

Problems with pyrethroid-resistant pollen beetles have developed rapidly in Europe where they have a significant impact on the yield of oilseed rape. For example, in 2006, Northern Germany experienced 100% crop loss in many fields (> 30,000 ha) and serious losses in a further 20,0000 ha (Slater *et al*, 2011). The first infestation of resistant pollen beetles in the UK was recorded in Kent in 2006. By 2007 resistance had spread as far as Dorset and North Yorkshire affecting most populations tested and, in 2010, resistant beetles were found right across Britain as far north as Scotland.

One way of restricting the spread of resistant pollen beetles in the UK would be to limit insecticide usage only to those crops where the threshold was exceeded. Current thresholds for pollen beetle in oilseed rape are 15 beetles per plant for winter rape, five beetles per plant for backward winter rape crops and three beetles per plant for spring rape. Data from the annual Fera oilseed rape pest and disease survey suggests that the majority of treatments against pollen beetle are applied to crops with pest numbers below the current UK thresholds (Summary Figure 1). Average pollen beetle counts per year rarely exceed 5 per plant and have never approached the current winter rape threshold of 15 beetles per plant. Although it is likely that a few crops exceeded threshold the mean values suggest that this was the exception rather than the norm.



Summary Figure 1. Mean number of pollen beetles per plant 1998-2006 in England and Wales (data courtesy of Fera)

Recent research has demonstrated that the optimum pod number for potential yield is 6,000 to 8,000 pods/m^2. The majority of crops produce significantly more flowers than the optimum pod number and therefore may be able to tolerate losing some to pollen beetle damage before yield is reduced. Current thresholds originated in the 1970s and provide no way of accounting for differences in tolerance to pest damage between current crop types. Farmers and agronomists have little confidence in current thresholds in relation to modern crops, particularly restored hybrids, which are alleged to be more susceptible to damage. If the levels of incidence of pollen beetle in the UK rarely cause economic damage and this is accepted by the industry, then the resulting reduced use of insecticides will restrict the spread of resistance.

The aim of this project is to produce up-to-date thresholds for pollen beetle control by relating the potential for pest damage to the inherent tolerance of the crop. The arrival of insecticide resistant pollen beetle in the UK makes it imperative that treatments are not applied unless really necessary to protect yield.

The specific objectives are given below:

1. To quantify flower bud loss resulting from pollen beetle attack.
2. To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety.
3. Use information from 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and the size of the crop.
4. Validate risk predictions by comparing actual yield losses with predicted yield losses.
5. Investigate pollen beetle distribution in the field as an aid to assessing pest numbers.

2.2. Materials and methods

2.2.1. Objective 1. To quantify bud loss resulting from pollen beetle attack

In both 2008 and 2009 pot experiments were done to quantify the bud loss in oilseed rape as a result of pollen beetle attack. The impact of a range of beetle populations (0, 1, 5, 10, 15, 20 and 50/plant) confined on rape plants at the green bud stage was assessed.

Pots were sown with spring oilseed rape seeds (cv Delight), maintained in a polythene tunnel and watered as necessary. There were three plants per pot in 2008 and one per pot in 2009. At the green bud stage each plant was inoculated with a number of beetles collected from a nearby crop of oilseed rape. There were 6 replicates of each population density in 2008 and 18 replicates in 2009. A perforated polythene bag was placed over the top of each plant to confine the beetles, and the open end gathered and secured around the stem base using a twist grip. Beetles were introduced to the bags in small open containers placed at the bottom of the bag. The bags were left in place until the plants had started to flower after which they were removed. The number of surviving beetles was recorded and these then released.

At full flower the number of buds, flowers, pods and blind stalks on each plant in each pot was assessed. Once the pods were fully formed (GS 6.1 or above) the number of pods on each plant in each pot was assessed, as were the number of blind stalks.

2.2.2. Objective 2. To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety

This objective was addressed by analysing existing datasets (LINK study OS49), carrying out measurements on existing variety experiments in 2007/08 and setting up specific experiments at High Mowthorpe and Rosemaund in 2008/09 and 2009/10. In the 2008 harvest year, differences in flower and pod number in the hybrid varieties Royal and PR45D01 (semi-dwarf), and open pollinated varieties Lioness, NK Bravour, Winner and Grizzly were investigated. The hybrid varieties were sown at 70 seeds/m^2 and the open pollinated varieties were grown at 100 seeds/m^2; these rates were the same as used in the HGCA Recommended List trials when the experiments were conducted.

In both 2009 and 2010, field experiments were established to compare the effect of seed rate and variety on the numbers of flowers, pods and excess flowers in both winter and spring sown oilseed rape. The winter rape experiments used three varieties: Castille (open pollinated), Excalibur (hybrid) and PR45D03 (semi dwarf hybrid) at five seed rates: (20, 40, 80, 120, 160 seeds/m^2 in 2009 and 10, 20 40, 80 and 160 seeds/m^2 in 2010). The spring rape experiments used two varieties - Heros (open pollinated) and Delight (hybrid) - at five seed rates (20, 40, 80, 120, 200 seeds/m^2 in both 2009 and 2010). The seed rates for both winter and spring crops were varied to simulate crops at variable stages of development. Low plant populations simulated backward/sparse crops and provided a test of whether these were less tolerant to pollen beetle damage than more dense or advanced crops. Spring plant establishment and canopy size were assessed as were the numbers of buds, flowers, blind stalks and pods at mid-flowering. At crop maturity pod number and seed yield were assessed.

2.2.3. Objective 3. Use information from 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and the size of the crop

Data generated in objectives 1 and 2 were used in a desk study to revise pollen beetle thresholds for both winter and spring crops.

2.2.4. Objective 4. Validate risk predictions by comparing actual yield losses with predicted yield losses

Field experiments to compare yield in pyrethroid treated and untreated strips

A total of five replicated treated and untreated plots were marked out in two crops each of winter and spring oilseed rape infested with pollen beetle. Pollen beetle numbers were assessed. A single spray of Hallmark (lamda-cyhalothrin) at 75ml/ha in 200 l water/ha was applied at late green/yellow bud (GS3,6 to GS3,7) (Sylvester-Bradley and Makepeace, 1984).

Pollen beetle numbers were assessed in each plot pre- and post spray and crop yield was recorded at the standard 91% dry matter.

Pruning experiments to simulate pollen beetle damage (2010 only)

In 2010 an additional experiment was done to determine the impact on yield if pollen beetle damage was confined to buds on the terminal raceme, compared with yield loss if buds were lost uniformly over all racemes. Three treatments were compared: removal of 100% of the buds on the terminal raceme, removal of 50% of the buds on the terminal raceme and no removal of buds. Pollen beetle damage was simulated by pruning off these buds with scissors at the late green bud to yellow bud stage (GS3, 6 to 3, 7). In winter rape buds were pruned in plots of all varieties sown at 20, 80 and 160 seeds/m^2 while in spring rape plots of all varieties sown at 20, 80 and 200 seeds/m^2 were pruned. Pod number and seed yield were assessed to determine the capacity of oilseed rape to compensate for damage to flower buds.

2.2.5. Objective 5. Investigate pollen beetle distribution in the field as an aid to assessing pest numbers

Pollen beetle numbers were assessed in total at 26 sites at green/yellow bud (GS 3.6/3.7) and at yellow bud (GS 3.9) in 2008 and 2009. At each visit, pollen beetle numbers were assessed along four transects (north, east, south and west) one from each edge of the field, assuming it to be approximately square. A total of 20 plants was assessed on each transect with one every 5 metres. Assessments were made by beating a plant over a white tray and counting the number of pollen beetles that were dislodged.

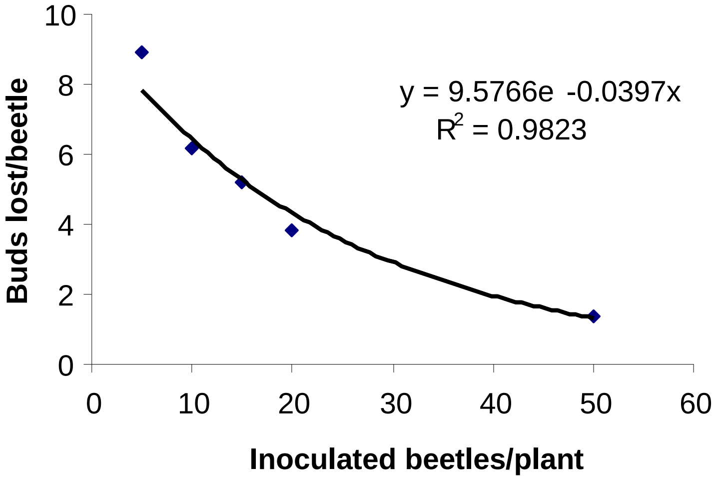
2.3. Results

2.3.1. Objective 1. To quantify bud loss resulting from pollen beetle attack

In 2008, increasing the number of beetles inoculated onto the plants increased the number of buds lost per plant up to 15 beetles per plant (Summary Table 1). In 2008 88% of pollen beetles survived being confined on plants until mid-flowering compared with 34% in 2009. This suggested that beetles were able to feed normally in 2008 whereas in 2009 the population appeared to be less fit. This was possibly because beetles were collected later in 2009 than in 2008. Therefore they were closer to the end of their life cycle in 2009 than in 2008. Nonetheless the number of buds destroyed by one beetle was similar in both experiments with 9.3 buds destroyed per beetle estimated in 2008 (Summary Figure 2) and 7.5 estimated in 2009. This indicates that most of the bud damage occurred soon after inoculation. It is assumed that one beetle may destroy nine buds for the purposes of threshold determination in order to minimise the chance of underestimating the chance of yield losses.

Summary Table 1. Mean numbers of buds, flowers, and pods per plant at mid-flowering and the number of buds lost per plant due to beetle damage compared with the un-inoculated treatment: 2008 only.

Number of inoculated beetles per plant	Mean plant parts per plant				Buds lost per plant	Buds lost/beetle
	Buds	Flowers	Pods	Total		
0	29.2	26.8	43.2	99.2	0	0
5	15.8	11.3	27.5	54.6	44.6	8.9
10	11.7	5.5	19.9	37.1	62.1	6.2
15	5.2	2.7	13.1	21.0	78.2	5.2
20	6.4	2.4	14.0	22.8	76.4	3.8
50	7.0	3.6	19.6	30.2	69.0	1.4



Summary Figure 2. Relationship between number of inoculated pollen beetles/plant and buds lost/beetle in 2008 experiment

2.3.2. Objective 2. To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety

The hypothesis underpinning this objective was that oilseed rape produces more buds and flowers (excess flowers) than are required to achieve optimum pod number for maximum yield. Therefore, data were analysed to test this hypothesis and also to quantify the potential impact of a range of variables on excess flower number. Analysis of existing data sets from LINK project OS49 “Canopy management in oilseed rape” showed that in 1996 and 1997 neither early (last week August to first week September) nor late sowing (last week September) nor seed rates of 60 or 120 seeds/m^2 had any significant effect on excess flower number. Also excess flower number did not differ significantly between three rates of N fertiliser application (0, 100 and 200 kg N/ha). Across these experiments the number of excess flowers ranged from 2,200/m^2 to over 10,000/m^2, with an average of more than 7,000/m^2, relating to between 100 and 200 excess flowers per plant.

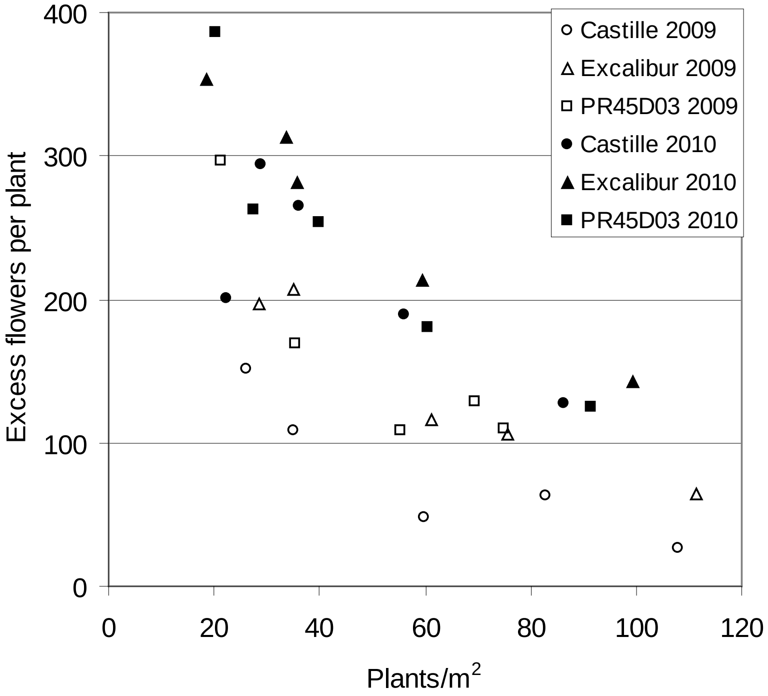
Comparison of excess flower numbers between varieties in 2007/08 showed there was no consistent trend for hybrid, semi-dwarf or late developing varieties to produce significantly less excess flowers than open pollinated varieties. Any differences in excess flower number were due to the specific variety and not variety type (i.e. hybrid vs open pollinated). The average number of excess flowers in these trials averaged just over 4000/m^2, relating to between 60 and 80 excess flowers per plant.

In 2008/09, excess flower number in winter oilseed rape differed significantly between variety with Castille averaging 3747/m^2, Excalibur 7019/m^2 and PR45D03 7107/m^2. Increasing seed rate from 20 seeds/m^2 (25 plants/m^2) to 160 seeds/m^2 (98 plants/m^2) had no effect on the number of excess flowers for any variety. The higher number of plants than expected produced at the low seed rate was due to the presence of volunteer oilseed rape plants from previous oilseed rape crops. In 2009/10, excess flower number did not vary significantly between varieties, although Castille tended to be lower than Excalibur with an average of 8816 /m^{2}compared with 10760/m^2 respectively. Increasing seed rate from 10 seeds/m^2 (20 plants/m^2) to 160 seeds/m^2 (92 plants/m^2) significantly increased excess flowers from 6274/m^2 to 12131/m^2 respectively.

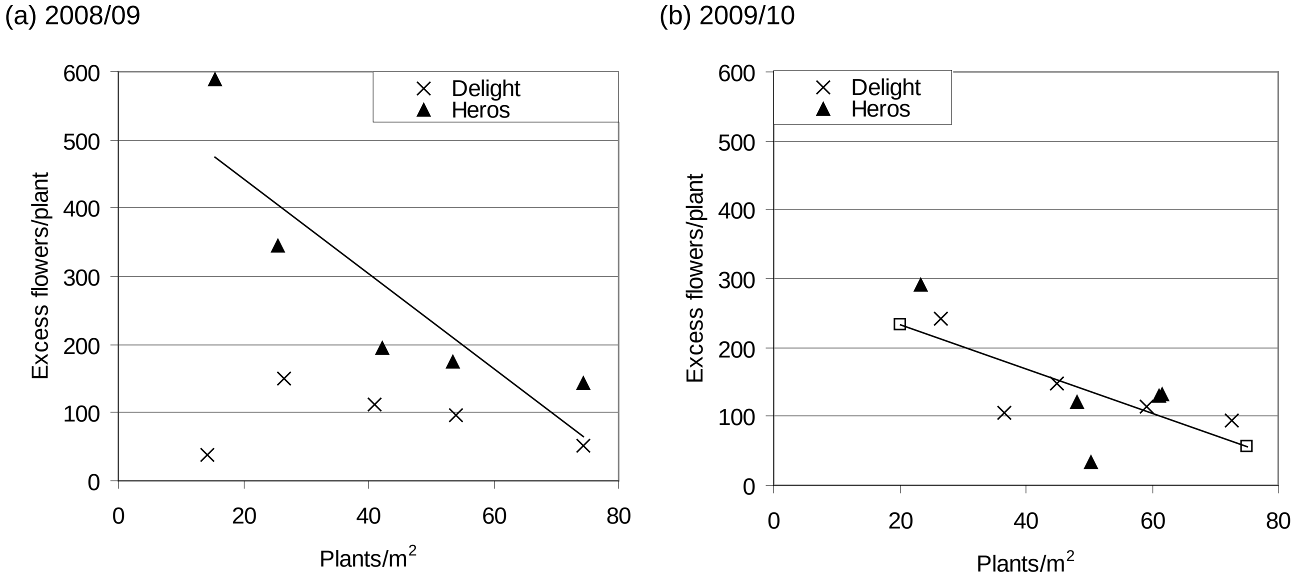
In the spring oilseed rape experiment of 2008/09, Delight produced 8,627 flowers/m^2 which was significantly less than Heros at 12,953/m^2. Seed rate did not significantly affect the number of flowers, although increasing seed rate from 20 seeds/m^2 (15 plants/m^2) to 200 seeds/m^2 (74 plants/m^2) increased the number of flowers from 9,569 flowers/m^2 to 12,088 flowers/m^2. In 2009/10, the seed rate treatment at 40 seeds/m^2 had significantly fewer excess flowers (2753/m^2) than the other seed rates (6233 to 7454/m^2), including 20 seeds/m^2. However, there was no apparent trend in excess flowers/m^2 between seed rates of 20 seeds/m^2 (25 plants/m^2) and

200 seeds/m^2 (67 plants/m^2). There was also no difference in excess flower number between Delight and Heros with both averaging just over 6,000/m^2.

In both the winter and spring oilseed rape experiments there were strong negative relationships between excess flowers per plant and plants/m^2 (Summary Figures 3 and 4). There were also strong negative relationships between excess flowers with GAI measured at green bud for the winter oilseed rape experiments with a weaker association in the spring oilseed rape experiments. This indicates that plants in low plant population crops may actually tolerate greater numbers of pollen beetles per plant than plants in high plant population crops. On average in the winter oilseed rape crops each additional plant/m^2 reduced the number of excess flowers per plant by 2.20. However, there were varietal differences in the number of excess flowers per plant which were consistent between the two seasons. For any given plant population, Castille produced 53-58 fewer excess flowers per plant than Excalibur and 31-49 fewer excess flowers compared with PR45D03. The average number of excess flowers per plant in 2009 was 127 compared with 239 in 2010. It therefore appears that seasonal variation in excess flowers per plant may be as large, or larger, than varietal differences in excess flower number. It was also shown that the spring crops produced a similar number of excess flowers per plant as the winter crops.



Summary Figure 3. Relationship between plants/m^2 measured in spring and the number of excess flowers (flower number minus final pod number) per plant for Castille 2009 (y=-2.20x + 217), Excalibur 2009 (y= -2.20x + 275), PR45D03 2009 (y=-2.20x + 266), Castille 2010 (y=-2.20x + 316), Excalibur 2010 (y= -2.20x + 369), PR45D03 2010 (y=-2.20x + 347). Fitting parallel best-fit lines using multiple regression analysis accounted for 84% of the variation.



Summary Figure 4. Relationship between plants/m^2 measured in spring and the number of excess flowers (flower number minus final pod number) per plant for a) 2008/09; Heros (y=-6.93x + 581; R^2 = 0.76), Delight (no significant relationship), b) 2009/10; both varieties (y=-3.21x + 297; R^2 = 0.49).

2.3.3. Objective 3. Use information from objectives 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and size of crop

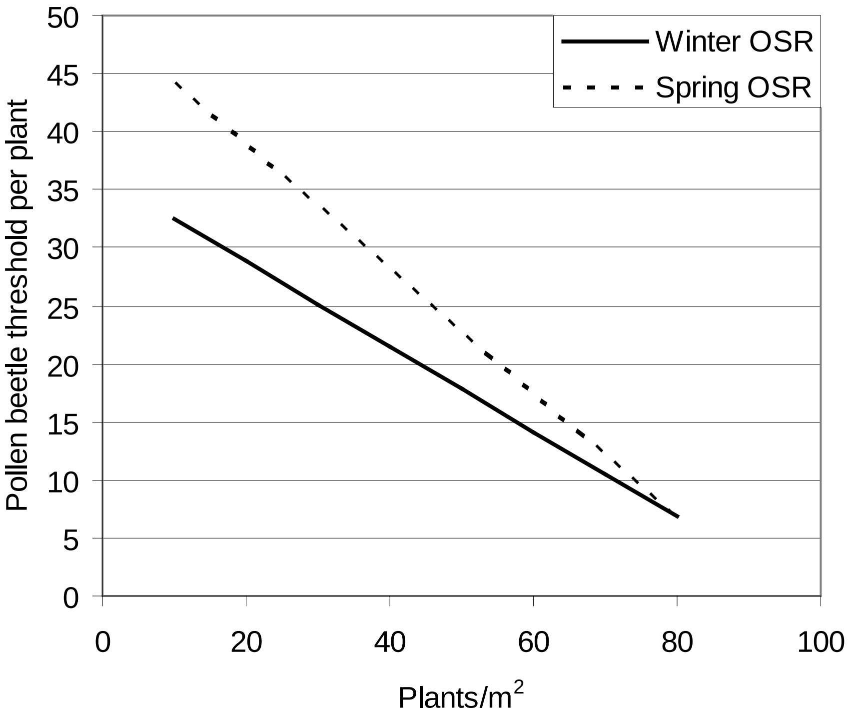
The following conclusions may be drawn from objectives 1 and 2;

1. An individual pollen beetle may damage an average of nine buds.
2. Oilseed rape crops produce significantly more flowers than pods and that there is therefore an excess number of flowers relative the final pod number. It is therefore hypothesised that plants could lose these excess flowers to pollen beetle attack without losing yield.
3. Spring oilseed rape crops produced a similar number of excess flowers to winter oilseed rape crops
4. Crops with fewer plants/m^2 had more excess flowers per plant.
5. There was no evidence that hybrid varieties had fewer excess flowers per plant than conventional open pollinated varieties.
6. The hybrid semi-dwarf had a similar number of excess flowers to standard height hybrid Excalibur.
7. There were large seasonal differences in the number of excess flower numbers which were as large, or larger, than the variety differences.
8. There is potential to predict the number of excess flowers per plant from measurements of plants/m^2 or GAI at green bud. There were no consistent varietal differences for excess flowers per plant and seasonal differences were large.

