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Project Report No. 590

Validation of an integrated pest management (IPM) strategy for pollen beetle to minimise the development of insecticide resistance.

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CONTENTS

1. Abstract

This project was done in response to industry feedback to refine guidelines for pollen beetle control. It aimed to (1) investigate the impact of different numbers of pollen beetles on the yield of winter and spring oilseed rape (2) consider whether pollen beetle damage to the primary raceme results in increased yield loss (3 & 4) investigate whether the compensatory ability of crops is affected by pigeon damage or infestation by cabbage stem flea beetle (CSFB) larvae (5) calibrate numbers of pollen beetle caught on the monitoring trap with numbers in the crop (6) provide guidelines on how to best estimate pollen beetles levels in the crop and (7) assess the accuracy of an on-line tool to predict timing of pollen beetle immigration and investigate effects of its use on spray timing and pest control.

In field experiments pollen beetle numbers did not exceed threshold and did not justify insecticide treatment suggesting that that sub-threshold populations of the pest are the norm rather than the exception. In further experiments pollen beetle damage was simulated by bud pruning and pigeon damage was simulated by mowing. There was no evidence to suggest that removing 100% of buds from the primary raceme increased yield loss, whereas mowing reduced yield but less than anticipated. Furthermore, mowing did not increase susceptibility to simulated pollen beetle damage and crops with low plant populations were no more susceptible to simulated pollen beetle damage than those with high plant populations. There was no evidence to suggest that crops with up to seven CSFB larvae/plant had an increased susceptibility to simulated pollen beetle damage.

An Oecos pollen beetle monitoring trap with an attractive lure was more effective than unbaited yellow sticky traps. The trap can be used to detect pest movement and abundance but as yet it has not been calibrated to detect threshold numbers of pollen beetles. Pollen beetle immigration is usually greatest on the north east side of the field (opposite to the prevailing wind) and this should be the focus for location of traps and crop walking.

The Bayer Pollen Beetle Predictor (BPBP) accurately predicted the peaks of pollen beetle migration helping to focus monitoring effort to when it is most needed. It reduced monitoring effort by about a third compared with weekly in-field assessments and also provided early and accurate detection of when the threshold was exceeded. Monitoring (weekly or via use of the BPBP) resulted in a reduction in insecticide use by about one-third compared with prophylactic treatment. However, in line with other experiments in this project, insecticide use did not significantly increase yield in comparison with untreated contols.

Overall the project has demonstrated that pollen beetle numbers are rarely damaging and that current thresholds and monitoring methods provide a good basis for an IPM strategy for this pest that minimises the need for insecticide treatment.

2. Introduction

Pesticide usage statistics suggest that insecticides are used against pollen beetles (*Meligethes aeneus*, also known as *Brassicogethes aeneus*) in oilseed rape (OSR) more frequently than is justified by the levels present in most crops (Figure 1). This is due in part to the low cost of pyrethroid insecticides but confidence in risk prediction and time required to monitor pollen beetle numbers are other factors that affect treatment decisions. Recent AHDB Cereals & Oilseeds funded studies (HGCA project No. 495 Ellis & Berry, 2012, and HGCA Project No. 504 Cook *et al*, 2013), have drawn attention to this pest and stimulated much discussion, particularly in response to the new threshold scheme.

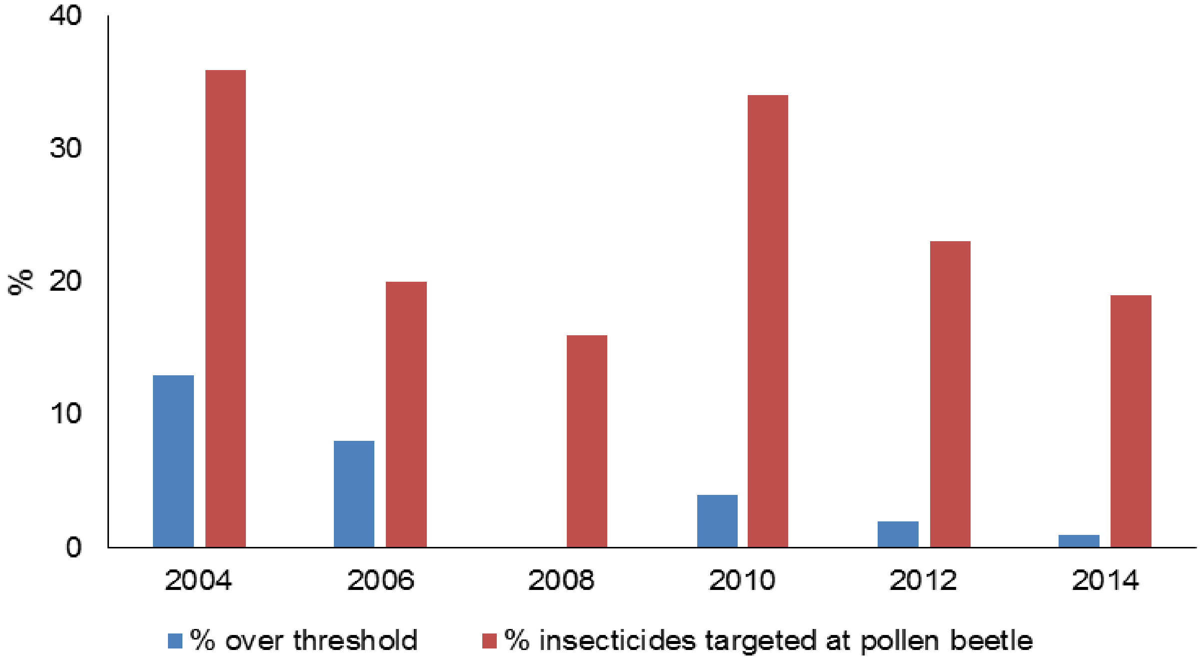


Figure 1. % crops over 15 pollen beetle/plant threshold from Fera survey data and % oilseed rape insecticides targeted at pollen beetle from Pesticide Usage Surveys (Arable crops in the UK) 2004-2014.

The arrival of insecticide-resistant pollen beetle in the UK makes it imperative that treatments are not applied unless necessary to protect yield. HGCA project No. 495 Re-evaluating thresholds for pollen beetle in oilseed rape (Ellis & Berry, 2012) produced 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 (Figure 2). The project hypothesised that many OSR crops produce significantly more flowers than are required to achieve the optimum pod number for potential yield so there is often an excess number of flowers which could be sacrificed to pollen beetle attack before yield is lost. An experiment in which a range of beetle populations (0, 5, 10, 15, 20 & 50/plant) were inoculated and confined on potted OSR plants showed that a single beetle is capable of destroying nine buds. Excess flower numbers (flower number – pod number at harvest) were assessed in a range of hybrid and conventional spring and winter OSR varieties sown at a range of seed rates (10 to 200 seeds/m^2) with numbers ranging from 531 to 14,087

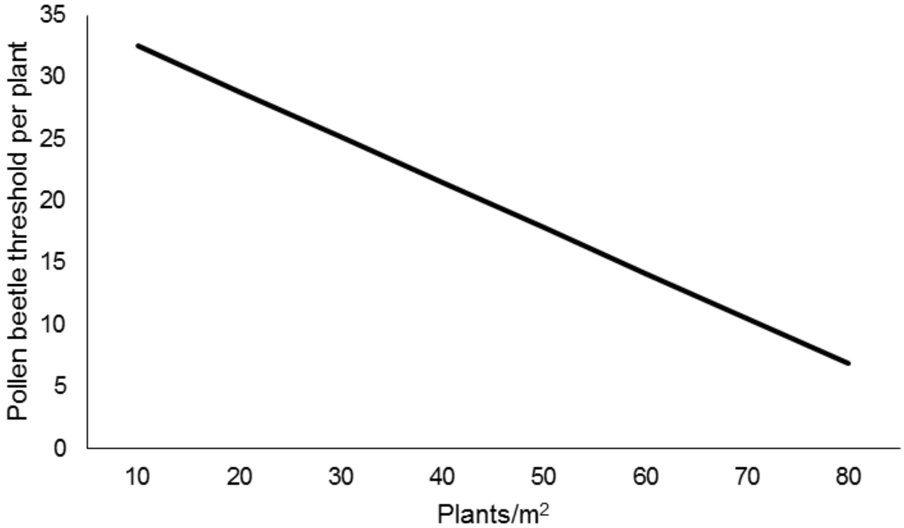


Figure 2. Pollen beetle threshold (number of pollen beetle/plant) for a range of OSR plant populations (From Ellis & Berry, 2012)