If it is assumed that oilseed rape can tolerate the loss of all excess flowers per plant and the number of buds likely to be damaged by an individual pollen beetle is nine then the threshold number of beetles per plant that would be required to destroy all the excess flowers can be calculated. These calculations show that the threshold number varies significantly (3-43 beetles/plant for winter rape, mean 20, 4-66 beetles/plant for spring rape, mean 18) depending on plant population, but that variety and season also have strong effects. Therefore there will be a significant proportion of crops which can tolerate a greater number of beetles than the current threshold of 15 per plant. In particular, crops with low plant populations of 25 plants/m^2 or less, which some growers/agronomists may define as backward, despite their high yield potential, should certainly have a threshold of more than five beetles per plant and probably should have a threshold equal to or greater than crops with higher plant populations. For spring oilseed rape the average threshold across all treatments was 18 beetles per plant, with none below the current threshold of three beetles per plant. It therefore appears that this threshold should be increased.

There is a strong relationship between the number of plants/m^2 and the threshold for treatment; crops with fewer plants are able to tolerate more beetles. This may seem counter-intuitive, but plants from low plant population crops have more excess flowers than plants from high plant population crops. Any pollen beetle threshold should therefore take account of plant population. Variety has an effect on the number of excess flowers as does season. Variety trials could be used to indicate variation between varieties in tolerance. On the basis of two seasons of research it was not possible to predict seasonal variation in tolerance at the time when pollen beetle control takes place. In the absence of prior knowledge about varietal tolerance and a reliable scheme for predicting seasonal variation it is proposed that a pollen beetle threshold scheme could be based on the variety and season with the fewest excess flowers, in order to minimise the risk of failing to identify crops for which it would be cost effective to control pollen beetles.

For winter oilseed rape the threshold is based on Castille in 2009. For spring oilseed rape it is based on Delight and Heros in 2010, and Delight in 2009 as these crops had similarly low tolerance to pollen beetle (Summary Figure 5)



Summary Figure 5. Suggested pollen beetle threshold estimates based on the variety and season with the fewest excess flowers per plant. Winter oilseed rape: Castille in 2010. Spring oilseed rape: Heros and Delight

2.3.4. Objective 5. Investigate pollen beetle distribution in the field as an aid to assessing pest numbers

A total of 28 sites at a range of locations in England and Wales, were assessed over the life of the study to investigate the distribution of pollen beetles in the field.

There was little difference in the numbers of beetles recovered either at 0-25, 26-50, 51-75 and 76-100 m from the edge of the field at both green and yellow bud. In a second series of analyses undertaken on beetle numbers 0-50 m and 51-100 m from the edge of the field, there were more beetles from 0-50 m than from 51-100 m in 35 of 51 assessments although differences between the counts were often small. At green bud there was an average of 3.03 beetles per plant in the 0 to 50 m region compared with 2.38 in the 51 to 100 m region. At yellow bud there was an average of 2.52 beetles per plant in the 0 to 50 m region compared with 2.22 in the 51 to 100 m region. These differences were statistically significant (paired two-tailed ‘T-test’).

Beetle numbers differed significantly between compass points at eight sites at green bud and seven sites at yellow bud. However, there was no consistent trend to find most beetles at a particular compass point. Over all sites a paired two-tailed ‘T test’ showed that significantly more beetles were found on the southern compared to the northern or eastern transects ($P<0.05$).

Summary Table 2. Mean numbers of pollen beetles recovered at north, east, south and west transects at both green and yellow bud

Site	North	East	South	West	Probability
Green bud	2.5	1.9	3.4	3.2	P<0.05*
Yellow bud	2.4	2.0	2.5	2.2	NS

In summary, assessments made closer to the headland were shown generally to recover higher numbers of pollen beetle than those further from the headland. At green bud there was a trend to find most beetles on the southern transect but not at yellow bud.

2.4. Conclusions

- A pollen beetle threshold scheme has been proposed based on an understanding of the number of buds that pollen beetles may damage and the number of buds that crops may lose without losing yield. In the proposed scheme the pollen beetle threshold is negatively related to plants/m^2. It is proposed that winter or spring crops with 20 plants/m^2 have a threshold of at least 29 beetles per plant and crops with more than 80 plants/m^2 have a threshold of less than 7 beetles per plant. Therefore the threshold is no longer a single value applicable to all crops. It varies in relation to the number of excess flowers produced by different varieties in different seasons. This is an important change in the development of thresholds which has potential for use in other pest/crop interactions. Further work is required to validate the prediction scheme, particularly whether crops are less tolerant to losing buds from the main raceme compared with later formed buds.
- An individual pollen beetle may damage an average of nine buds. This information was previously unknown and is pivotal in determining thresholds for the pest.
- Oilseed rape yields are maximised by achieving an optimum number of pods/m^2.
- Oilseed rape crops produce significantly more flowers than the optimum pod number so there is an excess number of flowers which could be sacrificed to pollen beetle attack before yield is lost.
- Spring oilseed rape crops produce a similar number of excess flowers to winter oilseed rape crops, which indicates that they are equally tolerant to pollen beetle attack. This is a significant change from current advice that suggests spring crops are inherently more susceptible to pollen beetles than winter crops.
- Hybrid, open pollinated and semi-dwarf varieties produce a similar number of excess flowers. This finding contradicts the perceived wisdom that hybrid varieties are potentially most susceptible to pollen beetle damage. However, there were significant differences between specific varieties for excess flower number, e.g. Castille had less than Excalibur.

- Crops with fewer plants/m^2 had more excess flowers per plant. Previous work indicates that sowing crops in late September or applying sub-optimal amounts of N does not affect the number of excess flowers. This suggests that small or ‘backward’ crops may not be as susceptible to pollen beetle attack as initially thought. This appears counter-intuitive but is supported by the fact that sparse crops have a greater ability for compensatory branching than those that are more densely planted. Further work is required to understand how pigeon grazing affects tolerance to pollen beetles.
- There were large seasonal differences in the number of excess flower numbers which were as large, or larger, than the variety differences. No way was found to predict these seasonal differences.
- There is potential to predict the number of excess flowers per plant from measurements of plants/m^2 or GAI at green bud. Both showed strong negative relationships with excess flowers per plant, although GAI was a less useful predictor for spring oilseed rape.
- Only small differences were detected between pollen beetle numbers measured in the field margins compared with the field centre, with less than one beetle per plant more (27% more) in the outer 50 m of the field.
- There was a weak trend for more pollen beetles along the southern side of a field, but the effect was not consistent.

3. TECHNICAL DETAIL

3.1. Introduction

Problems with insecticide-resistant pollen beetles have developed rapidly in Europe where they have a significant impact on the yield of oilseed rape. For example, in 2006, Northern Germany experienced 100% crop loss in many fields (> 30,000 ha) and serious losses in a further 20,0000 ha (Slater *et al*, 2011). The first infestation of resistant pollen beetles in the UK was recorded in Kent in 2006, by 2007 resistance had spread as far as Dorset and North Yorkshire affecting most populations tested and in 2010 resistant beetles were found right across Britain as far north as Scotland. Potentially these pests, if present in sufficient numbers, could have a serious effect on the yield of the UK oilseed rape crop. Pollen beetle treatments are usually applied when the beetles first arrive in the crop, insecticide treatment at this time could leave only resistant male and female beetles to mate, potentially increasing the level of resistance in the population. Where insecticide resistance develops there can be an increase in crop damage as the pests survive, but their natural enemies are killed.

One way of restricting the spread of resistant pollen beetles in the UK would be to limit insecticide usage only to those crops where the threshold was exceeded. The area of oilseed rape sprayed with pyrethroids is summarised in Figure 1. The pyrethroid treated area has increased steadily between 1998 and 2008 with 183% of the crop area treated in 2008 compared with 134% in 1998. In 2010 the treated area decreased slightly with 156% of the crop area sprayed. Not all these applications will have been against pollen beetles but 36%, 20%, 16% and 34% were targeted against these pests in 2004, 2006, 2008 and 2010 respectively. All of these figures are likely to be well above the proportion of crops that exceeded threshold in each of these years.

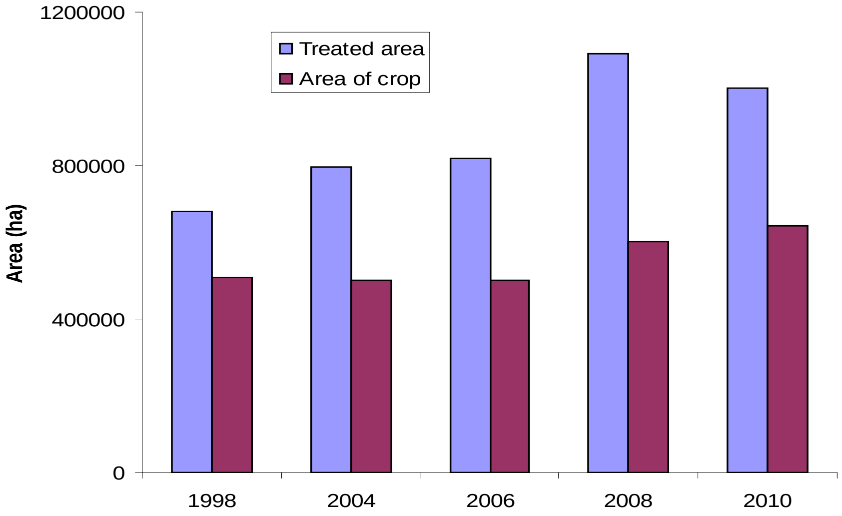


Figure 1. UK area (ha) of oilseed rape 1998-2008 and the area of crop treated with pyrethroid insecticides (Source: Fera Pesticide Usage Survey)

Current thresholds for pollen beetle in oilseed rape are 15 beetles per plant for winter rape, five beetles per plant for backward winter rape crops and three beetles per plant for spring rape (Anon, 2003). It has also been suggested that hybrids are more susceptible than conventional varieties because they are sown at a lower seed rate. These thresholds apply when the crop is at the susceptible green/yellow bud stage. Once in flower crops are no longer at risk as beetles will seek out the open flowers (Sam Cook, personal communication) in preference to the buds. It is unclear where the current thresholds originated and there is no published literature detailing their derivation. However, it is likely that the reason for the large difference in threshold between winter and spring crops is due to the coincidence between beetle migration and the susceptible stage of the crop. In winter crops the susceptible stage is often past before beetles migrate into the crop. In contrast, in spring crops there is a much greater chance of beetles being present at the susceptible stage. Spring crops may also be perceived as having less tolerance to pollen beetle damage than winter crops. Data from the Fera oilseed rape pest and disease survey suggests that the majority of treatments against pollen beetle are applied to crops with pest numbers below the current UK thresholds (Figure 2). Average pollen beetle counts per year rarely exceed five per plant and have never approached the current winter rape threshold of 15 beetles per plant. These are mean counts so it is possible that some crops have had threshold counts. However, as the mean counts are so low it is very unlikely that a significant number of sites would have been above threshold.

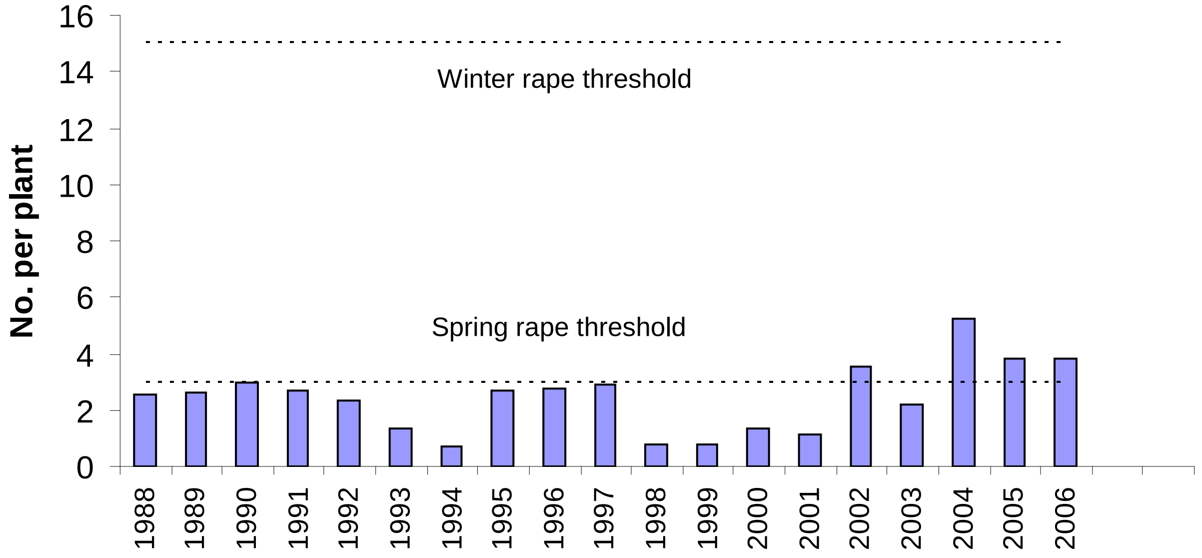


Figure 2. Mean number of pollen beetles per plant 1998-2006 in England and Wales (data courtesy of Fera)

Current thresholds originated in the 1970's and provide no way of accounting for differences in tolerance to pest damage between current crop types (Tatchell, 1983; Williams *et al.* 1979). Farmers and agronomists have little confidence in current thresholds in relation to modern crops, particularly restored hybrids, which are alleged to be more susceptible to damage. The HGCA 'Insect Pests on Oilseed Rape' review (OS1, 1991; Alford *et al*, 1991) highlighted the problem of treatment thresholds for pollen beetle and suggested that the first high priority research need for inflorescence pests should be 'To assess pollen beetle damage and to establish reliable threshold levels on new cultivars of oilseed rape'. In addition, the recent *Ad hoc* EPPO workshop on insecticide resistance of *Melegethes* spp (pollen beetles) on oilseed rape (Berlin, 3-5 September, 2007) highlighted the need for fresh work on thresholds and the need for practical thresholds that take account of varieties. If the levels of incidence of pollen beetle in the UK rarely cause economic damage and this is accepted by the industry, then the resulting lower use of insecticides will restrict the spread of resistance.

This project investigates whether new thresholds can be developed by understanding and taking account of the inherent tolerance of rape to pest attack.

Thresholds for pollen beetle in OSR vary throughout Europe (Richardson, 2007). In spring rape they range from 0.5 – 5/plant. In winter rape they are expressed as numbers per terminal raceme (range 0.8-3/terminal raceme) or more commonly numbers per plant (range 1-15/plant). Austria is unique in having two thresholds; one for the edge of the field (4-5 beetles/main shoot) and one for the middle (1-3 beetles/plant), indicating that pest numbers will vary depending upon where in the field they are assessed. In general, an understanding of the distribution of pollen beetles in the field is important for determining how to assess pest numbers and whether the threshold has been exceeded. Some farmers and/or agronomists may only assess the edge of the field when deciding on the need to treat and this could result in unnecessary spray application. The project will also investigate pest distribution within field to help formulate thresholds.

Most rape crops have a degree of tolerance to pest attack because they produce more flowers than are required to achieve the optimum pod number for maximum yield. For example, crops sown in late August/early September can produce more than 20,000 flowers/m^2. Only about 10,000 of these form fertile pods. Even crops sown as late as October can produce 10,000 flowers/m^2. This is significantly more than the optimum 6,000-8,000 pods/m^2 required to achieve maximum yields (Berry and Spink, 2006; HGCA Report OS49). It is therefore possible that many treatments against pollen beetle are applied unnecessarily, and will potentially reduce populations of non-target beneficial species and increase the risk of development of insecticide resistance. For example, pollen beetle larvae are attacked by three species of parasitoid wasps (Anon, 2010). Generally, 25-50% of larvae are killed by parasitoids in unsprayed crops in the UK. These parasitoids may not be affected by sprays applied against pollen beetle at green/yellow bud as they arrive in crops during flowering. However, they are vulnerable to sprays applied against seed weevil and pod midge so these treatments should only be used when absolutely necessary.

At present 45% of recommended list varieties and 40% of candidate varieties are restored hybrids. These are usually sown at 50 to 70% of the seed rate of conventional open pollinated varieties due to a combination of greater seed costs and the perception that they are better able to compensate for low plant populations. This means a lower plant stand and a perception of a reduced capacity to tolerate pest damage. Canopy management guidelines for oilseed rape advocate the production of optimum sized canopies with a green area index (m^2 of green tissue per m^2 of ground) at flowering of 3.5. Canopy managed crops often have smaller canopies than commonly achieved. This also increases the perceived threat from pollen beetle. The tolerance of new semi-dwarf varieties to pollen beetle is unknown.

It has been observed that crops with larger canopies in late winter/ early spring produce more flowers and pods/m^2 than crops with small canopies (Berry and Spink, 2006; HGCA Report OS49). This means that early canopy size could be a useful indicator of a crop's tolerance of pest attack. Early canopy size is also easy to assess quickly using visual aids or simple crop assessments. However, it is possible that the relationship between early canopy size and tolerance to pollen beetle attack will vary for different varietal types (conventional, hybrid and semi-dwarf).

The aim of this project is to produce up-to-date thresholds for pollen beetle control by relating the potential for pest damage to the inherent tolerance of the crop. The arrival of insecticide resistant pollen beetle in the UK makes it imperative that treatments are not applied unless really necessary to protect yield.

The specific objectives are given below:

1. To quantify flower bud loss resulting from pollen beetle attack.
2. To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety.
3. Use information from 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and the size of the crop.
4. Validate risk predictions by comparing actual yield losses with predicted yield losses.
5. Investigate pollen beetle distribution in the field as an aid to assessing pest numbers.

3.2. Materials and methods

3.2.1. Objective 1. To quantify bud loss resulting from pollen beetle attack

In both 2008 and 2009 a pot experiment was done to quantify the bud loss in oilseed rape as a result of pollen beetle attack. The impact of a range of beetle populations confined on rape plants at the green bud stage was assessed.

In spring 2008, 72, 25cm diameter pots were filled with multipurpose compost, and in spring 2009, 252, 25 cm diameter pots were filled. In both years half of these pots were sown with spring oilseed rape seeds (cv Delight) and the process repeated with the remaining pots two weeks later. The two sowing dates were used to increase the chances of having plants at the susceptible growth stage when pollen beetles were present in the field and could be collected for inoculation purposes. Pots were maintained in a polythene tunnel and watered as necessary. Once the plants were well established each pot was thinned to give three evenly-spaced plants per pot in 2008, but only one plant per pot in 2009. In total there were 126 plants in each year, but in 2008 these were distributed between 36 pots (three plants per pot) and in 2009 each plant had its own pot. This was done to facilitate better plant growth and to make it easy to differentiate between individual plants.

When plants were approaching the green bud stage approximately 2000 pollen beetles were collected from a nearby crop of oilseed rape. This was done by shaking infested rape heads over a plastic bag. A few rape heads were added as a food source and the bag sealed to prevent the beetles from escaping. The beetles were added to individual pots to achieve the populations per plant as shown in Table 1.

Table 1. Number of pollen beetles confined on oilseed rape plants grown in pots.

Treatment number	Number of pollen beetles per plant	
	2008	2009
1	0	0
2	5	1
3	10	5
4	15	10
5	20	15
6	50	20
7	N/A	50

A pooter was used to prepare inocula to minimise damage to the beetles. A single sheet of tissue paper and a few rape flowers were placed in each tube (3cm diameter x 7cm deep). The tissue paper absorbed any excess moisture and the flowers provided a food source. The beetles were not kept in the tubes for any longer than 24 hours. There were six replicates of each population density in 2008 and eighteen replicate plants of each level of beetle inoculation in 2009.

At the green bud stage each plant was inoculated with a known number of beetles. A perforated polythene bag (33 cm wide x 83 cm deep) was placed over the top of each plant and the open end gathered and secured around the stem base using a twist grip. The top was then removed from a tube of beetles and the open tube placed inside the gathered end of the bag after loosening the twist grip. The open end of the bag was then re-secured to the stem so that the tube of beetles was trapped inside and none could escape. The bags were left in place until the plants had started to flower after which they were removed. At this stage it was assumed that open flowers were more attractive to beetles than buds so further damage to the latter was unlikely. The number of beetles surviving on each inoculated plant was also assessed to give an indication of beetle viability. The surviving beetles were then released

Assessments

At full flower the number of buds, flowers, pods and blind stalks on each on each plant in each pot was assessed. Once the pods were fully formed (GS 6.1 or above) the number of pods on each plant in each pot was assessed, as were the number of blind stalks.

Statistical analysis

The number of damaged buds and blind stalks was calculated for each pot. Using these data it was possible to calculate the numbers of pods lost per beetle and this was plotted against number of inoculated beetles. Using this relationship the number of pods that could be damaged by a single beetle was calculated.