excess flowers per plant. Spring OSR crops produced a similar number of excess flowers to winter OSR crops, which indicates that they are equally tolerant to pollen beetle attack. This is a significant change from current thinking which suggests spring crops are inherently more susceptible to pollen beetles than winter crops (Ellis & Berry, 2012). Hybrid, open pollinated and semi-dwarf varieties produced a similar number of excess flowers suggesting they are also equally tolerant of pollen beetle damage, although there were significant differences between specific varieties, e.g. Castille had relatively few excess flowers. Crops with fewer plants/m^2 had more excess flowers per plant than more dense plant populations suggesting that crops with lower plant populations may not be as susceptible to pollen beetle attack as initially thought. Of course plants with a low plant population density are more likely to experience a greater number of pollen beetles per plant simply because the pollen beetle population must be spread over fewer plants. The project demonstrated it was possible to predict variation in the number of excess flowers per plant within a season from measurements of plants/m^2 or GAI at green bud. Both 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. A conceptual pollen beetle threshold scheme was proposed in which the pollen beetle threshold is negatively related to the number of plants/m^2. Further work is required to validate the prediction scheme in field situations, and in particular to consider the effects of previous damage by pigeons or cabbage stem flea beetle (CSFB; *Psylliodes chrysocephala*) and whether crops are less tolerant of losing buds from the main raceme.

Project No. 504 Development of an integrated pest management strategy for control of pollen beetles in winter oilseed rape (Cook *et al*., 2013) developed an integrated pest management (IPM) strategy for pollen beetles in winter OSR based on risk assessment, monitoring and alternative crop management to control pollen beetles with reduced insecticide inputs. One of the major limitations to the use of action thresholds is that monitoring of beetle populations is time consuming and has to be conducted over a prolonged period. To minimise this, input tools were developed to improve risk assessment. A pollen beetle monitoring study was conducted over four years in 178 OSR crops across the UK. Pollen beetles were sampled using sticky traps and plant scouting along transects in the crop. The data were used to test two decision support systems (DSS) for pollen beetles and to develop a monitoring trap. The two DSS systems tested were 1) the current advice system on the Crop Monitor website (www.cropmonitor.co.uk) and 2) ProPlant Expert which is a DSS available in mainland Europe that uses a phenological model of pollen beetle immigration and local meteorological data to forecast the start and end of pollen beetle immigration into the crop and main risk periods and advises when to monitor for the pest. This model was tested under UK conditions and compared monitoring advice with data on the numbers of beetles on plants and in traps from the pollen beetle monitoring study. Both DSS systems performed reassuringly well in prompting beetle monitoring that would detect when spray thresholds were exceeded. However, ProPlant required less input from the user and was best able to focus monitoring effort when it was most needed. In particular it could help to reduce unnecessary sprays in cases where beetle numbers are approaching threshold but the system indicates that either there will be limited further immigration or that immigration is complete. A simplified version of the ProPlant tool was made freely available as the Bayer Pollen Beetle predictor to growers and crop consultants in the UK via the Bayer CropScience website www.bayercropscience.co.uk/pollenbeetlepredictor/ from 2012. A small impact survey was conducted in 2012 with a total of 10 respondents. Nine of these indicated that the DSS had influenced the amount of crop monitoring (three monitored more often and six less often than they would have done otherwise) and seven out of ten respondents said that they had used fewer sprays as a result of using proPlant (Cook *et al*., 2013; Ferguson & Cook, 2014). Validation of the simplified tool is needed and grower/advisor uptake may improve if the online predictions are shown to be accurate at range of sites across the UK. Furthermore, it is predicted that more focussed monitoring will lead to faster detection of threshold populations (and therefore better control) than monitoring in the absence of DSS tools, but this has not been investigated. A pollen beetle monitoring trap was developed in Project 504 with the aim of replacing in-field pest assessments. This baited trap is commercially available from Oecos (http://www.oecos.co.uk/new%20products2.htm). The trap comprises a yellow sticky card mounted at 45°, baited with phenylacetaldehyde, a floral volatile produced naturally by several plant species. Unfortunately, the trap could not be calibrated with numbers of beetles in the crop and this requires further work. It nevertheless is still valuable for risk assessment for alerting farmers about the presence of pollen beetles, especially if used together with DSS tools.