3.2.2. Objective 2. To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety

This objective was investigated by analysing existing datasets, carrying out measurements on existing variety experiments in 2007/08 and setting up specific experiments in 2008/09 and 2009/10. In the 2008 harvest year, two existing variety trials which had been set up for LINK project LK0979 (Berry *et al*., 2011) were assessed to investigate variety differences in flower and pod number. The experiments were grown near ADAS High Mowthorpe and ADAS Rosemaund and included cvs Royal (Hybrid), PR45D01 (Hybrid semi-dwarf), Lioness (open pollinated), NK Bravour (open pollinated), Winner (open pollinated) and Grizzly (open pollinated).Grizzly is a particularly late developing variety and was chosen in order to test whether lateness of maturity affected flower and pod production. The hybrid varieties were sown at 70 seeds/m^2 and the open pollinated varieties were sown at 100 seeds/m^{2}consistent with seed rates used in Recommended

List trials when the experiments were conducted. These experiments received fertiliser rates recommended by the RB209 fertiliser manual (Anon., 2011) and disease and pests were minimised by using a pesticide programme. At High Mowthorpe the insecticide treatments were two sprays of cypermethrin at 0.25 l/ha on 8 October 2010 and 14 November 2011 and a single spray of Mavrik at 0.2 l/ha omn 19 May 2008. The fungicide treatments were a single spray of Prosaro at 0.37 l/ha on 14 November 2007 and a tank mix of Amistar and Prosaro both at 0.5 l/ha on 19 May 2008. At Rosemaund.

In both 2009 and 2010, field experiments were established to compare the effect of seed rate and variety on the numbers of flowers, pods and excess flowers in both winter and spring sown oilseed rape.

There were two sites in 2009 and 2010, with the winter rape sown near to ADAS High Mowthorpe and spring rape near to ADAS Rosemaund. The same varieties were used in each year but the seed rates for the winter rape experiment were modified in 2010 to include a lower minimum seed rate of 10 seeds/m^2 to ensure that at least one treatment had a sub-optimal plant population. The winter rape experiments used three varieties - Castille (open pollinated), Excalibur (hybrid) PR45D03 (semi dwarf hybrid) - and five seed rates (20, 40, 80, 120, 160 seeds/m^2 in 2009 and 10, 20 40, 80 and 160 seeds/m^2 in 2010). The spring rape experiments used two varieties - Heros (open pollinated), Delight (hybrid) - and five seed rates (20, 40, 80, 120, 200 seeds/m^2) in both 2009 and 2010.

For the winter oilseed rape experiments, a split plot design was used, with variety as the main plot and seed rate as the sub-plot; each treatment was replicated four times. For the spring oilseed rape experiments, all treatments were arranged in a fully randomised block design and replicated four times. The main plot size in all experiments was 3.5m x 24m.

Assessments

Crop growth stage

Crop growth stage was determined at each assessment using the growth stage guide described in Sylvester-Bradley and Makepeace (1984).

Spring plant establishment and canopy size (2009 and 2010 experiments only)

Before the start of stem extension the number of plants in five 0.5m x 0.5m quadrats per plot was counted. An overhead photo of a typical area of each plot was taken. Each photo covered an area of approximately 1m x 1m. This photo was uploaded onto a web tool at www.totaloilseedcare.co.uk to estimate the green area index. In replicate 2, the photographed area was sampled by cutting the plants from a 1m x 1m patch of crop at ground level. The same number of rows was included in each quadrat. The whole sample was then weighed. An approximate 25% representative sub-sample was taken, any dead leaves removed and the green area index of the leaves and stems in the sub-sample measured using a moving belt leaf area meter (Li-Cor Model 3100, Delta-T Devices, Burwell, Cambridge, UK). The destructive measurement of green area index was used to provide a check of the non-destructive estimate of green area index provided by the web tool, and a close correlation between the two estimates was confirmed.

Mid-flowering – Number of buds, flowers, blind stalks and pods (all experiments)

At around the middle of flowering, a 1m^2 sample of crop was taken from all plots. Four 1 m long rods were placed along the ground within the plot to define the area and the 1m x 1m square was positioned diagonally to the direction of drilling with a row running through opposite corners of the quadrat to ensure quadrats did not include different numbers of rows. The stems within the quadrat were cut at ground level and all flowers, pods and branches belonging to each plant were removed even if the foliage overhung the 1m x 1m area. The fresh weight of the whole sample was recorded. A 20-25% sub-sample of plants by weight was taken and the fresh weight recorded. The plants were kept whole during this process. In the sub-sample, the number of pods, flowers, blind stalks and flower buds were counted

Crop maturity – Determination of pod number and seed yield

Approximately three weeks before harvest another 1m^2 sample of crop was taken and analysed as described in the mid-flower assessment. The number of pods in the sub-sample was counted. The seed yield of all plots was measured using a small plot combine (Sampo 2025, with 2.34m cut width) and corrected to 91% dry matter. This was used to determine the yield effect of both variety and seed rate treatments.

3.2.3. Objective 3. Use information from 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and the size of the crop

This objective was a desk study and used data generated in objectives 1 and 2 to develop pollen beetle thresholds for both winter and spring crops.

3.2.4. Objective 4. Validate risk predictions by comparing actual yield losses with predicted yield losses.

Field experiments to compare yield in pyrethroid treated and untreated strips

In 2009 and 2010 experiments were planned to validate the pollen beetle thresholds derived in pot experiments in replicated treated and untreated plots in the field.

A total of four sites infested with pollen beetles were selected and pest numbers assessed. This was done by beating 25 plants selected randomly down a wheeling over a white tray (Xcm x Ycm) and counting the number of beetles dislodged. A mean count of beetles/plant was then calculated. These were managed from ADAS Boxworth, High Mowthorpe, Rosemaund and Terrington. There were two winter rape sites (Boxworth and Terrington) and two spring rape sites (High Mowthorpe and Rosemaund). If possible sites were selected where pest numbers were approaching the threshold of 15 beetles/plant in winter rape and 3 beetles/plant in spring rape, although such populations in winter rape are very rare.

Five replicate treated and untreated plots were marked out. This was done by creating two strips of crop each of about 12m x 60m which was sub-divided into five plots each of 12 x 12m. Where possible one of each pair of plots was randomly selected to be insecticide treated and the other untreated. If this was impractical the insecticide treatment was randomly allocated to one of the strips of five plots with the other strip remaining untreated. This created five replicate plots of both treatments. The preferred treatment was a spray of Hallmark (lambda-cyhalothrin) at 75ml/ha in 200 l water/ha. Where the spray was applied by the host farmer any approved pyrethroid insecticide was acceptable. Sprays were repeated if necessary to keep the treated plots clear of pollen beetle throughout the susceptible green/yellow bud period. In practice only one spray was required at each site. Where the host farmer sprayed the farm crop the spray boom was shut off over the untreated area to create the untreated plots.

Assessments

Pollen beetle numbers were assessed in each plot pre and 24 hours post spray application by beating 20 plants per plot over a white tray.

Crop yield at 91% dry matter was assessed in each of the five treated and untreated plots at each site using a small plot combine (Sampo 2025, with 2.34m cut width).

Statistical analysis

Yield data was subjected to analysis of variance.

Pruning experiments to simulate pollen beetle damage (2010 only)

In 2010 an additional experiment was superimposed on the seed rate and variety study to investigate if crops are able to compensate for loss of buds specifically from the terminal raceme. In other words, if pollen beetle damage were confined to buds on the terminal raceme, would the impact on yield be greater than if buds were lost uniformly over all racemes. In particular, the impact on flower number, pod number and yield of removing different proportions of buds from the terminal raceme was studied. Treatment 1 removed 100% of the buds on the terminal raceme and Treatment 2 removed 50% of the buds on the terminal raceme. Severe pollen beetle damage was simulated by pruning off these buds with scissors at the late green bud to yellow bud stage (GS3.6 to 3.7).

Bud pruning was done between late green bud (GS3.6) and yellow bud (GS3.7). At the winter rape site all varieties of plots sown at 20, 80 and 160 seeds/m^2 were pruned. At the spring rape site all varieties of plots sown at 20, 80 and 200 seeds/m^2 were pruned.

At the end of each plot, two areas were marked out each measuring 2m wide (across the plot) by 1m deep. There was approximately 0.3m between these areas. In the first area all the green or yellow buds on the main shoots from all plants were removed. This was done by trimming the buds with a pair of scissors. Care was taken to remove only the buds and to cut off as little of the stem as possible. The number of plants from which the main stem buds were removed was counted. In the second area the main stem buds were removed from half of the plants from which buds were removed in the first area. As far as was practical the buds were removed uniformly from the whole area. Again the number of plants from which the main stem buds were removed was recorded. Both of these pruned areas were clearly marked so that their yield could be assessed at harvest.

Assessments

Crop maturity – Determination of pod number and seed yield

Between three weeks before harvest and harvest a 1m^2 sample of crop was taken and analysed as described in the mid-flower assessment. The number of pods in the sub-sample was counted. Seed yield was also determined from the quadrat samples for the pruned and un-pruned areas.

3.2.5. Objective 5. Investigate pollen beetle distribution in the field as an aid to assessing pest numbers

In each year of the project 10 oilseed rape crops were visited to assess pollen beetle numbers. A total of two visits were made to each field, one at green/yellow (GS 3.6/3.7) and another at yellow bud (GS 3.9). At each visit, pollen beetle numbers were assessed along four transects (north, east, south and west) one from each edge of the field, assuming it to be approximately square. If the field was triangular, a transect was walked from each edge. Ideally, each transect was 100m long starting from the field edge and leading towards the centre of the crop. One plant was assessed every 5m. If walking 100m into the crop was beyond the centre a note was made of which plant assessment corresponded to the centre of the field.

Assessments

Assessments were made by beating a plant over a white tray and counting the number of pollen beetles that were dislodged. Ideally pollen beetle numbers were assessed on a warm, dry day at a time when beetles were most active after early morning. The temperature and weather conditions on the day of sampling were noted as was the approximate dimensions of the field so it was possible to locate where each sample was taken and indicate which transect was north, east, south or west. The type of field boundary (hedge, fence etc) was also noted together with and any notable boundary features

Statistical analysis

The numbers of pollen beetles recovered from different distances along each transect were compared using the analysis of variance. Initially the numbers recovered from 0-25m, 26-50m, 51-75m and 76-100m were compared. In a second analysis numbers recovered between 0-50m and 51-100m were compared. Numbers of beetles recovered on each of the north, east, south and west transect were compared within the block stratum of the analysis.

Due to the large variability in pollen beetle numbers within transects another non-parametric analysis was used to compare beetle numbers. This involved ranking the number of occasions across all sites that pollen beetle numbers were greatest at either 0-25m, 26-50m, 51-75m or 76-100m into the crop. The same analysis was used to rank how many times the north, east, west or southern transects had most pollen beetles.

3.3. Results

3.3.1. Objective 1. To quantify bud loss resulting from pollen beetle attack

The number of pollen beetles that survived until mid-flowering following inoculation to plants at late green bud/yellow bud was assessed in both years (Table 2). In 2008 the percentage of beetles that survived when 10 were inoculated was lower than for the other inoculation rates. This was due to plant 2 in pot 13 where all inoculated beetles were dead. Also on plant 3 in pot 27 no live beetles were recorded and only two dead beetles, suggesting that a number had escaped. In 2009 the overall level of beetle survival was lower than in 2009. It seems likely that these beetles were collected from a less fit population in 2009 than was the case in 2008 possibly because they were collected later in the season than in 2008.

Table 2. Mean pollen beetle survival in pots in 2008 and 2009

Number of inoculated beetles	2008		2009	
	Number surviving	% survival	Number surviving	% survival
1	N/A	N/A	0.4	44.4
5	4.3	86.3	2.8	31.1
10	7.7	76.9	6.4	31.7
15	11.5	91.8	8.3	27.8
20	18.8	94.2	10.0	26.1
50	43.3	89.6	26.6	40.1
Mean	-	87.8	-	33.5

The total pods lost per beetle were calculated in both 2008 and 2009 and these data appear in Table 3.

Table 3. Mean numbers of buds, flowers, and pods per plant at mid-flowering and the number of buds lost per plant due to beetle damage compared with the uninoculated treatment. (Figures in brackets are the actual number of beetles recovered from plants in 2009)

Number of inoculated beetles		Mean plant parts per plant				Buds lost per plant	Buds lost/beetle
		Buds	Flowers	Pods	Total		
2008	0	29.2	26.8	43.2	99.2	0	0
	5	15.8	11.3	27.5	54.6	44.6	8.9
	10	11.7	5.5	19.9	37.1	62.1	6.2
	15	5.2	2.7	13.1	21.0	78.2	5.2
	20	6.4	2.4	14.0	22.8	76.4	3.8
	50	7.0	3.6	19.6	30.2	69.0	1.4
2009	0	25.2	9.2	142.2	176.6	0	0
	1 (0.4)	8.8	6.4	160.8	175.9	0.7	0.7
	5 (2.8)	9.9	3.6	116.0	129.4	47.2	16.9
	10 (6.4)	24.5	5.6	112.2	142.3	34.3	5.4
	15 (8.3)	13.9	5.8	113.8	133.4	43.2	5.2
	20 (10.0)	7.4	3.6	106.1	117.1	59.5	6.0
	50 (26.6)	35.7	10.5	67.4	113.6	33.0	2.4

At mid-flowering the total number of buds per plant that had formed during the plant's development was calculated from counts of the number of flowers, buds and pods on each plant at mid-flower, assuming that no further buds would be produced at that stage). In 2008 there were fewer flowers per plant than in 2009 probably because each pot contained three plants in 2008 compared with one plant in 2009. The number of buds destroyed by pollen beetles was estimated by subtracting the total bud number in each inoculated treatment from the bud number in the uninoculated treatment.

The relationship between buds lost per beetle and the number of inoculated beetles are shown in Figures 3, 4 and 5. The proportion of variance accounted for (R^2) for the 2008 data was 0.98 in comparison with 0.90 in 2009. In 2008, the best-fit line ($y = 9.58^{-0.040x}$) indicated that the number of buds lost from a single beetle was 9.3. In 2009, the best-fit line ($y = 7.86e^{-0.051x}$) indicated that the number of buds lost from a single beetle was 7.5. The data point for a single inoculated beetle was not included in either Figure 3 or 4. This is because the survival rate of beetles at this inoculation rate in 2009 was less than 50%. Consequently more than half of the replicates at this inoculation rate effectively became additional control plots with no beetles. This is likely to have underestimated the potential bud loss from a single beetle. This contention is supported by the data in Table 3 in which there was minimal bud loss at the one beetle/plant inoculation rate. This data point appears to be an outlier when compared with other inoculation rates. In general, there was uncertainty regarding the number of beetles that were active in the 2009 experiment due to the high mortality rate. If the number of live beetles counted at the end of the experiment are used (rather than the number of beetles inoculated at the beginning of the experiment), then it is estimated that an individual beetle may destroy up to 19.9 buds (Figure 5). It was expected that much of the bud damage would have been caused soon after the beetles were inoculated, as they migrated to the flowers once they had opened. Therefore the number of inoculated beetles is likely to give the best estimate of numbers responsible for any bud loss. However, in 2009 the beetles were observed to be far less active on the rape heads and it was clear that a number had died before the plants were in flower. This is possibly because beetles were collected later in 2009 than in 2008 so they were closer to the end of their life cycle. Therefore in this experiment it is possible that using the inoculated beetle number may under-estimate the number of buds damaged per beetle. Equally, using the number of live beetles at the end of the experiment may over-estimate the number of buds damaged per beetle.

In view of greater statistical precision of the relationship in 2008 combined with uncertainty about how long the inoculated beetles survived for in 2009, it was decided to use the 2008 data set to determine the pod loss resulting from pollen beetle attack. The figure of 9.3 buds lost per beetle was rounded down to 9 beetles/plant for all subsequent calculations. One other factor to consider is whether confining the beetles between late green bud and mid-flowering resulted in greater bud damage than in a natural situation due to beetles exhausting pollen supply from opened flowers and returning to unopened buds to find more pollen. This may result in greater bud damaged per beetle than in natural situations.

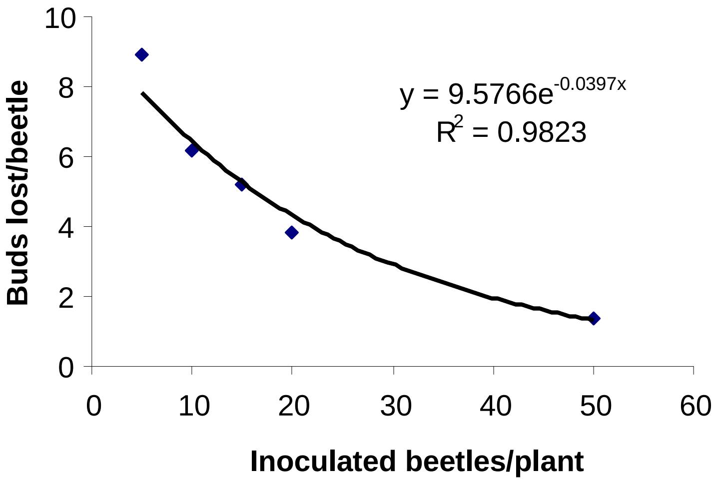


Figure 3. Relationship between number of inoculated pollen beetles/plant and buds lost/beetle in 2008 experiment

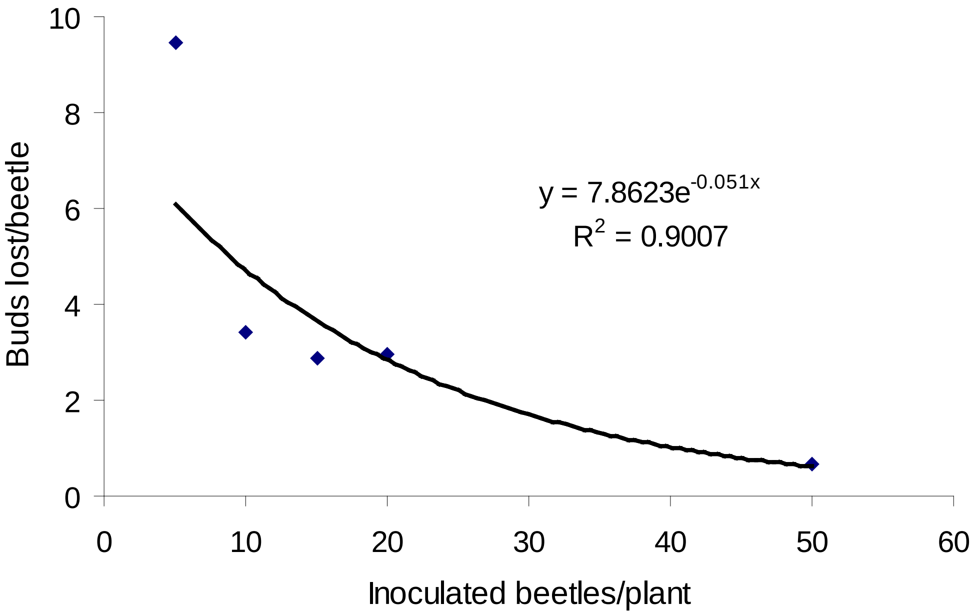


Figure 4. Relationship between number of inoculated pollen beetles/plant and buds lost/beetle in 2009 experiment

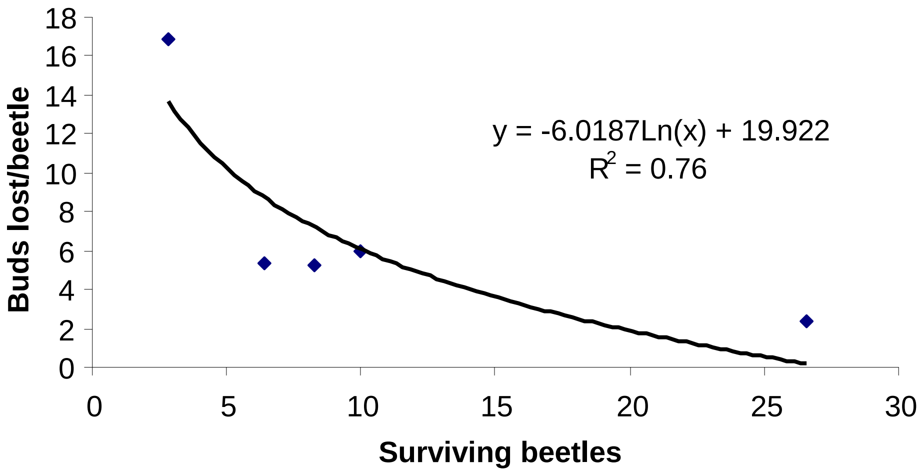


Figure 5. Relationship between number of surviving pollen beetles/plant and buds lost/beetle in 2009 experiment

3.3.2. Objective 2. To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety

This section assesses the number of excess flowers that are produced in relation to the final pod number, then investigates whether this is affected by any factors such as variety type, and finally investigates whether canopy size measured before late green bud can be used to predict the number of excess flowers. Extant data from Project Report OS49 (Lunn *et al*., 2001) and new experiments done as part of this study have been used.

Review of OS49

The number of flowers and final pod number were measured in several experiments done as part of OS49 ‘Canopy management in Oilseed rape’. These results are summarised in Table 4. The total flower number has or will be produced has been estimated by summing the number of buds, flowers, pods and blind stalks measured at mid-flowering. The data shows that the flower number ranged from 10,941/m^2 to 18,737/m^2, pod number at harvest ranged from 3,357/m^2 (without N fertiliser) to 10,726/m^2, and the number of excess flowers relative to the final pod number ranged from 2,250 to 10,949/m^2. None of the experimental treatments significantly affected the number of excess flowers. This included a comparison of crops sown in the last week of August or first week of September at 120 seeds/m^2 with crops sown in the last week of September at either 60 or 120 seeds/m^2, and crops receiving nil, 100, 200 or 300 kg N/ha. It should be noted that the field used for the experiment at Sutton Bonington in 1996 had a very high soil mineral N content which helps to explain why the greatest yielding treatment at this site received no N fertiliser. However, there were trends for crops sown late or sub-optimal N fertiliser rates to produce fewer excess flower numbers. The conventional variety used in these experiments was Apex, a conventional open-pollinated variety.

Table 4. Summary of flower and pod counts from experiments carried out in OS49 (Lunn *et al*., 2001)

Harvest year and site	Treatment	[††] Total flower number/m^2 at mid-flower	Pods/m^2 at harvest	Excess flowers/m^2	Yield (t/ha)
1996 Rosemaund	Early sown 120 seeds/m^2	13,348	7,369	5,979	4.03
1996 Rosemaund	Late sown 60 seeds/m^2	10,941	5,756	5,186	4.51
SED (3 df)		996.3[†]	240.1 **	1036.6 NS	0.543 NS
1997 Rosemaund	Early sown 120 seeds/m^2	12,573	9,252	3,322	4.63
1997 Rosemaund	Late sown 120 seeds/m^2	11,240	8,991	2,250	4.66
SED (3 df)		1318.4 NS	1703.6 NS	2114.3 NS	0.258 NS
1996 Sutton Bonington	0 kg N/ha	17,002	8,931	8,071	4.95
1996 Sutton Bonington	100 kg N/ha	18,737	8,943	9,974	4.54
1996 Sutton Bonington	200 kg N/ha	18,025	10,728	7,297	4.44
SED (4 df)		1,709 NS	509.8 *	1,893.1 NS	0.182[†]
1997 Sutton Bonington	0 kg N/ha	11,564	3,357	8,189	4.01
1997 Sutton Bonington	100 kg N/ha	15,478	5,637	9,841	5.20
1997 Sutton Bonington	300 kg N/ha	18,527	7,578	10,949	5.26
SED (4 df)		2,580 NS	818.1 *	1,875.6 NS	0.279 *

[†] $P<0.1$; * $P<0.05$; ** $P<0.01$

[††] Total flower number estimated from the sum of buds, flowers, pods and blind stalks counted at mid-flowering

Winter oilseed rape experiments 2007/08

In order to assess whether there are varietal differences for the number of flowers and pods produced, measurements were carried out in 2008 in two existing variety trials (Table 5). At High Mowthorpe, there were significant differences in the total number of flowers produced by different varieties. The semi-dwarf hybrid (PR45D01) and the late developing variety (Grizzly) produced the most flowers (11-12,000/m^2) and Lioness the least (6,395/m^2). There were no significant differences in the final number of pods between varieties, but there were significant differences in the number of excess flowers(flower number minus pod number) with the varieties which produced a high number of flowers tending to have high numbers of excess flowers in excess of 6000/m^2. In the Rosemaund experiment, there were no significant varietal differences for flower number, pod number or excess flower number, with excess flower numbers averaging 4,274/m^2. These results indicate that neither hybrid, semi-dwarf nor late developing varieties produce significantly less flowers than open pollinated varieties. These results take account of the generally lower sowing rates used for hybrid varieties as these were sown at 70 seeds/m^2 compared with 100 seeds/m^2 for the open pollinated varieties. The average yield in these trials was 3.3/ha.

Table 5. Measurements of total flower number and pod number in two variety trials carried out in 2007/08 as part of LINK project LK0979.

	High Mowthorpe			Rosemaund		
Variety	†Total flower number/m^2	Pods/m^2 at harvest	Excess flowers/m^2	†Total flower number/m^2	Pods/m^2 at harvest	Excess flowers/m^2
Grizzly (O)	11,328	4,540	6,788	10,024	5,778	4,246
Lioness (O)	6,395	5,187	1,208	10,251	5,009	5,242
NK Bravour(O)	9,073	4,683	4,390	10,045	5,597	4,448
Winner (O)	8,144	4,134	4,010	8,236	5,076	3,160
Royal (H)	7,290	4,761	2,529	9,483	4,355	5,128
PR45D01 (H)	12,016	5,979	6,037	8,192	5,013	3,179
Mean	8,735	4,636	4,099	9,639	5,365	4,274
SED (15 df)	1,351.3 **	1,133.8	1,507.9 *	1,031.0	718.0	970.1

O – open pollinated variety; H – hybrid variety

* P<0.05; ** P<0.01

†Total flower number estimated from the sum of buds, flowers, pods and blind stalks counted at mid-flowering

Winter oilseed rape experiments 2008/09 and 2009/10

In the 2008/09 experiment both variety and seed rate treatments significantly affected the number of plants/m^2 established (Table 6). Increasing seed rate from 20 seeds/m^2 to 160 seeds/m^2 increased plants/m^2 from 25 to 98 plants/m^2. At low seed rates, more plants were established than seeds sown due to the emergence of volunteer plants. As seed rates increased the plant establishment decreased due to inhibition on seed germination by close neighbours. This effect is commonly observed in seed rate experiments (e.g. Spink *et al*., 2004). The semi-dwarf hybrid variety PR45D03 established fewer plants (51 plants/m^2 on average) compared with Excalibur and Castille which averaged 62 plants/m^2. Interestingly, the greatest seed yield of 4.66 t/ha was obtained from the 40 seeds/m^{2}seed rate (35 plants/m^2) but the yield from the 20 seeds/m^{2}rate was not significantly different at 4.60 t/ha (Table 6). The open pollinated and hybrid varieties responded similarly to different seed rates. Increasing seed rate above 40 seeds/m^2 to 160 seeds/m^2 reduced yield to 4.25 t/ha. The total flower number, estimated from the combined number of buds, flowers, pods and blind stalks measured at mid-flowering, was significantly affected by variety. Castille achieved an average of 11,274 flowers/m^2, PR45D03 had 13,123 flowers/m^2 and Excalibur had 14,782 flowers/m^2. Flower number per m^{2}was not affected by seed rate. At harvest the number of pods/m^2 averaged just over 7000/m^2 and was not affected by variety or seed rate. Differences in excess flower number (defined as the difference between flower number and pod number at harvest) mainly reflected treatment differences in flower number measured at mid-flowering. Castille averaged 3747 excess flowers/m^2, which was significantly less than Excalibur and PR45D03, which averaged just over 7000/m^2 ($P<0.1$). Excess flower number was not affected by the seed rate. The number of excess flowers **per plant** was significantly affected by variety and seed rate. On average, Castille had the fewest excess flowers per plant (60), followed by Excalibur at 112 and PR45D03 at 139 per plant. Increasing seed rate from 20 to 160 seeds/m^2 reduced the number of excess flowers per plant from 209 to 62.

In the 2009/10 experiment only the seed rate significantly affected the number of plants/m^2 established with no differences between variety (Table 7). Increasing seed rate from 10 seeds/m^2 to 160 seeds/m^2 increased plants/m^2 from 20 to 93 plants/m^2. Similar to the 2008/09 experiments there were volunteer plants and the percentage of seeds that established plants decreased as the seed rate increased. The greatest seed yield of 4.79 t/ha was observed from the 40 seeds/m^{2}rate (37 plants/m^2). Yield dropped to 4.46 t/ha and 4.57 t/ha at the 20 and 10 seeds/m^2 treatments respectively. Increasing the seed rate to 160 seeds/m^2 (92 plants/m^2) reduced the yield to 4.27 t/ha. PR45D03 yielded 4.73 t/ha on average which was significantly more than Castille (4.45 t/ha) and Excalibur (4.32 t/ha). It is of importance that the open pollinated and hybrid varieties responded very similarly to different seed rates in both experiments and there appears to be little justification for targeting different optimum plant populations for the different variety types. Increasing seed rate from 10 to 160 seeds/m^2 significantly increased the number of flowers from

10,960 flowers/m^2 to 16,784 flowers/m^2. Flower number was not affected by variety. At harvest the number of pods/m^2 averaged just under 5000/m^2 and was not affected by variety or seed rate. Differences in excess flower number mainly reflected treatment differences in flower number measured at mid-flowering. Increasing seed rate from 10 to 160 seeds/m^2 significantly increased the number of excess flowers from 6,274 excess flowers/m^2 to 12,131 excess flowers/m^2. Excess flower number was not affected by variety.

The number of excess flowers **per plant** was significantly affected by seed rate. Increasing seed rate from 10 to 160 seeds/m^2 reduced the number of excess flowers per plant from 309 to 131. Variety did not significantly affect excess flowers per plant, on average, Castille had the fewest excess flowers per plant (184 per plant) and Excalibur had the most at 234.

In the 2009/10 experiment, the number of excess flowers/m^2 was strongly and positively related with GAI measured at the green bud stage (GS3,3 to 3,5) and plants/m^2 (Figures 6b and 7b). Each variety was shown to have the same relationship between either GAI and excess flower number or plant number and excess flower number. In 2008/09, the number of excess flowers/m^2 was more weakly correlated with GAI and plant number for Excalibur and PR45D03 and there was no relationship for Castille (Figures 6a and 7a).

In both experiments there were strong negative relationships between the number of excess flowers per plant and either GAI measured at green bud (Figure 8) or plants/m^2 (Figure 9). Multiple regression analysis for both experiments combined showed that parallel best-fit lines best explained the varietal relationships between excess flowers per plant and either GAI or plants/m^2. This means that the effect of changes to GAI or plants/m^2 on the number of excess flowers per plant was the same for each variety and in each season. On average each additional unit of GAI reduced the number of excess flowers per plant by 104. Each additional plant/m^2 reduced the number of excess flowers per plant by 2.20. However, there were varietal differences in the number of excess flowers per plant which were consistent between the two seasons. For any given GAI, Castille produced 82-88 fewer excess flowers per plant than Excalibur and 43 to 48 fewer excess flowers compared with PR45D03. For any given plant population, Castille produced 53-58 fewer excess flowers per plant than Excalibur and 31-49 fewer excess flowers compared with PR45D03. The average number of excess flowers per plant in 2009 was 127 compared with 239 in 2010. Similarly there were twice as many excess flowers per unit GAI in 2010 (9315) compared with 2009 (4525). It therefore appears that seasonal variation in excess flowers per plant may be as large, or larger, than varietal differences in excess flower number.

Table 6. Seed yield and numbers of plants, flowers and pods on winter oilseed rape experiment near High Mowthorpe 2008/09

Variety	Seeds/m^2	Plants/m^2	GAI (24 March)	[††]Total flower number/m^2	Pods/m^2 at harvest	Excess flowers /m^2	Yield (t/ha)
Castille	20	26.2	0.85	10562	6590	3972	4.71
Castille	40	35.2	1.14	11469	7637	3832	4.74
Castille	80	59.8	2.05	9804	6911	2893	4.54
Castille	120	83.0	1.98	13082	7894	5188	4.37
Castille	160	107.8	2.37	11452	8605	2848	4.20
Excalibur	20	28.4	0.85	14725	8442	5574	4.61
Excalibur	40	35.2	1.41	14749	8757	7264	4.75
Excalibur	80	61.2	2.18	13266	7235	7106	4.54
Excalibur	120	75.8	2.44	15812	6846	8039	4.37
Excalibur	160	111.4	2.66	15356	7094	7111	4.31
PR45D03	20	21.2	0.65	12103	6529	6283	4.46
PR45D03	40	35.4	1.08	12781	5517	5991	4.50
PR45D03	80	55.4	1.50	13165	6059	6031	4.43
PR45D03	120	69.6	1.64	13869	5831	8966	4.38
PR45D03	160	75.0	1.85	13695	6584	8262	4.24
Castille	Mean	62.4	1.68	11274	7527	3747	4.51
Excalibur	Mean	62.4	1.91	14782	7675	7019	4.51
PR45D03	Mean	51.3	1.35	13123	6104	7107	4.40
Mean	20	25.3	0.78	12463	7187	5277	4.60
Mean	40	35.3	1.21	13000	7304	5696	4.66
Mean	80	58.8	1.91	12078	6735	5343	4.50
Mean	120	76.1	2.02	14255	6857	7398	4.37
Mean	160	98.1	2.29	13501	7427	6074	4.25
Variety SED (6 df)		2.68 **	0.172 *	595.7 **	827.7 NS	1296.9 [†]	0.073 NS
Seed rate SED (36 df)		4.62 ***	0.134 ***	862.2 NS	462.2 NS	877.1	0.097 ***
Var x seed SED (42 df)		7.64 [†]	0.269 NS	1462.6 NS	1128.9 [†]	1878 NS	0.167 NS

[†] P<0.1; * P<0.05; ** P<0.01

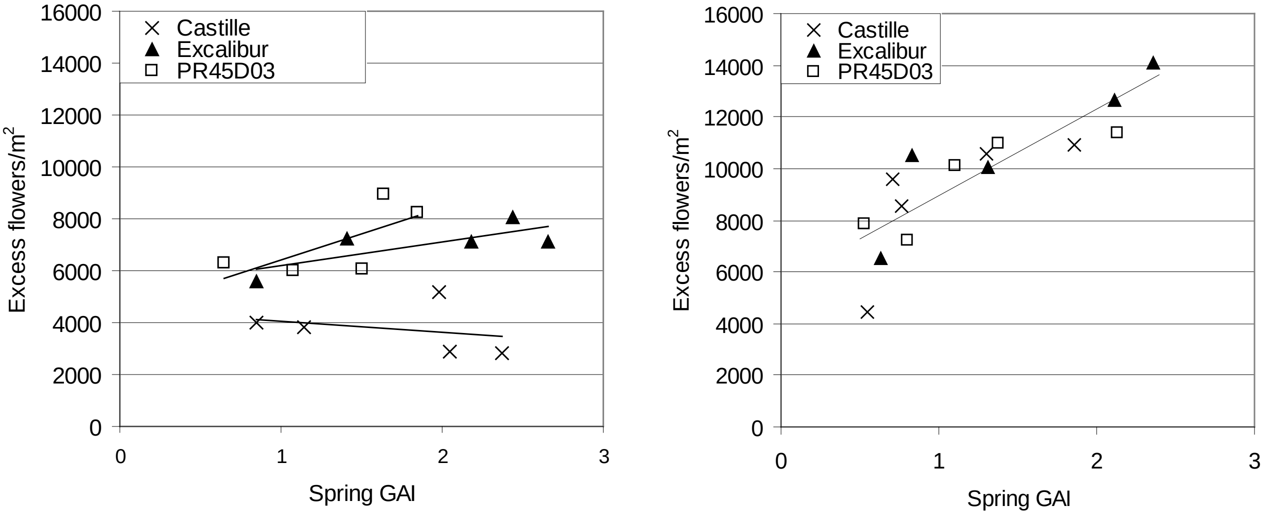
[††] Total flower number estimated from the sum of buds, flowers, pods and blind stalks counted at mid-flowering

Table 7. Seed yield and numbers of plants, flowers and pods on winter oilseed rape experiment near High Mowthorpe 2009/10

Variety	Seeds/m^2	Plants/m^2	GAI (6 April)	[††]Total flower number/m^2	Pods/m^2 at harvest	Excess flowers/m^2	Yield (t/ha)
Castille	10	22.2	0.55	9608	5165	4443	4.51
Castille	20	29.0	0.76	13855	5313	8542	4.35
Castille	40	36.2	0.71	15331	5755	9576	4.79
Castille	80	56.0	1.30	15959	5375	10584	4.23
Castille	160	86.2	1.86	15998	5062	10936	4.39
Excalibur	10	18.4	0.63	10690	4181	6510	4.40
Excalibur	20	33.6	0.83	15803	5305	10498	4.37
Excalibur	40	35.8	1.31	14760	4707	10054	4.61
Excalibur	80	59.4	2.11	17323	4671	12652	4.31
Excalibur	160	99.2	2.36	18793	4706	14087	3.91
PR45D03	10	20.4	0.53	12581	4711	7870	4.81
PR45D03	20	27.6	0.80	11915	4676	7239	4.67
PR45D03	40	39.8	1.10	14565	4480	10084	4.97
PR45D03	80	60.6	1.38	15544	4582	10961	4.68
PR45D03	160	91.4	2.13	15560	4189	11371	4.51
Castille	Mean	48.0	1.03	14150	5334	8816	4.45
Excalibur	Mean	45.9	1.45	15474	4714	10760	4.32
PR45D03	Mean	49.3	1.19	14033	4528	9505	4.73
Mean	10	20.3	0.57	10960	4686	6274	4.57
Mean	20	30.1	0.80	13858	5098	8760	4.46
Mean	40	37.3	1.04	14885	4981	9905	4.79
Mean	80	58.7	1.59	16275	4876	11399	4.41
Mean	160	92.3	2.12	16784	4652	12131	4.27
Variety SED (6 df)		2.35 NS	0.110 *	1096.4 NS	405.5 NS	635.3 NS	0.065 **
Seed rate SED (36 df)		3.69 ***	0.108 ***	1186.1 ***	523.5 NS	455.7 ***	0.085 ***
Var x seed SED (42 df)		6.18 NS	0.200 [†]	2139.8 NS	906.8 NS	949.7 NS	0.147 NS

[†] P<0.1; * P<0.05; ** P<0.01

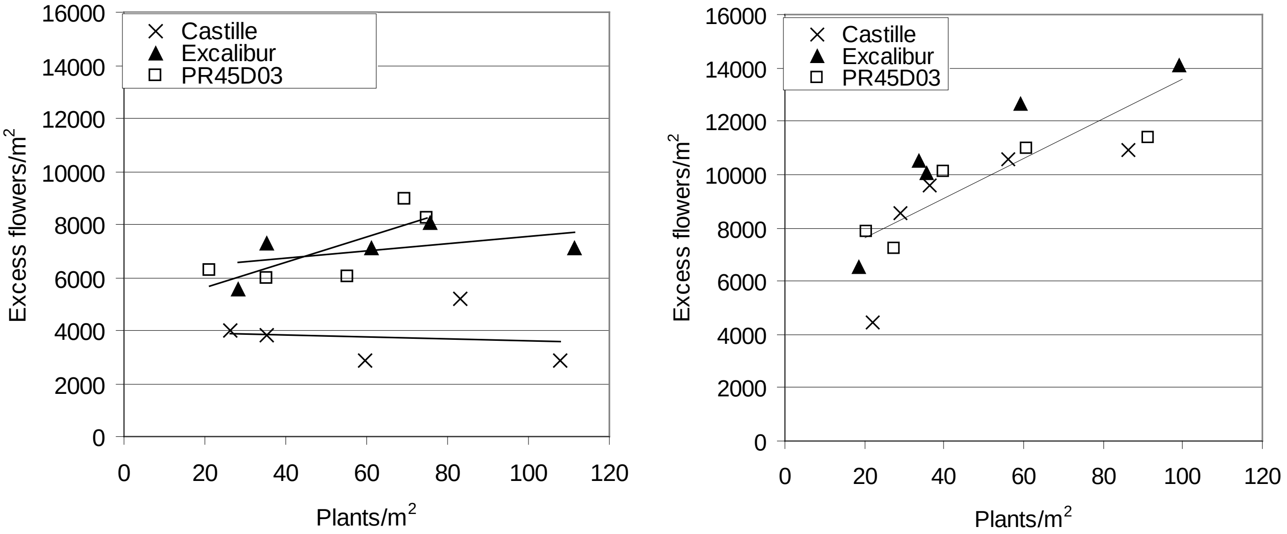
[††] Total flower number estimated from the sum of buds, flowers, pods and blind stalks counted at mid-flowering



(a) 2008/09

(b) 2009/10

Figure 6. Relationship between GAI measured at green bud (GS3.3 to 3.5) and the number of excess flowers (flower number minus final pod number) for a) 2008/09; PR45D03 ($y=1994x + 4426$; $R^2 = 0.46$), Excalibur ($y= 892x +5317$; $R^2 = 0.57$), Castille (no significant relationship), b) 2009/10; all varieties ($y=3332x + 5215$; $R^2 = 0.72$).



(a) 2008/09

(b) 2009/10

Figure 7. Relationship between plants/m^2 measured in spring and the number of excess flowers (flower number minus final pod number) for a) 2008/09; PR45D03 ($y=48.0x + 4642$; $R^2 = 0.61$), Excalibur ($y= 13.5x + 6175$; $R^2 = 0.26$), Castille (no significant relationship), b) 2009/10; all varieties ($y=73.9x + 6166$; $R^2 = 0.65$).

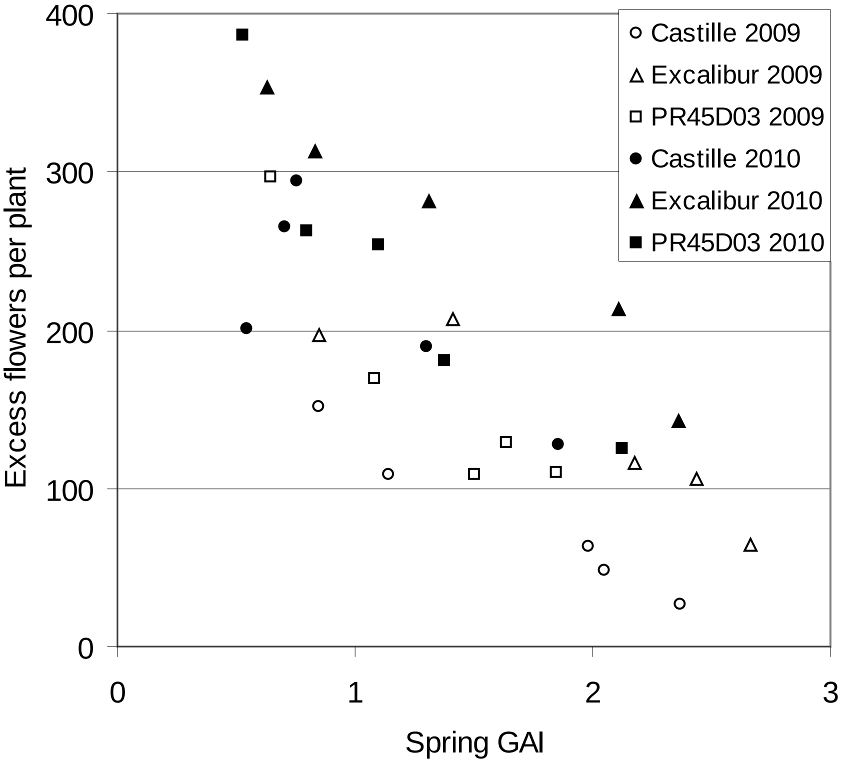


Figure 8. Relationship between GAI measured at green bud (GS3.3 to 3.5) and the number of excess flowers (flower number minus final pod number)per plant for Castille 2009 (y=-104x + 254), Excalibur 2009 (y= -104x + 336), PR45D03 2009 (y=-104x + 302), Castille 2010 (y=-104x + 323), Excalibur 2010 (y= -104x + 411), PR45D03 2010 (y=-104x + 365). Fitting parallel best-fit lines using multiple regression analysis accounted for 86% of the variation.