To maintain the momentum generated by the projects discussed above it was important to demonstrate that researchers are responding to industry feedback in order to refine guidelines for pollen beetle control. This is particularly important in light of the presence of pyrethroid resistant pollen beetles in the UK. The current usage of insecticides against pollen beetle is not sustainable and could also encourage resistance in other insects that are unintentional targets of sprays against pollen beetle. For example in 2002, 2004 and 2006 25%, 36% and 20% of insecticides applied to oilseed rape, respectively (Gartwaite *et al*, 2003, 2005, 2007), were targeted against pollen beetele when mean beetle numbers never exceeded 6/plant (Fera survey data) which was well below the threshold of 15 beetles/plant at that time. Pyrethroid resistance in CSFB has been detected in the UK and in Germany resistance in seed weevils (*Ceutorhynchus obstrictus*) has recently been demonstrated (Heimbach & Muller, 2013). Developing an effective IPM strategy for pollen beetle will also provide a general framework for developing IPM strategies which could be applied to work on other pests and help to promote a rational approach to insecticide use. This will become increasingly important as the range of available active ingredients continues to decline.

The project aimed to validate the conclusions from projects No. 495 and No. 504 to deliver an IPM strategy for farmers and agronomists to predict the likely risk of pollen beetle damage and make rational decisions on the need for insecticide treatment. In particular, it takes account of industry feedback to refine the conclusions from previous pollen beetle studies. Particular areas of concern to be addressed included whether beetle damage that is concentrated on the primary raceme results in increased yield loss; if the compensatory ability of crops to tolerate pollen beetle damage was affected by pigeon damage or infestation CSFB larvae, calibration of the monitoring trap with the numbers in the crop; and how/where/when to get the best estimate of pollen beetles levels in the crop by crop scouting methods.

In 2014/15 and 2015/16 the Fera Crop Monitor survey of mean numbers of CSFB larvae per plant by region showed a significant increase in the incidence of the pest. In autumn 2016, a total of 10 out of 80 surveyed sites exceeded the five larvae/plant threshold compared with a single site in 2014. In the east of England numbers of larvae have been particularly high with up to 45 larvae/plant recorded in Cambridgeshire and 19 larvae/plant recorded in Essex in spring. Feeding by these larvae can affect crop vigour which in turn may affect the ability of the crop to tolerate attack by other pests such as pollen beetle. In view of the high levels of larval infestation recorded at some locations in spring 2016, the opportunity was taken to compare the tolerance of two crops to simulated pollen beetle damage imposed by bud pruning. One site was chosen because it had numbers of cabbage stem flea beetle larvae above the five larvae/plant threshold and the second was chosen because levels of pest infestation were below this level.

Specific objectives were:

1. To investigate the impact of different numbers of pollen beetles on the yield of winter and spring oilseed rape in the presence or absence of insecticide treatments in crops with a range of plants/m^2 and canopy size.
2. To simulate pollen beetle feeding damage by pruning buds to provide data on crop tolerance at a range of levels of bud loss to supplement data from objective 1.
3. To investigate the impact of pigeon grazing and plant population on the compensatory ability of plants by simulating damage using a defoliation treatment.
4. To investigate whether or not infestation by cabbage stem flea beetle (CSFB) larvae has an impact on response of oilseed rape plants subjected to simulated pollen beetle damage by bud pruning.
5. To calibrate pollen beetle traps developed in project No. 504 against field populations of the pest.
6. To provide guidelines on how best to monitor pollen beetle numbers.
7. To validate the accuracy of the Bayer Pollen beetle Predictor on-line decision support tool for pollen beetle immigration risk under local conditions and investigate effects of use on spray timing and control.