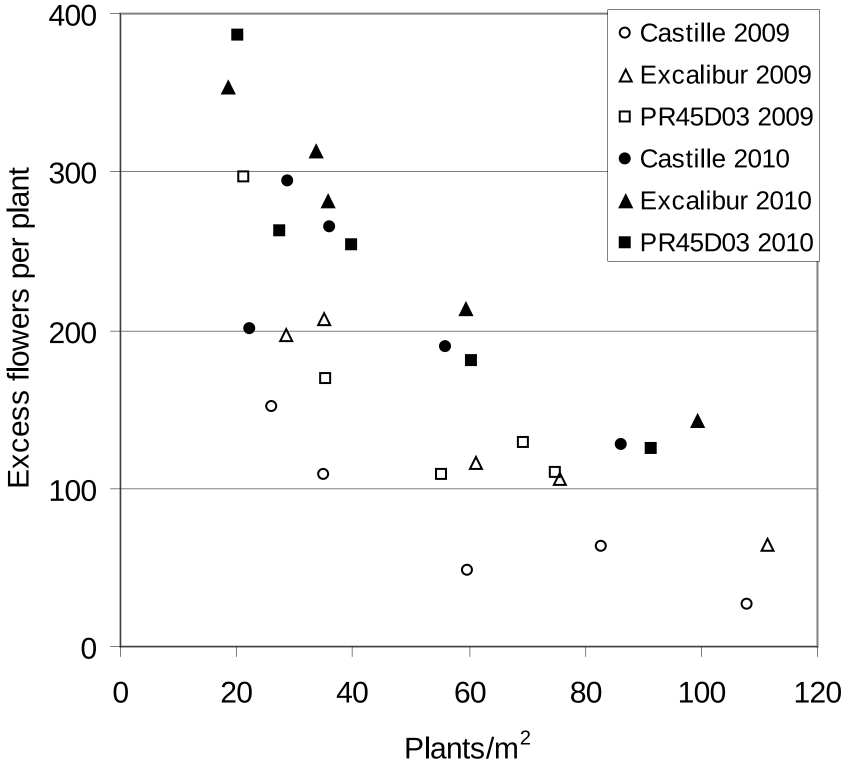


Figure 9. Relationship between plants/m^2 measured in spring and the number of excess flowers (flower number minus final pod number)per plant for Castille 2009 (y=-2.20x + 217), Excalibur 2009 (y= -2.20x + 275), PR45D03 2009 (y=-2.20x + 266), Castille 2010 (y=-2.20x + 316), Excalibur 2010 (y= -2.20x + 369), PR45D03 2010 (y=-2.20x + 347). Fitting parallel best-fit lines using multiple regression analysis accounted for 84% of the variation.

Spring oilseed rape experiments 2008/09 and 2009/10

In the 2008/09 experiment only the seed rate significantly affected the number of plants/m^2 established with no differences between variety (Table 8). Increasing seed rate from 20 seeds/m^2 to 200 seeds/m^2 increased plants/m^2 from 15 to 74 plants/m^2. Similar to the winter oilseed rape experiments the percentage of seeds that established plants decreased as the seed rate increased. The greatest seed yield of 1.98 t/ha was observed for the 120 seeds/m^2seed rate (54 plants/m^2). Delight yielded 1.92 t/ha on average which was significantly more than Heros (1.66 t/ha). Delight produced 8,627 flowers/m^2 which was significantly less than Heros at 12,953/m^2. Seed rate did not significantly affect the number of flowers, although increasing seed rate from 20 to 200 increased the number of flowers from 9,569 flowers/m^2 to 12,088 flowers/m^2. At harvest, Delight had 5,008 pods/m^2, which was significantly more than Heros at 3,784 pods/m^2. Seed rate did not significantly affect the number of pods. Heros had significantly more excess flowers/m^2 (9,199) compared with Delight at 3,620 flowers/m^2. Seed rate did not significantly affect the number of excess flowers, although increasing seed rate from 20 to 200 increased the number of excess flowers from 4,807/m^2 to 7,211 flowers/m^2. The number of excess flowers per plant was significantly affected by variety and seed rate. On average Delight had 86 excess flowers per plant while Heros had 218 excess flowers per plant. Increasing seed rate from 20 to 200 seeds/m^2 reduced the number of excess flowers per plant from 325 to 97 across both varieties.

In the 2009/10 experiment, only the seed rate significantly affected the number of plants/m^2 established, with no differences between variety (Table 9). Increasing seed rate from 20 seeds/m^2 to 200 seeds/m^2 increased plants/m^2 from 25 to 67 plants/m^2. The greatest seed yield of 3.43 t/ha was observed from the 80 seeds/m^{2}seed rate (47 plants/m^2). There was no difference in yield between Delight and Heros. Heros produced 10,964 flowers/m^2 which was significantly more than Delight at 9,246/m^2. The seed rate treatment at 40 seeds/m^2 had significantly fewer flowers than the other seed rates, including 20 seeds/m^2. There was no apparent trend in flowers/m^2 between seed rates of 20 and 200 seeds/m^2. At harvest, Heros had significantly more pods than Delight. Increasing seed rate from 80 to 200 seeds/m^2 reduced pods/m^2 from 4,454 pods/m^2 to 3,187 pods/m^2 ($P<0.1$). The seed rate treatment at 40 seeds/m^2 had significantly fewer excess flowers than the other seed rates, including 20 seeds/m^2. There was no apparent trend in excess flowers/m^2 between seed rates of 20 and 200 seeds/m^2. On average, Delight and Heros had 126 excess flowers per plant. Increasing seed rate from 20 to 200 seeds/m^2 reduced the number of excess flowers per plant from 264 to 111.

In 2008/09, there were positive relationships between GAI and plants/m^2 and the number of excess flowers/m^2 (Figures 10a and 11a). In 2009/10, there was no clear trend between GAI or plants/m^2 with the number of excess flowers (Figures 10b and 11b). There were either negative or neutral relationships between excess flowers per plant and GAI or plants/m^2. The most consistent relationships occurred for plants/m^2 with excess flowers per plant for which only Delight in 2008/09 showed no relationship. Across both varieties in both years, each additional plant/m^2 resulted in a reduction in excess flowers per plant of 3.57 flowers per plant (Equation for the best-fit line; $y = 3.57x + 327$; $R^2 = 0.29$). There were no consistent differences between varieties for the relationship between excess flowers per plant and plants/m^2. On average the number of excess flowers per plant in 2009 was 189 compared with 141 in 2010, however these averages masked large seasonal differences for each variety. The relationship between GAI and excess flowers per plant was inconsistent with a negative relationship for Heros and no relationship for Delight in 2008/09 Figure 12), and a negative relationship for Delight and no relationship for Heros in 2009/10 (Figure 13). On average the number of excess flowers per unit GAI was 3302 compared with 4252 in 2010.

Table 8. Seed yield and numbers of plants, flowers and pods on spring oilseed rape experiment near Rosemaund 2008/09

Variety	Seeds/m^2	Plants/m^2	[†††]GAI	[††]Total flower number/m^2	Pods/m^2 at harvest	Excess flowers/m^2	Yield (t/ha)
Delight	20	14.2	1.28	7280	6749	531	1.61
Delight	40	26.4	1.94	8209	4254	3955	1.94
Delight	80	41.0	2.56	9470	4882	4588	1.96
Delight	120	54.0	2.40	9860	4618	5242	2.12
Delight	200	74.4	4.42	8319	4537	3782	1.99
Heros	20	15.4	1.04	11858	2776	9083	1.38
Heros	40	25.4	1.08	12840	4085	8756	1.55
Heros	80	42.2	2.84	11704	3485	8219	1.81
Heros	120	53.4	2.85	12504	3209	9295	1.84
Heros	200	74.4	3.89	15856	5216	10640	1.74
Delight	Mean	42.0	2.52	8627	5008	3620	1.92
Heros	Mean	42.2	2.34	12953	3754	9199	1.66
Mean	20	14.8	1.16	9569	4762	4807	1.49
Mean	40	25.9	1.51	10525	4169	6355	1.74
Mean	80	41.6	2.70	10587	4184	6403	1.89
Mean	120	53.7	2.62	11182	3913	7269	1.98
Mean	200	74.4	4.15	12088	4876	7211	1.86
Variety SED (27 df)		2.62		994.7***	559.1*	1039.1***	0.084***
Seed rate SED (27 df)		4.15***		1572.7	884.0	1642.9	0.133***
Var x seed SED (27 df)		5.86		2224.2	1250.0	2323.5	0.189

[†] $P<0.1$; * $P<0.05$; ** $P<0.01$

[††] Total flower number estimated from the sum of buds, flowers, pods and blind stalks counted at mid-flowering

[†††] Measured on replicate 2 only

Table 9. Seed yield and numbers of plants, flowers and pods on spring oilseed rape experiment near Rosemaund 2009/10

Variety	Seeds/m^2	Plants/m^2	†††GAI	††Total flower number/m^2	Pods/m^2 at harvest	Excess flowers/m^2	Yield (t/ha)
Delight	20	26.6	0.53	10388	3964	6424	2.96
Delight	40	36.6	1.46	7032	3219	3813	3.27
Delight	80	45.0	1.35	9860	3233	6627	3.39
Delight	120	59.2	2.76	9906	3106	6800	3.41
Delight	200	72.6	2.88	9044	2155	6889	3.49
Heros	20	23.4	1.21	11552	4752	6800	2.83
Heros	40	50.2	1.37	7118	5425	1693	3.22
Heros	80	48.0	1.72	11512	5674	5838	3.47
Heros	120	61.6	2.16	12467	4360	8107	3.37
Heros	200	61.0	1.98	12171	4219	7952	2.98
Delight	Mean	48.0	1.80	9246	3135	6111	3.30
Heros	Mean	48.8	1.69	10964	4886	6078	3.17
Mean	20	25.0	0.87	10970	4358	6612	2.89
Mean	40	43.4	1.42	7075	4322	2753	3.25
Mean	80	46.5	1.54	10686	4454	6233	3.43
Mean	120	60.4	2.46	11187	3733	7454	3.39
Mean	200	66.8	2.43	10608	3187	7421	3.24
Variety SED (27 df)		4.73 NS	0.284 NS	828.2 *	294.2*	937NS	0.094 NS
Seed rate SED (27 df)		7.48 ***	0.449 ***	1309.0 *	465.2†	1481.1 *	0.149 *
Var x seed SED (27 df)		10.58 NS	0.635 NS	1851.1 NS	657.9 NS	2095 NS	0.211 NS

† P<0.1; * P<0.05; ** P<0.01

†† Total flower number estimated from the sum of buds, flowers, pods and blind stalks counted at mid-flowering

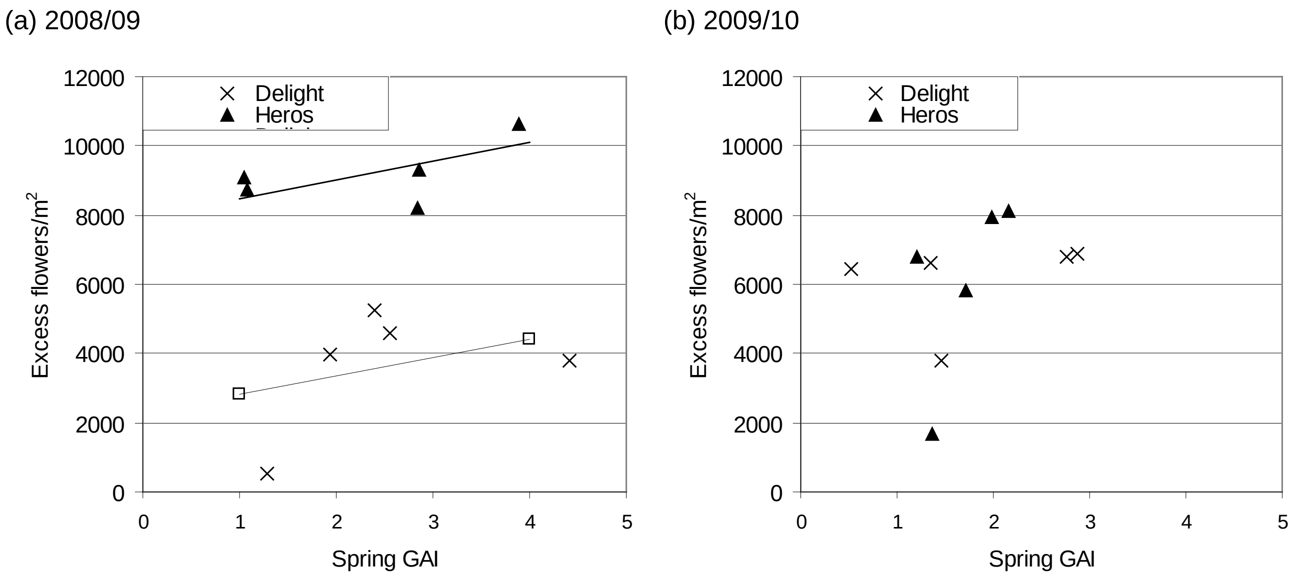


Figure 10. Relationship between GAI measured at green bud (GS3.3 to 3.5) and the number of excess flowers (flower number minus final pod number) for a) 2008/09; Heros (y=538x + 7940; R^2 = 0.25), Delight (y= 538x +2264; R^2 = 0.25), b) 2009/10; no significant relationship for either variety.

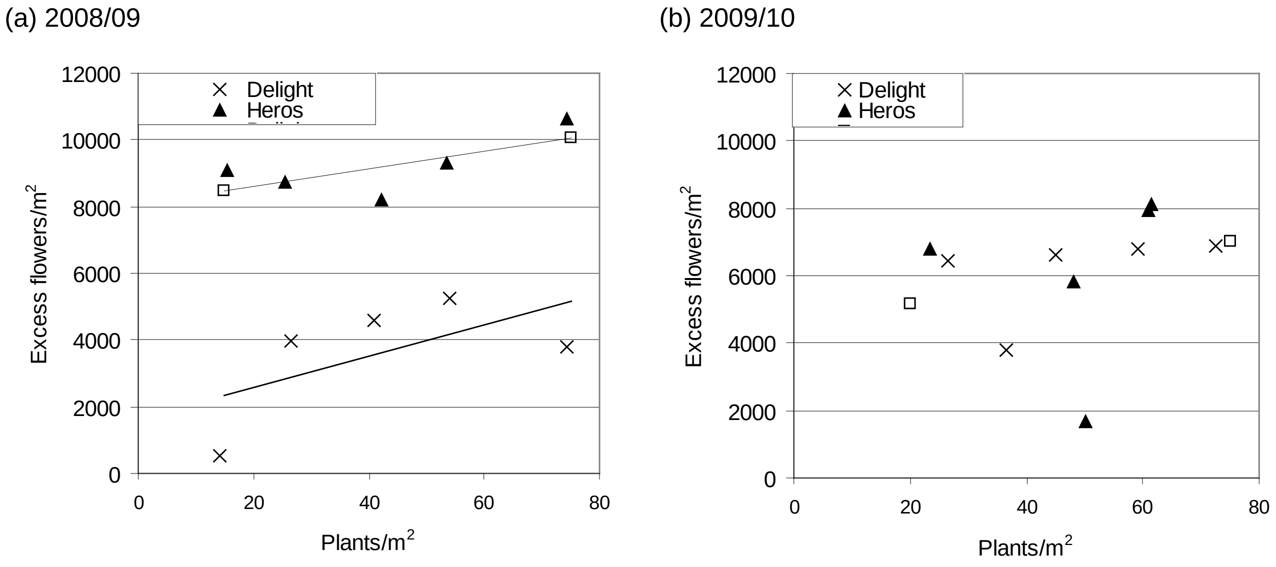
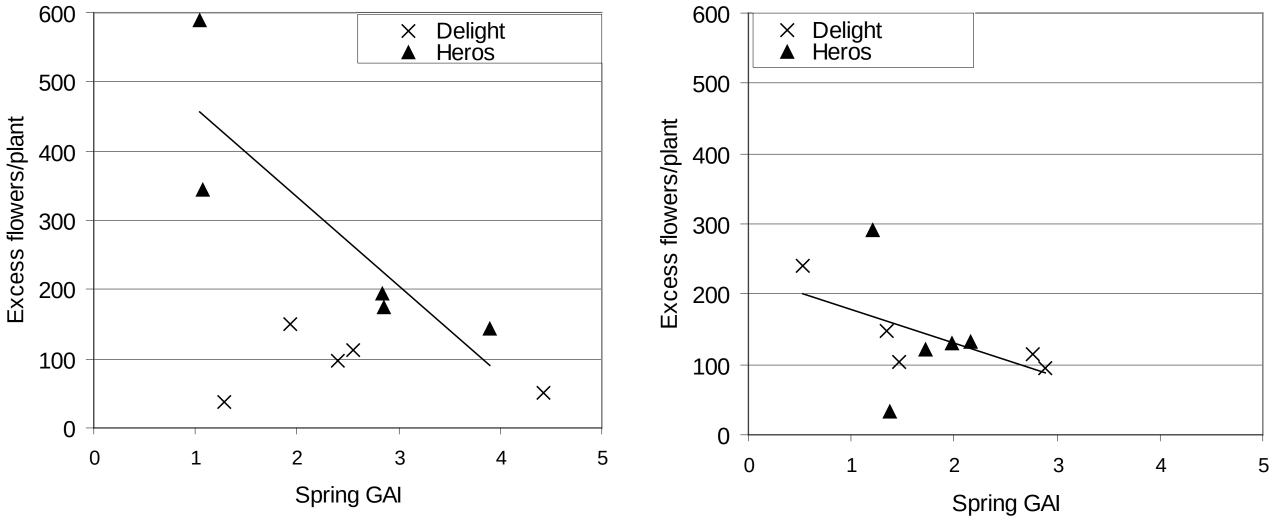
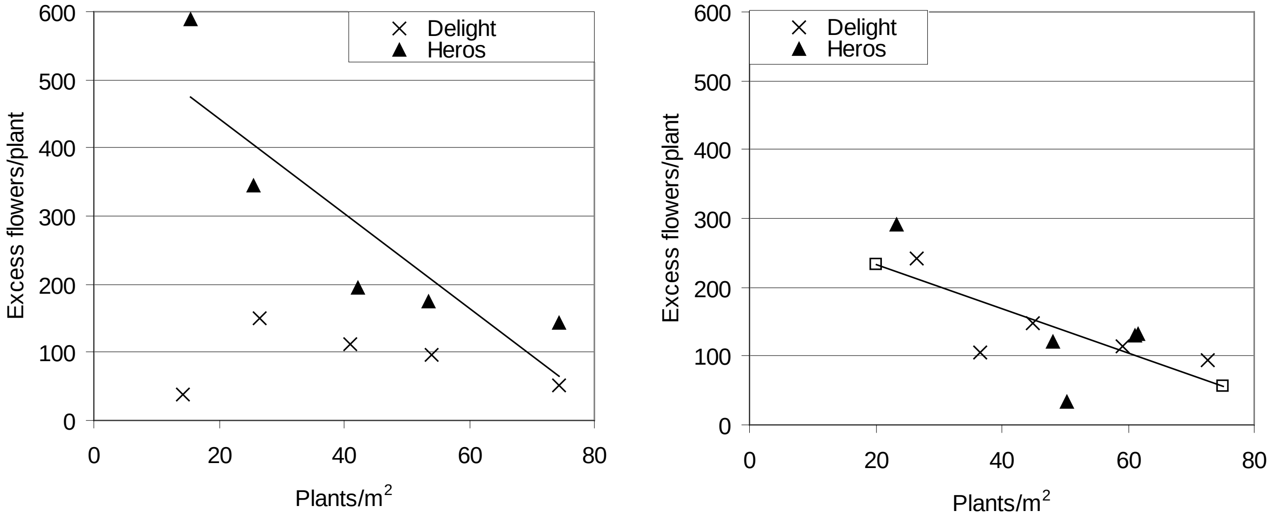


Figure 11. Relationship between plants/m^2 measured in spring and the number of excess flowers (flower number minus final pod number) for a) 2008/09; Heros (y=26.8x + 8067; R^2 = 0.48), Delight (y= 47.2x + 1636; R^2 = 0.37), b) 2009/10; no significant relationship for either variety.


(a) 2008/09

(b) 2009/10

Figure 12. Relationship between GAI measured at green bud (GS3.3 to 3.5) and the number of excess flowers (flower number minus final pod number) per plant for a) 2008/09; Heros (y=-128x + 519; $R^2 = 0.74$), Delight (no significant relationship), b) 2009/10; Heros (no significant relationship), Delight (y=-48x + 227; $R^2 = 0.64$).


(a) 2008/09

(b) 2009/10

Figure 13. Relationship between plants/m^2 measured in spring and the number of excess flowers (flower number minus final pod number) per plant for a) 2008/09; Heros (y=-6.93x + 581; $R^2 = 0.76$), Delight (no significant relationship), b) 2009/10; both varieties (y=-3.21x + 297; $R^2 = 0.49$).

3.3.3. Objective 3. Use information from objectives 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and size of crop

The following conclusions may be drawn from objectives 1 and 2;

1. An individual pollen beetle may damage up to nine buds.
2. A review of previous work showed that oilseed rape yields are maximised by achieving an optimum number of pods/m^2. Increasing pod numbers above the optimum reduces yield.
3. It has been shown that oilseed rape crops produce significantly more flowers than pods and that there is therefore an excess number of flowers relative the final pod number. It is therefore hypothesised that plants could lose these excess flowers to pollen beetle attack without losing yield.
4. Spring oilseed rape crops produced a similar number of excess flowers to winter oilseed rape crops
5. Crops with fewer plants/m^2 had more excess flowers per plant.
6. There was no evidence that hybrid varieties had fewer excess flowers per plant than conventional open pollinated varieties. In fact open pollinated variety Castille had fewer excess flowers per plant than hybrid varieties Excalibur and PR45D03 in both seasons when compared at the same seed rates. When the generally lower plant population of hybrid varieties is taken into account then the hybrids produced even more excess flowers than Castille. For the spring oilseed rape varieties compared at the same seed rate the hybrid variety Delight produced more flowers than the open pollinated variety Heros in one season and less in the other season.
7. The hybrid semi-dwarf had a similar number of excess flowers to standard height hybrid Excalibur.
8. There were large seasonal differences in the number of excess flower numbers which were as large, or larger, than the variety differences.
9. There is potential to predict the number of excess flowers per plant from measurements of plants/m^2 or GAI at green bud. Both showed strong negative relationships with excess flowers per plant, although GAI was a less useful predictor for spring oilseed rape. For winter oilseed rape, each additional plant/m^2 reduced the number of excess flowers per plant by 2.20, and each additional unit of GAI reduced the number of excess flowers per plant by 104. These relationships held across a range of varieties and across two seasons. It should be possible to include variety factors to account for inherent varietal differences in excess flower number. However, it was also shown that the seasonal variation in excess flower number per plant or per unit GAI was high and as yet no method of predicting this has been developed. For spring oilseed rape it was estimated that each additional plant/m^2 reduced the number of excess flowers per plant by 3.57. There were no consistent varietal differences for excess flowers per plant and seasonal differences were large.

If it is assumed that oilseed rape can tolerate the loss of all excess flowers per plant without affecting yield, and the mean number of buds likely to be damaged by an individual pollen beetle is nine, then the threshold number of beetles per plant that would be required to destroy all the excess flowers can be calculated and these are described below in Table 10. These calculations show that the threshold number varies significantly depending on plant population, but that variety and season also have strong effects. For winter oilseed rape, in 2008/09, increasing seed rate from 20 to 160 seeds/m^2 reduced the pollen beetle threshold per plant from 17 to 3 for Castille and from 22 to 7 for Excalibur. In 2009/10, increasing seed rate from 20 to 160 seeds/m^2 reduced the pollen beetle threshold per plant from 33 to 14 for Castille and from 35 to 16 for Excalibur. For what may be regarded as typical seed rates of 80 seeds/m^2 for an open pollinated variety and 40 seeds/m^2 for a hybrid the thresholds were estimated at 5 to 21 for Castille and 19 to 31 for the hybrid varieties. It should be noted that the yield response to seed rates showed that the open pollinated variety Castille responded very similarly to the hybrid varieties and therefore 40 seeds/m^2 may be more appropriate for this variety too. The threshold range at 40 seeds/m^2 was 12 to 21. It therefore appears that there will be a significant proportion of crops which can tolerate a greater number of beetles than the current threshold of 15 per plant. In particular, it is shown here that crops with low plant populations of 25 plants/m^2 or less, which may be defined as backward should certainly have a greater threshold than 5 beetles per plant and probably should have the same threshold as ‘normal’ crops. This may not apply to crops which are defined as backward for reasons other than low plant population (e.g. pigeon damage). For spring oilseed rape the average threshold across all treatments was 18 beetles per plant, with none below the current threshold of 3 beetles per plant. It therefore appears that this threshold should be increased.

It is clear that there is a strong relationship between the number of plants/m^2 and the pollen beetle threshold, with crops with fewer plants having a higher threshold. This may seem counter-intuitive as one may expect that low plant populations would inherently be more susceptible to pest damage. However, the evidence for plants from low plant population crops having more excess flowers than plants from high plant population crops was clear (See Figures 9 and 13). Any pollen beetle threshold should therefore take account of plant population. The winter oilseed rape experiments demonstrated that variety also had an effect on the number of excess flowers. Ideally information about the excess flower number of different varieties would be gathered during variety testing to provide information about pollen beetle tolerance as new varieties are recommended. At the moment the number of excess flowers produced by new varieties is not measured. It is proposed that the pollen beetle threshold scheme should be based on the variety with the fewest excess flowers in order to develop a scheme that does not under-estimate pest damage. Season also had a large influence on the number of excess flowers, but it was not possible to predict these effects. It is proposed that the pollen beetle threshold scheme is based on information from the season with the fewest excess flowers. This approach is justified to minimise the chance of wrongly predicting that a crop is not at risk to pollen beetle damage. Even after choosing the season and variety with fewest excess flowers the threshold scheme still generally predicts greater beetle number thresholds than the current schemes (as discussed below).

For winter oilseed rape the pollen beetle threshold scheme should be based on Castille in 2009 where the fewest excess flowers were produced (Figure 9). The threshold scheme described in Figure 14 shows that for low plant populations of 20 plants/m^2 the pollen beetle threshold would be 29 beetles per plant. This threshold would decrease to 7 beetles per plant for crops with high plant populations of 80 plants/m^2. For spring oilseed rape the pollen beetle threshold should be based on data for cvs Delight and Heros in 2010, and Delight in 2009, which had the lowest excess flower numbers. The threshold scheme described in Figure 14 shows that for low plant populations of 20 plants/m^2 the pollen beetle threshold would be 39 beetles per plant. This threshold would decrease to seven beetles per plant for crops with higher plant populations of 80 plants/m^2, which this study found to be significantly above the economic optimum plant number.

The majority of winter oilseed rape crops are likely to have plant populations of between 30 and 60 plants/m^2. The pollen beetle threshold for these crops is estimated to be between 15 and 25 beetles per plant compared with the current threshold for winter rape of 15 beetles per plant. The new threshold scheme is based on an understanding of the number of buds consumed per beetle and the relationship between plant number/m^2 and excess flowers/m^2. This has allowed the development of a dynamic method of calculating a pest threshold which is linked to the crops potential tolerance to attack. The pollen beetle threshold is no longer a single value of beetles per plant which is applicable to all crops. Instead it is a variable value which is linked to the crop’s tolerance to pest attack. This is a fundamental change in the development of pest thresholds which has potential for application to other arable pest/crop interactions, e.g. dipterous stemborers in cereals.

In some seasons the winter rape crop is beyond the susceptible green/yellow bud growth stage before pollen beetle migration is underway. This makes it increasingly unlikely that the crop will require insecticide treatment against pollen beetle. If the susceptible stage of the crop and pollen beetle migration does coincide then in the majority of crops high counts of beetles will be required to justify treatment as discussed above. Based on monitoring data, the numbers of beetles per plant will rarely if ever exceed thresholds of 15 or more per plant. Therefore for winter rape the probability that an insecticide will be needed is often low.

In spring rape beetle migration is likely to be underway when the crop reaches the susceptible stage. However, as results have indicated that spring crops are likely to be as tolerant of pollen beetle attack as winter crops, a relatively high beetle number per plant (above the current threshold of 3 per plant for spring crops of 3) is therefore required to justify insecticide treatment.

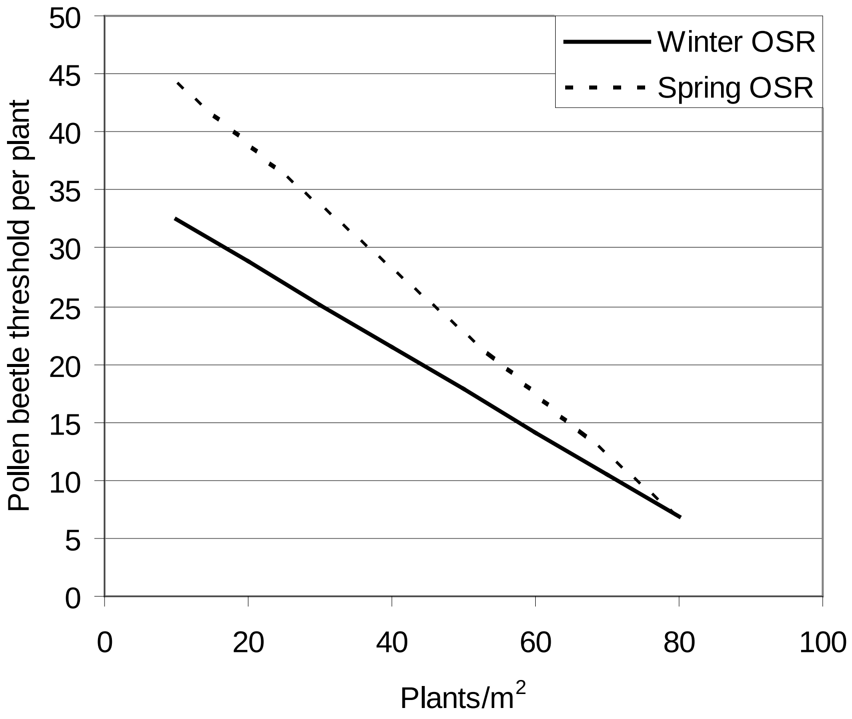


Figure 14. Pollen beetle threshold estimated based on the variety and season with the fewest excess flowers per plant. Winter oilseed rape: Castille in 2010. Spring oilseed rape: mean of Heros and Delight in 2010

Table 10. Thresholds (pollen beetle/m^2) calculated for winter oilseed rape crops at a range of seed rates over two years

Year	Variety	Seed rate (seeds/m^2)	Plant number (plants/m^2)	Excess flowers/m^2	Excess flowers per plant	Threshold pollen beetles/plant
2008/09	Castille	20	26.2	3972	152	17
	Castille	40	35.2	3832	109	12
	Castille	80	59.8	2893	48	5
	Castille	120	83	5188	63	7
	Castille	160	107.8	2848	26	3
	Excalibur	20	28.4	5574	196	22
	Excalibur	40	35.2	7264	206	23
	Excalibur	80	61.2	7106	116	13
	Excalibur	120	75.8	8039	106	12
	Excalibur	160	111.4	7111	64	7
	PR45D03	20	21.2	6283	296	33
	PR45D03	40	35.4	5991	169	19
	PR45D03	80	55.4	6031	109	12
	PR45D03	120	69.6	8966	129	14
	PR45D03	160	75	8262	110	12
2009/10	Castille	10	22.2	4443	200	22
	Castille	20	29	8542	295	33
	Castille	40	36.2	9576	265	29
	Castille	80	56	10584	189	21
	Castille	160	86.2	10936	127	14
	Excalibur	10	18.4	6510	354	39
	Excalibur	20	33.6	10498	312	35
	Excalibur	40	35.8	10054	281	31
	Excalibur	80	59.4	12652	213	24
	Excalibur	160	99.2	14087	142	16
	PR45D03	10	20.4	7870	386	43
	PR45D03	20	27.6	7239	262	29
	PR45D03	40	39.8	10084	253	28
	PR45D03	80	60.6	10961	181	20
	PR45D03	160	91.4	11371	124	14

Table 11. Thresholds (pollen beetle/m^2) calculated for spring oilseed rape crops at a range of seed rates over two years

Year	Variety	Seed rate (seeds/m^2)	Plant number (plants/m^2)	Excess flowers/m^2	Excess flowers per plant	Threshold pollen beetles/plant
2008/09	Delight	20	14.2	531	37	4
	Delight	40	26.4	3955	150	17
	Delight	80	41.0	4588	112	12
	Delight	120	54.0	5242	97	11
	Delight	200	74.4	3782	51	6
	Heros	20	15.4	9083	590	66
	Heros	40	25.4	8756	345	38
	Heros	80	42.2	8219	195	22
	Heros	120	53.4	9295	174	19
	Heros	200	74.4	10640	143	16
2009/10	Delight	20	26.6	6424	242	27
	Delight	40	36.6	3813	104	12
	Delight	80	45.0	6627	147	16
	Delight	120	59.2	6800	115	13
	Delight	200	72.6	6889	95	11
	Heros	20	23.4	6800	291	32
	Heros	40	50.2	1693	34	4
	Heros	80	48.0	5838	122	14
	Heros	120	61.6	8107	132	15
	Heros	200	61.0	7952	130	14

3.3.4. Objective 4. Validate risk predictions by comparing actual yield losses with predicted yield losses

The results of four validation sites established in 2010 are summarised in Table 12.

Pollen beetle numbers were below the current thresholds for control at 3 of 4 sites (15 beetles/plant in winter rape, 3 beetles/plant in spring rape). For the spring OSR site at Kirby Grindalythe beetle numbers were double the threshold at six per plant. Highest counts pre-treatment were at Pinchbeck, Lincolnshire where six beetles/plant were recorded. Additional counts undertaken earlier as part of Objective 5 showed even greater numbers of pollen beetles with a mean of 13.7 beetles/plant which is approximately 4.5 times the current spring rape threshold. At all sites a single spray of lambda-cyhalothrin greatly reduced pollen beetle numbers compared with pre-treatment counts. At Boxworth numbers were reduced by 89%, at Pinchbeck numbers were reduced by 98%, at Kirby Grindalythe numbers were reduced by 95% and at

Weobley numbers were reduced by 100%. The level of control suggested there was limited if any resistance at all sites. There was also little, if any recolonisation of plots.

At Boxworth and Weobley there was no statistically significant effect on yield of controlling pollen beetle. In contrast, at Pinchbeck yield was significantly increased ($P < 0.01$). Yield in the treated plots was 0.23 t/ha (6.3%) greater in the treated than untreated plots. At Kirby Grindalythe there was also a trend for a higher yield in the treated plots ($P = 0.054$). The treated yield was 0.13 t/ha or 4.4% higher than in the untreated plots.

At Kirby Grindalythe pest numbers were almost twice the current threshold of three beetles/plant in spring rape. The new threshold scheme proposed in Figure 14 suggests that the plant population of this crop must have been more than 80 plants/m^2 for six pollen beetles per plant to cause damage. The pollen beetle levels from Pinchbeck on winter oilseed rape were below the current threshold, yet yield losses were observed. The new threshold proposed in Figure 14 indicates that if the plant population was greater than 80 plants/m^2, then yield losses may be expected from this level of pollen beetles.

Table 12. Pollen beetle numbers and crop yield at validation sites in winter and spring rape in 2010

Site	Cv	Pollen beetle numbers/plant			Yield t/ha @ 91% DM		Probability	SED 8df
		Pre-treatment	3-5 days post-treatment		Untreated	Treated		
			Untreated	Treated				
Winter OSR								
Boxworth, Cambs	D03	4.7	3.8	0.5	2.14	2.14	NS, 0977	0.126
Pinchbeck Lincs	Bravour	6.0	3.4	0.1	3.65	3.88	P<0.01,**	0.063
Spring OSR								
Kirby Grindalythe, North Yorkshire		5.8	1.3	0.3	2.98	3.11	NS, 0.054	0.060
Weobley, Herefordshire	Castille	0.9	0.3	0	3.28	3.22	NS, 0.820	0.246

Pruning experiments

In sub-plots in the winter and spring variety x seed rate experiments in 2009/2010, either half or all of buds were pruned from the main stems of each plant at the green bud stage in an attempt to imitate the effect of severe pollen beetle damage confined to the terminal raceme. Just before harvest the pod number, pod weight and seed weight were measured within the pruned and unpruned areas of each plot.

In the winter oilseed rape experiment pruning did not affect the number of pods/m^2 with 4876 pods/m^2 in the unpruned areas and 5025 pods/m^2 in the treatment in which all the buds of the main stems had been pruned (Table 13). Pruning significantly reduced the seed yield with on average 323 g/m^2 in the unpruned treatments, 260 g/m^2 in the half pruned treatments and 228 g/m^2 in the fully pruned plots. There was no indication that either variety or seed rate modified the pruning effect on seed weight. Increasing seed rate from 20 to 160 seeds/m^2 reduced seed weight from 288 to 258 g/m^2. The seed weights measured from quadrat sampling were consistent in terms of rank order for the seed rate treatments, but were about 15% less than the yields estimated from the whole plot using a small plot combine (after accounting for differences in seed moisture content), which suggests some seed may have been lost during sampling and processing the plants from the quadrats. Pruning significantly increased the weight of the pod walls from 307 g/m^2 for unpruned to 427 g/m^2 for half pruning to 464 g/m^2 for the fully pruned treatments. Increasing seed rate significantly reduced the pod wall dry weight. It is interesting that increased seed rate reduced the weight of both the seed and pod wall, whereas greater pruning reduced the weight of the seed but increased the weight of the pod wall.

In the spring oilseed rape experiment pruning did not affect the number of pods/m^2 with 4278 pods/m^2 in the unpruned areas and 3978 pods/m^2 in the treatment in which all the buds of the main stems had been pruned (Table 14). Heros had significantly more pods than Delight. Pruning half of the buds significantly increased the seed weight from 288 to 330 g/m^2, with no effect from the fully pruned treatment. There was no indication that either variety or seed rate modified the pruning effect on seed weight. Heros had a greater seed weight than Delight which was not consistent with the combine yields, although the seed weights measured from the quadrat sampling were similar in size. Pruning did not affect the weight of the pod wall, apart from at the greatest seed rate treatment for which pruning appeared to cause an increase.

Previous unpublished work by ADAS has shown that terminal racemes may produce up to 100 flowers for typical plant populations of 30 to 50 plants/m^2. It is likely that lower plant populations will produce more flowers per terminal raceme and higher plant populations will produce fewer flowers. Pruning the main buds is therefore expected to have reduced the number of flowers per plant by approximately 100. Table 10 shows that the winter oilseed rape experiment that the pruning treatments were carried out on produced 262-354 excess flowers per plant at 20 seeds/m^2, 181-213 excess flowers per plant at 80 seeds/m^2 and 124-142 excess flowers per plant at 160 seeds/m^2. Therefore it would have been expected that the plants could have withstood the loss of 100 flowers without losing yield, whereas in fact they did lose yield. Table 14 shows that the spring oilseed rape seed rate treatments had a similar number of excess flowers to the winter oilseed rape experiment. However, in this experiment the same levels of pruning did not result in any loss of yield.

Several factors may have caused the yield losses observed from pruning in the winter oilseed rape experiment. For example, this may indicate that winter oilseed rape is less tolerant to losing the first formed flowers than later formed flowers. This hypothesis seems unlikely given that there was no yield loss from pruning the main bud in the spring oilseed rape experiments and the yield of spring oilseed rape relies more heavily on the main bud because it has a shorter developmental period in which to develop compensatory branches. The idea that spring oilseed rape produces fewer compensatory branches is supported by the observation that spring oilseed rape had a greater optimum plant number than winter oilseed rape. It is possible that environmental conditions in the winter oilseed rape experiment prevented the later formed pods from setting as many seeds. Estimates for the soil moisture deficit at this site made using the ‘IRRIGUIDE’ model estimate that the soil moisture deficit reached 100mm on 23 May and remained about 100mm until early July when it was 140 mm. If it is assumed that drought stress occurs at 100mm then it is clear that this site was under increasing drought stress during the pod development and seed filling period which may have limited the crop’s ability to fill the later formed pods on the pruned treatments. An alternative hypothesis is that removing the entire top of the raceme may have caused greater damage to the plant than simply removing individual flower buds as the pollen beetles do. It is noticeable that even after quite severe pollen beetle damage the terminal raceme continues to produce new flowers and it is very rare that it produces no pods at all. Differences in pruning technique between the sites may have resulted in greater damage in the winter oilseed rape experiment compared with the spring oilseed rape experiment. Future pruning treatments should snip a proportion of flowers after they have opened in order to replicate pollen beetle damage more accurately.

Table 13. Winter oilseed rape 2009/10. Effect of pruning the main stem buds at GS3.5 from half or all of the plants. All crop weights at 100% dry matter.

Variety	Seed rate (seeds/m^2)	Pruning	Pods/m^2	Pod wall dry weight (g/m^2)	Seed dry weight (g/m^2)
Castille	20	Control	5313	365	317
Castille	20	Half	5180	588	301
Castille	20	All	4716	484	216
Castille	80	Control	5375	295	293
Castille	80	Half	5517	457	219
Castille	80	All	5621	498	246
Castille	160	Control	5062	267	267
Castille	160	Half	5291	475	221
Castille	160	All	5558	451	193
Excalibur	20	Control	5305	323	414
Excalibur	20	Half	3864	361	248
Excalibur	20	All	4874	440	185
Excalibur	80	Control	4671	331	327
Excalibur	80	Half	4622	410	286
Excalibur	80	All	4813	443	239
Excalibur	160	Control	4706	312	310
Excalibur	160	Half	3890	318	236
Excalibur	160	All	4792	407	241
PR45 D03	20	Control	4676	347	355
PR45 D03	20	Half	4689	445	305
PR45 D03	20	All	5120	524	255
PR45 D03	80	Control	4582	250	294
PR45 D03	80	Half	4258	397	252
PR45 D03	80	All	4445	447	222
PR45 D03	160	Control	4189	274	329
PR45 D03	160	Half	4144	388	274
PR45 D03	160	All	5288	484	253
Castille	Mean	Mean	5292	431	253
Excalibur	Mean	Mean	4615	372	276
PR45 D03	Mean	Mean	4599	395	282
Mean	20	Mean	4860	431	288
Mean	80	Mean	4878	392	264
Mean	160	Mean	4769	375	258
Mean	Mean	Control	4876	307	323
Mean	Mean	Half	4606	427	260
Mean	Mean	All	5025	464	228
SED					
Variety (6 df)			407.2	45.6	23.6
Seed rate (18 df)			201.1	20.8 *	9.5 *
Pruning (6 df)			172.2	18.4 ***	17.8 **
Variety x Seed rate (12 df)			495.9	54.3	27.1 †
Variety x Pruning (15 df)			537.6	52.7 *	32.3
Seed rate x Pruning (49 df)			356.7	34.7	24.1
Variety x Seed rate x Pruning (49 df)			774.2	73.3	43.8

Table 14. Spring oilseed rape 2009/10. Effect of pruning the main stem buds at GS 3.5 from half or all of the plants. All crop weights at 100% dry matter.