3. Materials and methods

3.1. Insecticide experiments

Over three project years a total of seven field experiments were established, six in winter oilseed rape (WOSR) and one in spring oilseed rape (SOSR) (Table 1) to evaluate the impact of pollen beetle on the yield of the crop. Sites were selected to provide crops which had a range of plant populations and pollen beetle infestations.

Table 1. Location of winter and spring rape sites for insecticide experiments

Year	Crop	Location & site	Grid reference	County
2014	Winter oilseed rape cv Extrovert	Rillington, High Mowthorpe	SE 84172 74267	North Yorkshire
2014	Winter oilseed rape cv Camelot	Boxworth, Boxworth	TL 34254 61969	Cambridgeshire
2015	Winter oilseed rape cv PR46W21	East Heslerton, High Mowthorpe	SE 49394 47804	North Yorkshire
2015	Winter oilseed rape cv Harper	Downham Market, Terrington	TL 61591 95201	Norfolk
2016	Winter oilseed rape cvPR46W21	East Heslerton, High Mowthorpe	SE 93698 78057	North Yorkshire
2016	Winter oilseed rape cv Fencer	Terrington	TF 54551 23599	Norfolk
2015	Spring oilseed rape cv Delight	Brandesburton, High Mowthorpe	TA 09708 47774	East Yorkshire

A total of four insecticide treatments were compared together with an untreated control. The insecticides represented the four modes of action approved for pollen beetle control in the UK. The full treatment list is given in Table 2.

Table 2. Insecticide treatments

Treatment	Active ingredient	Insecticide	Insecticide group	Rate of product*
1		Untreated	N/A	
2	Indoxacarb	Rumo	Oxadiazine	85g/ha
3	Lambda-cyhalothrin	Hallmark	Pyrethroid	75ml/ha
4	Pymetrozine	Plenum	Azomethine	150g/ha
5	Thiacloprid	Biscaya	Chloronicotinyl	0.3l/ha

*Full label rate

Plots were 12 m long and 3 m wide, except at the Terrington site in 2015 where they were 18 m long and 3 m wide. Insecticide sprays were applied at late green bud/early flowering (GS 36/50, Lancashire *et al*., 1991), when the day maximum temperature was at least 15°C using an Oxford Precision Sprayer in 200 litres water/ha at a pressure range of 200-300kPa with LD02 F110 flat fan nozzles to deliver a medium spray quality. All sites received routine applications of herbicides, fungicides and fertilisers to ensure that crop yield was not limited by lack of nutrients or presence of disease, pests or weeds. Other than the experimental insecticide treatments, insecticides were only applied when the crop was in flower and the susceptible period to pollen beetle attack had passed.

3.1.1. Assessments

At the beginning of March, the number of plants within five 0.5 m x 0.5 m quadrats orientated diagonally to the rows of each plot were counted. At the time of the first insecticide application, a sample of crop from an area of 1 m x 1 m was taken at the end of each untreated plot to determine the green area index (GAI). The same number of crop rows were included in each quadrat. This was done by arranging the quadrat so that a plant row ran from one of its corners to the diagonally opposite corner. The plants in each quadrat were dug up and the roots removed. A sub-sample of approximately 25% of the fresh weight was taken and the fresh weight recorded. The combined green area of the leaves and shoots in the sub-sample was measured using a Licor LI-3100 area meter

Before sprays were applied the number of pollen beetles per plot was assessed. This was done as close to the time of spraying date as possible. The assessment involved beating 10 plants from the untreated control plots individually over a white tray and counting the number of beetles dislodged. A second assessment was done two days after spray application to determine the impact of the treatments on beetle numbers.

Each plot was harvested with a combine harvester and samples taken for determination of moisture content. Yield in tonnes/ha was calculated and adjusted to 91 % dry matter.