Variety	Seed rate (seeds/m^2)	Pruning	Pods/m^2	Pod wall dry weight (g/m^2)	Seed dry weight (g/m^2)
Delight	20	Control	3964	338	361
Delight	20	Half	3767	314	270
Delight	20	All	3927	267	256
Delight	80	Control	3233	243	237
Delight	80	Half	3577	277	303
Delight	80	All	2719	219	260
Delight	200	Control	2155	150	185
Delight	200	Half	3180	250	273
Delight	200	All	3335	287	296
Heros	20	Control	4752	338	254
Heros	20	Half	5014	425	363
Heros	20	All	4562	324	335
Heros	80	Control	5674	441	323
Heros	80	Half	5298	427	389
Heros	80	All	4322	330	296
Heros	200	Control	4204	286	249
Heros	200	Half	4535	366	293
Heros	200	All	4188	311	300
Delight	Mean	Mean	3317	261	271
Heros	Mean	Mean	4766	365	314
Mean	20	Mean	4331	334	307
Mean	80	Mean	4137	323	301
Mean	160	Mean	3600	275	266
Mean	Mean	Control	4278	333	288
Mean	Mean	Half	4072	328	330
Mean	Mean	All	3978	307	277
SED					
Variety (14 df)			233.1 ***	21.2 ***	18.8 *
Seed rate (14 df)			285.5 †	26.0	23.1
Pruning (6 df)			339.4	37.7	13.4 *
Variety x Seed rate (14 df)			403.7	36.7	32.6
Variety x Pruning (13 df)			424.4	44.5	25.3
Seed rate x Pruning (19 df)			478.1 *	49.2 *	32.0
Variety x Seed rate x Pruning (32 df)			611.5	61.3	46.6 *

3.3.5. Objective 5. Investigate pollen beetle distribution in the field as an aid to assessing pest numbers

A total of 28 sites at a range of locations in England and Wales, were assessed over the life of the study to investigate the distribution of pollen beetles in the field (Table 15). The mean numbers of pollen beetles recovered from 0-25 m, 26-50 m, 51-75 m and 76-100 m at both green and yellow bud are summarised in Table 16.

Table 15. Location of sites for assessment of pollen beetle distribution in the field

Site	County
Duggleby 1	North Yorkshire
Duggleby 2	North Yorkshire
Sutton Bridge	Lincolnshire
Brawby	North Yorkshire
Carnaby	East Yorkshire
Thorneholme	East Yorkshire
Grindale	East Yorkshire
Deeping St Nicholas	Lincolnshire
Barton	North Yorkshire
Eddlethorpe	North Yorkshire
Ryton	North Yorkshire
Rillington	North Yorkshire
Towthorpe	East Yorkshire
Whaplode St Catherine 1	Lincolnshire
Whaplode St Catherine 2	Lincolnshire
Pinchbeck 1	Lincolnshire
Pinchbeck 2	Lincolnshire
Boxworth 1	Cambridgeshire
Boxworth 2	Cambridgeshire
Boxworth 3	Cambridgeshire
Fawley Court	Herefordshire
Weobley 1	Herefordshire
Weobley 2	Herefordshire
Preston Wynne	Herefordshire
Kings Capel	Herefordshire

Table 16. Mean numbers of pollen beetles recovered at 0-25, 26-50, 51-75 and 76-100 m from the edge of the field at both green and yellow bud

Site		Distance from field edge (m)				Probability
		Headland 0-25 m	26-50 m	51-75 m	76-100 m	
Green bud						
Barton	2010	-	-	-	-	-
Boxworth 1	2010	5.3	2.9	3.0	3.5	0.279, NS
Boxworth 2	2010	4.8	4.2	3.7	4.0	0.879, NS
Boxworth 3	2010	10.4	11.3	5.8	7.1	0.142, NS
Brawby	2009	1.6	1.0	2.2	2.0	0.671, NS
Canon Pyne	2010	0.7	0.4	0.4	0.5	0.833, NS
Carnaby	2009	0.7	0.9	0.7	0.5	0.116, NS
Deeping St Nicholas	2009	1.3	1.3	1.4	1.3	0.998, NS
Duggleby 1	2008	0.5	0.7	0.6	0.5	0.853, NS
Duggleby 2	2008	0.5	0.7	0.4	0.7	0.887, NS
Eddlethorpe	2010	5.6	5.5	3.9	6.9	0.473, NS
Fawley Court	2010	1.2	2.3	2.9	5.0	0.232, NS
Grindale	2009	0.7	0.9	0.7	0.5	0.116, NS
Kings Capel	2010	0.8	1.1	1.1	0.7	0.827, NS
Pinchbeck 1	2010	19.1	16.2	9.1	11.1	0.145, NS
Preston Wynne	2010	0.6	0.7	1.7	0.8	0.323, NS
Rillington	2010	2.1	2.3	1.6	1.9	0.834, NS
Ryton	2010	2.4	1.8	1.7	1.9	0.712, NS
Sutton Bridge	2009	1.5	1.2	1.1	0.7	0.174, NS
Sutton Bridge	2010	2.2	4.0	3.8	2.8	0.181, NS
Thornholme	2009	0.9	0.5	0.5	0.5	0.440, NS
Thornholme	2010	2.4	1.3	1.9	1.0	0.251, NS
Towthorpe	2010	2.3	3.0	2.3	2.4	0.942, NS
Weobley 1	2010	0.4	0.2	0.5	0.2	0.524, NS
Weobley 2	2010	0	0.5	0.3	0.2	0.312, NS
Whaplode St Catherine 1	2010	6.9	9.2	3.5	6.3	<0.05*
Whaplode St Catherine 2	2010	3.6	4.2	3.4	5.5	0.189, NS
Average		**3.02**	**3.01**	**2.24**	**2.63**	NS

Table 16 cont'd

Site		Distance from field edge (m)				Probability
		Headland 0-25 m	26-50 m	51-75 m	76-100 m	
Yellow bud						
Barton	2010	0.2	0	0.3	0.1	0.376, NS
Boxworth 1	2010	4.0	3.8	3.0	2.9	0.329, NS
Boxworth 2	2010	0.2	0.7	0.3	0.7	0.310, NS
Boxworth 3	2010	9.3	8.4	7.4	7.7	0.314, NS
Brawby	2009	1.6	0.9	2.3	0.8	0.113, NS
Canon Pyne	2010	0.6	0.4	0.9	0.9	0.093, NS
Carnaby	2009	0.3	0.4	0.2	0.2	0.672, NS
Deeping St Nicholas	2009	1.12	2.0	1.8	1.2	0.410, NS
Duggleby 1	2008	0.9	0.8	0.6	0.3	0.231, NS
Duggleby 2	2008	0.3	0.4	0.5	0.6	0.828, NS
Eddlethorpe	2010	Not assessed*				
Fawley Court	2010	1.9	3.0	2.2	2.7	0.603, NS
Grindale	2009	0	0	0	0.1	0.088, NS
Kings Capel	2010	0.9	1.3	1.5	1.5	0.307, NS
Pinchbeck 1	2010	10.0	10.8	9.7	10.6	0.944, NS
Preston Wynne	2010	0.4	1.4	1.2	1.0	0.476, NS
Rillington	2010	2.2	2.4	2.0	2.9	0.612, NS
Ryton	2010	0.1	0	0.2	0.1	0.591, NS
Sutton Bridge	2009	1.3	0.9	0.9	0.6	0.425, NS
Sutton Bridge	2010	4.3	3.1	2.5	2.7	0.204, NS
Thornholme	2009	0.3	0.2	0.3	0	0.274, NS
Thornholme	2010	Not assessed*				
Towthorpe	2010	2.5	3.4	2.0	1.9	0.448, NS
Weobley 1	2010	0.9	1.1	1.3	1.8	0.225, NS
Weobley 2	2010	0.1	0.2	0.5	0.2	0.677, NS
Whaplode St Catherine 1	2010	6.1	6.8	4.2	4.9	0.185, NS
Whaplode St Catherine 2	2010	5.4	4.1	3.7	4.9	0.277, NS
Average		**2.20**	**2.26**	**1.98**	**2.05**	NS

* Host farmer applied an insecticide between green and yellow bud

Numbers of pollen beetle only differed significantly (P <0.05) between distances at Whaplode St Catherine 1 at the green bud assessment. At this site beetles were most numerous 26-50 m from the edge of the field. At all other sites at all other assessments there was no significant difference in pollen beetle numbers between distances from the edge of the field. Across all sites, there were trends for more pollen beetles at the edge of the field with at green bud an average of 3.02 beetles per plant in the first at 0 to 25m compared with 2.24 beetles per plant between 50 and 75m (Table 15). However, a paired t-test (two-tailed) across all sites showed that this difference was not statistically significant at green or yellow bud (Table 16).

The results of a second series of analyses undertaken on beetle numbers 0-50 m and 51-100 m from the edge of the field are summarised in Table 17.

These data confirmed the results of the previous analyses with no significant difference in beetle numbers between 0-50 and 51-60 m from the edge of the field at individual sites, except at Brawby in 2009 where most beetles were recorded between 51 and 100 m from the edge of the field. There were more beetles from 0-50 m than from 51-100 m in 35 of 51 assessments although differences between the counts were often small. At green bud there was an average of 3.03 beetles per plant in the 0 to 50 m region compared with 2.38 in the 51 to 100 m region. At yellow bud there was an average of 2.52 beetles per plant in the 0 to 50 m region compared with 2.22 in the 51 to 100 m region. These differences were statistically significant (P<0.05, paired two-tailed 'T-test').

The results of a simple non-parametric analysis in which the number of pollen beetle at either 0-25 m, 26-50 m, 51-75 m and 76-100 m from the edge of the field were ranked (highest count = 1, lowest count = 4) across all sites at both green and yellow bud are shown in Table 18 and Figures 15 and 16.

Overall beetle numbers at 0-25, and 26-50 m from the edge of the field were ranked first or second more often than numbers 51-75 m and 76-100 m from the edge. This result supports the analyses comparing beetle numbers 0-50 m from the edge of the crop with 51-100 m from the edge of the crop.

Table 17. Mean numbers of pollen beetles recovered from 0-50 and 51-100 m from the edge of the field at both green and yellow bud

Site		Distance from edge of field (m)		Probability
		0-50	51-100	
Green bud				
Barton	2010	-	-	-
Boxworth 1	2010	3.7	3.2	0.556, NS
Boxworth 2	2010	4.4	3.9	0.583, NS
Boxworth 3	2010	10.9	6.4	0.094, NS
Brawby	2009	1.3	2.1	0.515, NS
Canon Pyne	2010	0.5	0.4	0.857, NS
Carnaby	2009	0.8	0.6	0.239, NS
Deeping St Nicholas	2009	1.3	1.3	0.927, NS
Duggleby 1	2008	0.7	0.5	0.736, NS
Duggleby 2	2008	0.6	0.5	0.789, NS
Eddlethorpe	2010	5.6	5.4	0.937, NS
Fawley Court	2010	1.9	3.9	0.204, NS
Grindale	2009	0.1	0.1	0.638, NS
Kings Capel	2010	1.0	0.9	0.818, NS
Pinchbeck 1	2010	17.4	10.0	0.169, NS
Preston Wynne	2010	0.7	0.5	0.323, NS
Rillington	2010	2.3	1.8	0.627, NS
Ryton	2010	2.1	1.8	0.446, NS
Sutton Bridge	2009	1.3	0.9	0.135, NS
Sutton Bridge	2010	3.3	3.1	0.781, NS
Thorneholme	2009	0.7	0.5	0.487, NS
Thorneholme	2010	1.7	1.4	0.469, NS
Towthorpe	2010	2.7	2.3	0.717, NS
Weobley 1	2010	1.2	1.3	0.763, NS
Weobley 2	2010	0.3	0.3	0.638, NS
Whaplode St Catherine 1	2010	8.3	4.9	0.068, NS
Whaplode St Catherine 2	2010	4.0	3.9	0.923, NS
Average		**3.03**	**2.38**	<0.05*

Table 17 cont'd

Site		Distance from edge of field (m)		Probability
		0-50	51-100	
Yellow bud				
Barton	2010	1.0	1.8	0.058, NS
Boxworth 1	2010	3.9	2.9	0.294, NS
Boxworth 2	2010	5.0	4.5	0.783, NS
Boxworth 3	2010	8.8	7.5	0.293, NS
Brawby	2009	1.2	2.0	<0.05*
Canon Pyne	2010	0.5	0.9	0.073, NS
Carnaby	2009	0.4	0.2	0.340, NS
Deeping St Nicholas	2009	1.6	1.5	0.848, NS
Duggleby 1	2008	0.9	0.4	0.226, NS
Duggleby 2	2008	0.4	0.5	0.555, NS
Eddlethorpe	2010	Not assessed		
Fawley Court	2010	2.3	2.4	0.892, NS
Grindale	2009	0	0.1	0.182, NS
Kings Capel	2010	1.1	1.5	0.147, NS
Pinchbeck 1	2010	10.5	10.1	0.863, NS
Preston Wynne	2010	1.0	1.1	0.664, NS
Rillington	2010	2.3	2.4	0.734, NS
Ryton	2010	0.5	1.3	0.547, NS
Sutton Bridge	2009	1.0	0.7	0.464, NS
Sutton Bridge	2010	3.6	2.6	0.163, NS
Thorneholme	2009	0.2	0.1	0.474, NS
Thorneholme	2010	Not assessed		
Towthorpe	2010	3.0	2.0	0.340, NS
Weobley 1	2010	2.3	0.3	0.789, NS
Weobley 2	2010	0.2	0.4	0.213, NS
Whaplode St Catherine 1	2010	6.5	4.5	0.145, NS
Whaplode St Catherine 2	2010	4.6	3.8	0.502, NS
Average		**2.51**	**2.22**	<0.05*

Table 18. Ranking of pollen beetle counts at 0-25 m, 26-50 m, 51-75 m and 76-100 m from the edge of the field at green and yellow bud across all sites (Ranking 1 = highest count, ranking 4 = lowest count)

Ranking		Ranking of distances from edge of field			
		0-25 m	26-50 m	51-75 m	76-100 m
Green bud	1	8	10	3	5
	2	5	7	8	6
	3	6	5	4	9
	4	7	4	11	6
Yellow bud	1	9	6	8	5
	2	7	7	3	4
	3	5	7	8	7
	4	4	5	6	9

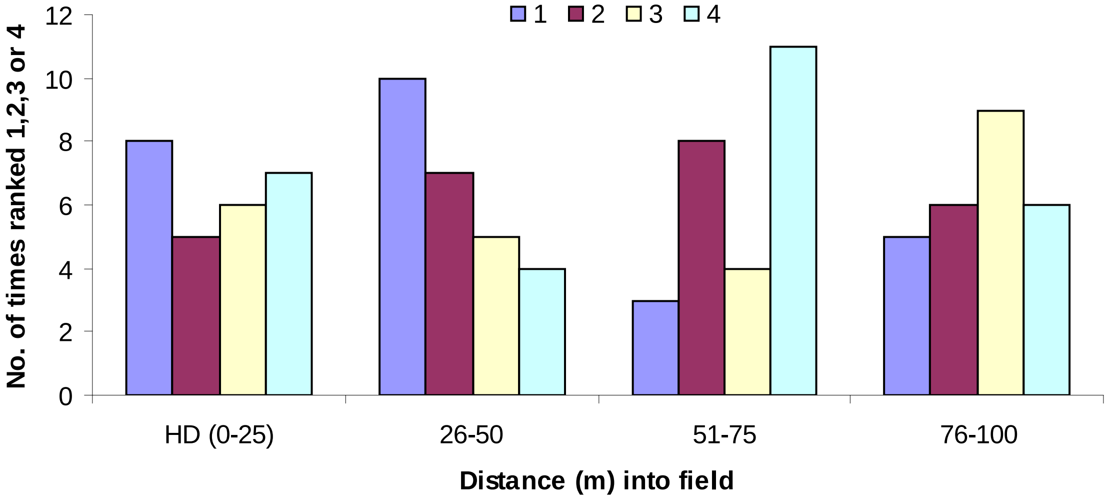


Figure 15. Ranking of pollen beetle counts at four distances into the crop at green bud over all assessed sites

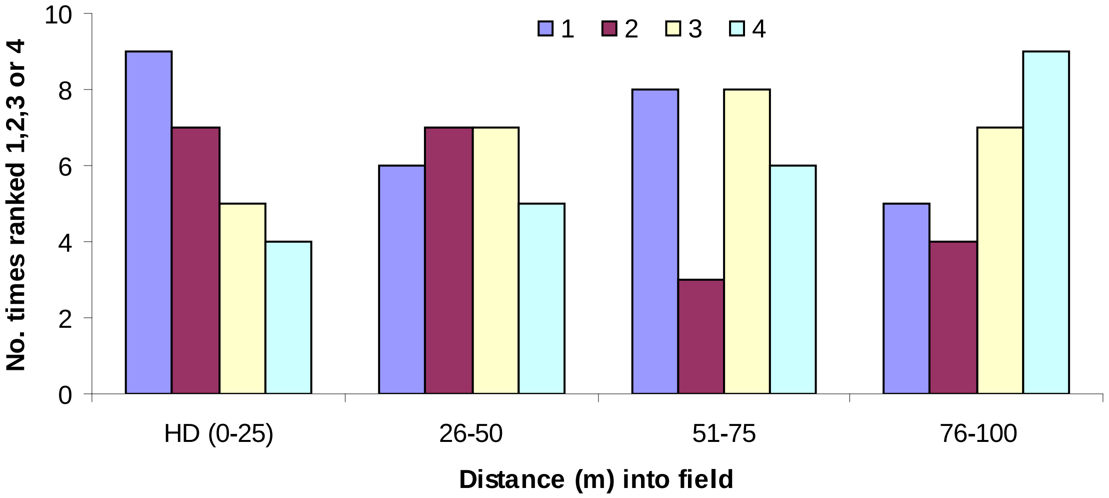


Figure 16. Ranking of pollen beetle counts at four distances into the crop at yellow bud over all assessed sites

The mean numbers of pollen beetles recovered from north, east, south or west transects from 22 of 28 sites at green and yellow bud are summarised in Table 18.

Beetle numbers differed significantly between compass points at eight sites at green bud and seven sites at yellow bud. However, there was no consistent trend to find most beetles at a particular compass point. Over all sites a paired two-tailed 'T test' showed that significantly more beetles were found on the southern compared to the northern or eastern transects (P<0.05).

A simple non-parametric analysis was also conducted in which the mean number of pollen beetles at each compass point were ranked (1 = highest count, 4 = lowest count) at both green and yellow bud (Table 19 and Figures 17 and 18). At green bud there was a trend to find most pollen beetles in the southern transect. This transect ranked first or second on 16 occasions in comparison with eight occasions for the northern transect and nine occasions for the eastern and western transects. These data support the paired 'T-test' data on the original counts. At yellow bud the differences between the compass points were far less marked with the northern transect ranking first or second on 12 occasions compared with 11, 9 or 9 occasions for the eastern, southern and western transects respectively.

Table 19. Mean numbers of pollen beetles recovered at north, east, south and west transects at both green and yellow bud

Site	North	East	South	West	Probability
Green bud					
Boxworth 1 2010	2.4	3.9	5.2	3.2	0.222, NS
Boxworth 2 2010	2.9	3.9	5.0	4.9	0.439, NS
Boxworth 3 2010	7.0	6.6	11.1	9.8	0.263, NS
Brawby 2009	0.8	1.2	3.1	1.7	0.175, NS
Canon Pyon 2010	0.7	0.3	0.7	0.3	0.563, NS
Carnaby 2009	0.3	0.6	1.5	0.3	<0.001, ***
Crow Wood 2008	1.1	0.4	0.5	0.3	0.102, NS
Deeping St Nicholas 2009	1.1	0.4	1.2	2.5	<0.05, *
Fawley Court 2010	2.4	1.6	4.0	3.4	0.546, NS
Grindale 2009	0.6	0.3	1.5	0.3	<0.001, ***
Homefield 2009	0.4	0.9	0.5	0.4	0.462, NS
Kings Capel 2010	0.9	1.2	0.6	1.1	0.650, NS
Pinchbeck 2010	15.3	5.7	14.5	20.0	<0.05, *
Preston Wynne 2010	0.4	0.9	0.3	2.2	<0.05, *
Sutton Bridge 2009	0.7	1.4	1.6	0.7	0.069, NS
Thornholme 2009	1.3	0.6	0.2	0.3	<0.05, *
Sutton Bridge 2010	4.2	1.3	5.0	2.3	<0.01, **
Weobley 1 2010	1.5	0.9	1.3	1.3	0.590, NS
Weobley 2 2010	0.2	0.7	0.1	0.1	0.104, NS
Whaplode St Catherine 1 2010	5.0	1.5	9.6	9.8	<0.001, ***
Whaplode St Catherine 2 2010	3.4	5.4	4.9	2.9	0.088, NS
Average	**2.5**	**1.9**	**3.4**	**3.2**	**<0.05***
Yellow bud					
Boxworth 1 2010	2.1	5.1	3.9	2.6	<0.01 **
Boxworth 2 2010	0.3	0.5	0.4	0.6	0.842, NS
Boxworth 3 2010	9.1	6.6	11.1	6.1	<0.01, **
Brawby 2009	1.0	2.0	2.6	1.0	<0.05, *
Canon Pyon 2010	0.7	0.8	0.2	1.0	<0.05, *
Carnaby 2009	0.2	0.2	0.6	0.1	0.096, NS
Crow Wood 2008	0.9	0.8	0.5	0.3	0.340, NS
Deeping St Nicholas 2009	2.5	0.9	1.2	1.6	0.092, NS
Fawley 2010	1.5	4.4	3.2	0.7	<0.01, **
Grindale 2009	0	0.1	0.1	0	0.436, NS
Homefield 2009	0.7	0.5	0.3	0.3	0.334, NS
Kings Capel 2010	1.8	1.2	0.9	1.3	0.118, NS
Pinchbeck 2010	12.5	5.4	7.2	15.9	<0.01, **
Preston Wynne 2010	1.4	0.9	0.7	1.1	0.737, NS
Sutton Bridge 2009	0.5	0.8	0.8	1.6	0.077, NS
Sutton Bridge 2010	4.5	3.3	2.9	2.4	0.075, NS
Thorneholme 2009	0.2	0.2	0.1	0.3	0.439, NS
Weobley 1 2010	0.4	0.3	0.2	0.3	0.524, NS
Weobley 2 2010	0.1	0.8	0.1	0.1	0.109, NS
Whaplode St Catherine 2010	6.4	2.1	9.9	3.5	<0.001, ***
Whaplode St Catherine 2010	4.1	4.4	5.0	4.5	0.753, NS
Average	**2.4**	**2.0**	**2.5**	**2.2**	

Table 20. Ranking of pollen beetle counts at the north, east, south and west transects at green and yellow bud over all assessed sites

Ranking		Ranking of transects			
		North	East	South	West
Green bud	1	4	4	9	4
	2	4	5	7	5
	3	9	4	1	6
	4	4	8	3	6
Yellow bud	1	7	4	6	5
	2	5	7	3	4
	3	3	7	6	4
	4	5	3	6	8

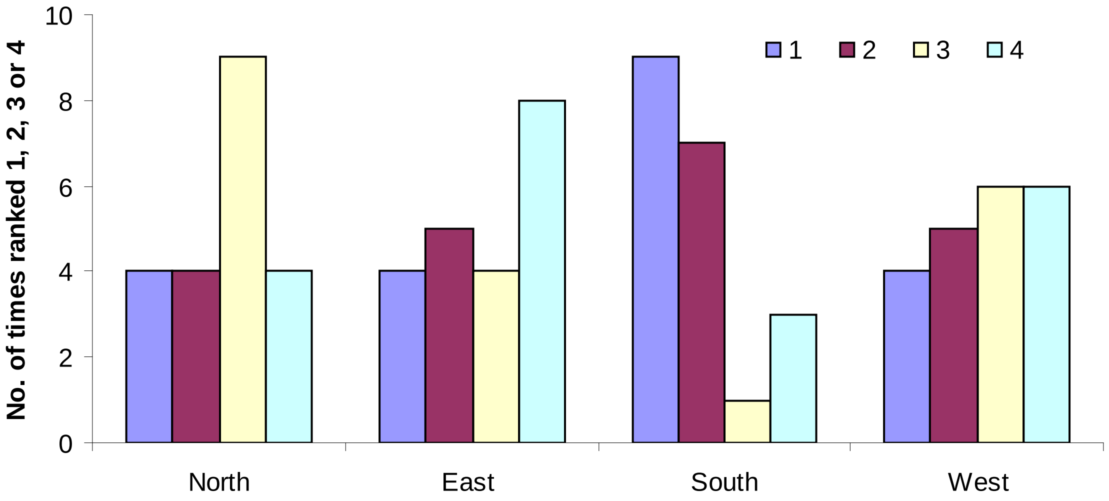


Figure 17. Ranking of pollen beetle counts at the north, east, south and west transects over all assessed sites at green bud.

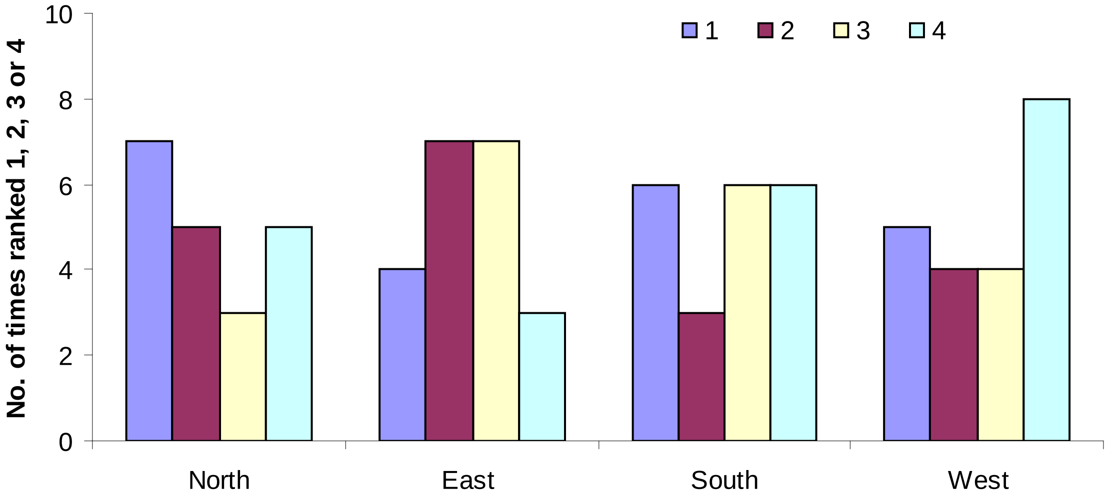


Figure 18. Ranking of pollen beetle counts at the north, east, south and west transects over all assessed sites at yellow bud.

In summary, assessments made closer to the headland were shown generally to record higher numbers of pollen beetle than those further from the headland. It should be emphasised that whilst there was a trend to find more beetles at the edge of fields (when all sites were compared together) the differences were less than one beetle per plant and are therefore unlikely to make a significant difference to the decision about whether or not to apply an insecticide. At green bud there was a trend to find most beetles on the southern transect. This was no longer evident by the time the crop had reached yellow bud when there was little difference in the number of beetles found on each transect

3.4. Discussion

The overall objective of this project was to investigate the potential to develop new thresholds for pollen beetle in oilseed rape, with the aim of minimising unnecessary applications of pyrethroid insecticides to the crop. This has a number of benefits, firstly, to minimise the environmental impact of insecticide use in oilseed rape, secondly to safeguard natural enemies of pest species and finally to limit the potential spread of resistance to insecticides generally, and to synthetic pyrethroids in particular, in pollen beetle populations. A novel approach has been investigated in which the tolerance of oilseed rape to pest attack forms the basis of threshold development. This approach recognises that an assessment of crop tolerance is fundamental in determining the susceptibility of the crop to pest attack, and ultimately the number of pests that are required to reduce crop yield. The project hypothesises that oilseed rape produces far more buds/flowers than are required to achieve the optimum pod number for maximum yield, and that these excess flowers can be sacrificed to pollen beetle before there is any impact on crop yield. A discussion of the work associated with each project objective follows, together with recommendations for the industry and suggestions for further research.

3.4.1. Objective 1 To quantify bud loss resulting from pollen beetle attack

An understanding of the number of oilseed rape buds potentially damaged by pollen beetle attack is fundamental to the development of revised thresholds for this pest. To assess this in the field would be particularly difficult and costly as it requires work to be undertaken on a number of crops with a range of pollen beetle numbers both below and above the current thresholds. Bearing in mind that mean pollen beetle numbers in winter oilseed rape have not exceeded 6/plant over the last 20 years, it was decided to use pot grown rape plants which could be inoculated with a controllable range of pollen beetle numbers. A further advantage of using pot grown plants was that pollen beetle inoculation rates could be replicated and so improve the precision with which their effect on the crop could be assessed. Beetles needed to be confined to pots, so it was important to determine whether this had any impact on beetle survival.

In 2008, mean survival of beetles confined to pots was approximately 88%, suggesting that the pests were able to feed normally on oilseed rape buds. Using the relationship between number of inoculated beetles and buds lost per beetle it was calculated that on average each pollen beetle consumed/damaged nine buds. In a repeat study in 2009, the same relationship suggested that each pollen beetle consumed/damaged 7.5 buds. Therefore data from both years were in close agreement as regards the potential loss of buds per beetle. One potential area of uncertainty was that beetle survival was only 33.5% in 2009, however it seems likely that the majority of the damage would be done soon after inoculation before the flowers opened and when most of the beetles were alive, so basing the relationship for number of buds destroyed per beetle on the inoculated beetle numbers seems reasonable. so it is difficult to be precise about the numbers of beetles that were present at the time the buds were damaged. Consequently the 2008 dataset was used to provide the most reliable estimate of pods lost due to pollen beetle feeding/egg laying (nine buds/beetle).

3.4.2. Objective 2 To quantify the relationship between early canopy size, flower number and the number of viable pods set in conventional varieties, restored hybrids and a semi-dwarf variety.

The hypothesis behind this objective was that oilseed rape produces more buds and flowers (excess flowers) than are required to achieve optimum pod number for maximum yield. Therefore, this objective set out to determine if this was the case and also to quantify the potential impact of a range of variables on excess flower numbers. Analysis of existing data sets from LINK project OS49 “Canopy management in oilseed rape” showed that in 1996 and 1997 neither early (last week August to 1st week September) or late sowing (last week September) or seed rates of 60 or 120 seeds/m^2 had any significant effect on excess flower number. Also excess flower number did not differ significantly between three rates of N fertiliser application (0, 100 and 200 kg N/ha). Comparison of excess flower numbers between varieties in 2007/08 showed there was no consistent trend for hybrid, semi-dwarf or late developing varieties to produce significantly less excess flowers than open pollinated varieties. Any differences in excess flower number were due to the specific variety and not variety type. Field experiments in 2008/09 and2009/10 produced contrasting results in terms of the effect of treatments on excess flower number. In 2008/09 excess flower number in winter oilseed rape differed significantly between variety and not seed rate, whereas the opposite was true in 2009/10. Similarly, in spring oilseed rape excess flower number differed significantly between varieties in 2008/09 but not between seed rates, whereas in 2009/10 seed rate had an effect on excess flower number but not variety.

Spring crops produced as many excess flowers as winter rape crops. This is interesting in view of the perceived increased susceptibility of spring rape to pollen beetle in comparison with the winter crop, and suggests that the current threshold for the spring crop is too low. Also, assessment of excess flower numbers suggest that claims that hybrid varieties are at greater risk from pollen beetle than conventional open pollinated varieties are misguided. There is no indication from excess flower numbers that any distinction should be drawn between variety types in terms of susceptibility to pollen beetle attack, although it was shown that excess flower number does vary for specific varieties. Pollen beetle thresholds are currently lower for so called backward/thin crops, as it is believed that they have limited ability to compensate for pest attack. This appears to be untrue, as crops sown at only 20-25plants/m^{2}were shown to produce a significant number of excess flowers. Indeed crops with low plant populations/m^{2}generally had more excess flowers/plant than more densely populated crop. However, it should be emphasised that it is not known whether small crops caused by pigeon grazing also produce a similar number of excess flowers to ungrazed crops.

Therefore, over all field experiments there were no trends for nitrogen fertiliser to have a consistent affect on excess flower number, but there was a strong effect for crops with lower plant populations to have more excess flowers per plant, and in winter crops Castille tended to have fewer flowers per plant than Excalibur and PR45D03. There was no consistent difference between the two spring OSR varieties. Excess flower number did vary from season to season, but there appeared to be no reliable method for predicting these changes. Changes in excess flower number per plant due to variations in plant population data could be predicted from GAI or plant populations/m^2. Plant population gave better prediction for spring oilseed rape. GAI is currently assessed in early spring to help optimise nitrogen fertiliser applications. Relationships linking plant population or GAI with excess flower number could potentially be used, in conjunction with information about how many buds a beetle can destroy, to predict a crop's tolerance to pollen beetle.

3.4.3. Objective 3 Use information from objectives 1 and 2 to develop methods for predicting the risk of yield loss from pollen beetle damage based on variety type and size of crop

Field experimentation has shown that oilseed rape crops produce more flowers than pods, and so there is an excess number of flowers relative to the final pod number. Objective 1 showed that on average an individual pollen beetle will destroy nine buds. Objective 2 measured excess flower number for a range of winter and spring rape varieties. Therefore, dividing excess flower number/m^2 by 9 will give the number of pollen beetles needed per m^2 to destroy that reservoir of excess buds/flowers. If the plant population/m^2 is known, then the “threshold” in terms of numbers of pollen beetle/plant can be calculated.

These calculations show that the threshold can vary significantly depending on plant population, and also that variety and season can have strong effects. Interestingly it was shown that crops with fewer plants/m^2 had a greater pollen beetle threshold because they had more excess flowers. The concept of the threshold having a sliding scale rather than a specific value is very different from the pest management strategies adopted currently in most arable crops. However, if thresholds are to be related to the crops ability to tolerate pest attack, then it is logical that the number of pests required to reduce yield will vary. Decisions on the need to control pests should be made on an individual crop basis and this greatly increases the potential to rationalise pesticide use. Potentially, this could make risk assessment more time consuming and complex. However, as our understanding of crop physiology progresses, it is likely that simple crop assessments will be identified which are indicators of crop tolerance to pest attack, e.g. the measurement of plants/m^2 or GAI in oilseed rape as an indicator of excess flower number. In this study, a pollen beetle threshold scheme has been proposed in which the pollen beetle threshold is inversely related to plants/m^2. These thresholds are risk averse in that they are based on information from varieties and seasons which showed the least tolerance to pollen beetle damage in terms of excess flower number. This threshold scheme predicts that for low plant populations of 20 plants/m^2 the pollen beetle threshold would be 29 beetles per plant for winter oilseed rape and 39 for spring oilseed rape. This threshold would decrease to 7 beetles per plant for crops with high plant populations of 80 plants/m^2 for both winter and spring crops. This should allow more precise prediction of pollen beetle risk. Furthermore, the chances of recording 29 or 39 beetles/plant are very low in the UK. It may therefore be possible to discount pollen beetle as a threat to yield in some crops in some years. Therefore, by assessing crop tolerance (by measuring plants/m^2 or possibly GAI), farmers/agronomists could avoid the time consuming and weather dependent methods of assessing pollen beetles in crops.

3.4.4. Objective 4 Validate risk predictions by comparing actual yield losses with predicted yield losses

During the first two years of this project, numbers of pollen beetles in oilseed rape crops were generally low. Consequently it was not possible to establish any field experiments with the range of pollen beetles required to validate the risk predictions generated in objective 3. In the 2010 harvest year, pollen beetle populations were higher than in 2008 and 2009 and four field experiments were set up, two in both winter and spring rape. Pollen beetle numbers in winter rape crops did not exceed a mean of 6.0/plant, and so were well below the current threshold. Despite the relatively low beetle number a yield response was observed from pollen beetle control. The new thresholds developed within this study indicate that a yield response would have occurred if this crop had more than 80 plants/m^2. However, plant number was not measured in the validation field trials because at the time of carrying out these assessments this crop character had not yet been identified as an important part of a pollen beetle threshold scheme. It is therefore not possible to fully validate the new prediction scheme. In spring rape, the current threshold was exceeded at Kirby Grindalythe (5.8 beetles/plant compared with a threshold of 3.0 beetles/plant) where there was a trend for a higher yield in insecticide treated plots. According to the new threshold scheme developed in this study there would need to be more than 80 plants/m^2 for there to be a yield response to pollen beetle control. However, as described earlier the number of plants was not recorded which means that the new threshold scheme cannot be fully validated for spring oilseed rape.

Pruning experiments investigated the impact of removing different proportions of buds from the terminal racemes in both winter and spring crops. If the new pollen beetle threshold scheme is correct then the pruning treatments would have been expected to have no effect on yield for either the winter or spring oilseed rape crops (assuming each terminal raceme would have had 100 flowers). This was borne out for the spring oilseed experiment, but significant yield losses were observed for the winter oilseed rape experiment. There are a number of factors that may have contributed to yield loss in the winter rape. Firstly, it is possible that the crop is not particularly tolerant of losing its first formed flowers, although this appeared to have no effect on spring rape. Secondly, it is possibly that increasing levels of water stress as the season progressed in this trial, prevented later formed pods from setting seed. Thirdly, it may be that the method of pruning, by cutting off the entire top of the raceme, was more damaging than if individual buds had been removed. A repeat of this study would be necessary, to determine whether the crop is particularly sensitive to losing the first formed buds compared with those of the side branches.

3.4.5. Objective 5 Investigate pollen beetle distribution in the field as an aid to assessing pest numbers

In general, pollen beetle counts did not vary much between a range of distances from the crop headland or at the north, east, south or west aspects of the field. Pollen beetle numbers were relatively low in both 2008 and 2009, but higher counts were recorded in 2010. There was evidence that a higher count was likely if plants were assessed between 0-50 m from the edge than at 51-100 m. However the increase was not statistically significant and less than one pollen beetle per plant (3.03 at the edge compared with 2.38 in centre, equating to an increase of about 27%) so unlikely to have a significant impact on spray decisions. Also, at green bud most pollen beetles were counted on the southern transect. Beetles are known to migrate upwind in response to plant volatiles in the prevailing wind. As this is south westerly it may be expected that most beetles would be found at northern or eastern transects. Therefore, the dominance of the southern transect in this study is difficult to explain. By the time crops reached the yellow bud stage, there was no difference in beetle counts between transects. In summary, assessing pollen beetles on the headland only is likely to result in a slight over-estimate of beetle numbers (25%), therefore to gain a representative count of beetle numbers, assessments should be taken up to 100 m into the field. It is unlikely that counts will be biased by assessing a transect along a particular compass point, although it is possible that the southern transect could give an over estimate of numbers if assessed at green bud.

3.4.6. Further research

Validate the pollen beetle threshold scheme proposed in this study by:

- carrying out realistic and more precise pruning experiments to quantify crop tolerance to bud loss and to test whether crops are less tolerant of losing buds from the terminal raceme compared with those that are formed later;
- quantifying the number of excess flowers produced in a wider range of crops to i) test whether the proposed scheme represents a crop with a low number of excess flowers, ii) identify whether there are any current varieties with particularly low numbers of excess flowers, iii) identify factors that could be used to help predict varietal differences in excess flower number;
- investigating whether pigeon grazing significantly reduces excess flower number;
- undertaking pollen beetle control experiments using insecticides in crops with a wide range of pest numbers and in which the plants/m^2 and GAI have been measured.

There is considerable scope to use the methodology developed in this study, which takes into account the tolerance that crops have for pest damage, to re-evaluate thresholds for a number of other pests of cereals and oilseed rape. In particular, the need for control of dipterous stem borers in cereals (wheat bulb fly, yellow cereal fly, frit fly) should be investigated further. This would involve quantifying the amount of damage that individual pests can cause together with the tolerance that crops have for losing tillers.

3.4.7. Conclusions

- A pollen beetle threshold scheme has been proposed based on an understanding of the number of buds that pollen beetles may damage and the number of buds that crops may lose without losing yield. In the proposed scheme the pollen beetle threshold is negatively related to plants/m^2. It is proposed that winter or spring crops with 20 plants/m^2 have a threshold of at least 29 beetles per plant and crops with more than 80 plants/m^2 have a threshold of less than 7 beetles per plant. Therefore the threshold is no longer a single value applicable to all crops. It varies in relation to the number of excess flowers produced by different varieties in different seasons. This is an important change in the developmental approach to thresholds which has potential for application to other pest/crop interactions. Further work is required to validate the prediction scheme, particularly whether crops are less tolerant to losing buds from the main raceme compared with later formed buds.

- An individual pollen beetle may damage up to nine buds. This information was previously unknown and is pivotal in determining thresholds for the pest
- A review of previous work showed that oilseed rape yields are maximised by achieving an optimum number of pods/m^2.
- Oilseed rape crops produce significantly more flowers than the optimum pod number so there is an excess number of flowers which could be sacrificed to pollen beetle attack before yield is lost.
- Spring oilseed rape crops produce a similar number of excess flowers to winter oilseed rape crops, which indicates that they are equally tolerant to pollen beetle attack. This is a significant change from current advice that suggests spring crops are inherently more susceptible to pollen beetles than winter crops.
- Hybrid, open pollinated and semi-dwarf varieties produce a similar number of excess flowers. This finding contradicts the perceived wisdom that hybrid varieties are potentially more susceptible to pollen beetle damage However, there were significant differences between specific varieties for excess flower number, e.g. Castille had less than Excalibur.
- Crops with fewer plants/m^2 had more excess flowers per plant. Previous work indicates that sowing crops in late September or applying sub-optimal amounts of N does not affect the number of excess flowers. This indicates that small or ‘backward’ crops may not as susceptible to pollen beetle attack as initially thought. This appears counter-intuitive but is supported by the fact that sparse crops have a greater ability for compensatory branching than those that are more densely planted. It is not known how pigeon grazing affects tolerance to pollen beetles.
- There were large seasonal differences in the number of excess flower numbers which were as large, or larger, than the variety differences. No way was found to predict these seasonal differences.
- There is potential to predict the number of excess flowers per plant from measurements of plants/m^2 or GAI at green bud. Both showed strong negative relationships with excess flowers per plant, although GAI was a less useful predictor for spring oilseed rape.
- Only small differences were detected between pollen beetle numbers measured in the field margins compared with the field centre, with less than one beetle per plant more (27% more) in the outer 50 m of the field.
- There was a weak trend for more pollen beetles along the southern side of a field, but the effect was not consistent.

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