3.1.2. Statistical analysis

Data were subjected to the parametric analysis of variance (ANOVA) using a single factor treatment structure. Data were also analysed in a cross-site analysis using a two-way ANOVA. This used a factorial treatment structure to assess the impact of site/year, insecticide treatments and their interaction on the various measured parameters. Where there was a significant treatment effect ($P < 0.05$) least significant difference values (LSD) are reported to allow comparisons between means.

3.2. Simulated pollen beetle and pigeon damage experiments

Over three project years a total of five field experiments were established, four in winter oilseed rape (WOSR) one in spring oilseed rape (SOSR) (Table 3) to evaluate the interaction between simulated pigeon damage and simulated pollen beetle damage. In particular the experiments were designed to determine if simulated pigeon damage increased the susceptibility of the crop to simulated pollen beetle damage.

Table 3. Location of winter and spring oilseed rape sites for experiments involving simulated pigeon damage and simulated pollen beetle damage

Year	Crop	Location & site	Grid reference	County
2014	Winter oilseed rape cv Extrovert	Rillington, High Mowthorpe	SE 84199 74235	North Yorkshire
2014	Winter oilseed rape cv PR46W21	Brockhampton, Rosemaund	SO 59047 30359	Herefordshire
2014	Spring oilseed rape Cv Delight	Brandesburton	TA 09708 47774	East Yorkshire
2015	Winter oilseed rape cv PR46W21	East Heslerton, High Mowthorpe	SE 49394 47804	North Yorkshire
2015	Winter oilseed rape cv PR46W21	Burley Gate, Rosemaund	SO 58763 47245	Herefordshire

In 2013/14 the High Mowthorpe site was originally established at Wintringham, North Yorkshire. When the crop emerged plant counts showed clear differences between the two seed rate treatments. Subsequently however, there was a significant germination of volunteer SOSR such that it confounded the differences in plant populations created by the two seed rates. Consequently, the sown crop could no longer be considered a typical WOSR crop and this may have affected how it reacted to the defoliation and pruning treatments. As a result it was decided to establish another experiment on an existing crop of WOSR. The seed rate comparison was lost but further data on this was collected from experiments near ADAS Rosemaund in 2013/14 and from both ADAS High Mowthorpe and Rosemaund in 2014/15.

A split plot design was used for all experiments (except High Mowthorpe 2014) with seed rate and defoliation treatment on the main plots. There were two seed rate treatments, two defoliation treatments and four replicates giving a total of 16 main plots (Table 4). Main plots were 24 m long and 3 m wide. The three pruning treatments (quadrats) were randomised as sub plots within each 24 m x 3 m main plots. At High Mowthorpe 2014 a factorial treatment structure was used to compare the impact of defoliation and pruning over four replicates giving 24 plots in total.

Table 4. Seed rate, defoliation and bud pruning treatments.

Treatment	Seed rate (seeds/m^2)	Defoliation	Pruning (% buds removed from main raceme)
1	30	Defoliation	0
2	30	Defoliation	50
3	30	Defoliation	100
4	30	No Defoliation	0
5	30	No Defoliation	50
6	30	No Defoliation	100
7	120	Defoliation	0
8	120	Defoliation	50
9	120	Defoliation	100
10	120	No Defoliation	0
11	120	No Defoliation	50
12	120	No Defoliation	100

The two seed rates were either low (30 seeds/m^2) or high (120 seeds/m^2). The two defoliation treatments, which were designed to simulate pigeon feeding, were either no defoliation or complete defoliation. This was planned for December/January, but at Brockhampton and Rillington in 2014 it was delayed until March due to poor weather conditions. Simulated pigeon damage was achieved by mowing off plants with an Allen auto scythe, a motorised mower with reciprocating blades. Before and after photos of the defoliated plots from the 120 seeds/m^2 treatment at Rosemaund in 2015 are shown in Figure 3.

Figure 3. Non-defoliated (A) and defoliated (B) winter oilseed rape plots for the 120 seeds/m^2 treatment at Rosemaund in 2015.

The three pruning treatments were removal of none, 50% or 100% of the buds on the main raceme. The pruning treatments were applied to a 1.2 m x 1.2 m quadrat when the crop reached the late green bud stage (GS 34, Lancashire *et al*., 1991). These treatments were randomised as sub plots within the main plots so that the order of pruning treatments was not the same in each main plot. The pruning treatment quadrats were positioned in one half of each plot to leave at least 12 m of plot for combine yield determination.

The pruning was done with a pair of sharp scissors and individual buds were cut off the main raceme of all plants within the quadrat area without damaging the stem. The objective was to mimic as closely as possible pollen beetle damage which only affects individual buds. Figure 4 shows close up images of buds on the main raceme immediately following pruning for each of the 0, 50 and 100% pruning treatments.

All plots received standard insecticide, fungicide, herbicide and fertiliser treatments. It was intended that an insecticide against pollen beetle would be applied at green/yellow bud to limit further bud damage beyond that imposed by the pruning treatments but this was not necessary as pollen beetle numbers never exceeded threshold at any of the sites.

Figure 4. Images demonstrating the 0% (A), 50% (B), and 100% (C) pruning treatments at High Mowthorpe in 2015. Either 0, 50 or 100% of the buds were pruned from the main raceme of winter oilseed rape plants using sharp scissors. All sites used the same method of pruning.

3.2.1. Assessments

Once five true leaves had emerged the number of plants within five 0.5 m x 0.5 m quadrats orientated diagonally to the rows of each plot was counted.

About two weeks before harvest, a 1 m x 1 m area of crop was sampled from each of the pruned areas and one unpruned area close to the pruned areas. Care was taken to sample from the centre of each of the 1.2 m x 1.2 m pruned areas. The seed was threshed from a representative sub-sample and the seed weight recorded at 100% dry matter.

Following the quadrat sampling, the remaining plot area was used to determine the combine yield. Sub-samples of seed were taken to determine moisture content and yield calculated yield in tonnes/ha adjusted to 91% dry matter.

3.2.2. Statistical analysis

Data were subjected to the parametric analysis of variance (ANOVA) using a factorial treatment structure to compare seed rate and defoliation but a split plot design to investigate the impact of bud pruning. Seed rate and defoliation were the main plot factors and were completely randomised. At High Mowthorpe in 2014 the seed rate element of the experiment was lost so bud pruning treatments were completely randomised across defoliation treatments in a factorial treatment structure. The pruning and defoliation data were also analysed across sites but in a single factor treatment design. The site was used as blocks and either pruning or defoliation treatments as the treatment effect. Where there is a significant treatment effect ($P < 0.05$) least significant difference values (LSD) are reported to allow comparisons between means.

3.3. Experiments to investigate the susceptibility of plants damaged by cabbage stem flea beetle to pollen beetle attack.

Two commercial WOSR fields were identified, one with below threshold numbers of CSFB larvae (3.3 larvae/plant) and one where the numbers of larvae were above the threshold (6.6 larvae/plant). One WOSR site was at East Heslerton, North Yorkshire and the other was at Boxworth, Cambridgeshire.

In each field, three bud pruning treatments were set up (zero, 50% and 100% of buds on the terminal raceme), each with seven replicates, to make a total of 21 quadrat areas. Quadrats were 1 m x 1 m. A fully randomised block design was used when deciding where to place the quadrats and assign treatments.

Table 5. Location of winter oilseed rape sites for experiments involving simulated pollen beetle damage to crops infested with cabbage stem flea beetle larvae

Year	Crop and cv	Location	Grid reference	County
2015/16	Winter oilseed rape cv PR46W21	East Heslerton, High Mowthorpe	SE 93698 78057	North Yorkshire
2015/16	Winter oilseed rape cv Campus	Boxworth, Boxworth	TL 32597 64632	Cambridgeshire

Pruning was undertaken with a pair of sharp scissors when the crop reached the green/yellow bud stage (GS 34, Lancashire *et al*., 1991) as described in Section 3.2. Sites received routine herbicide, fungicide and fertiliser treatments but insecticide treatments that could have had a negative effect on CSFB were avoided.

3.3.1. Assessments

In April 2016, the number of plants within five 0.5 m x 0.5 m quadrats within the experimental area were counted. Also, 25 plants from around the experimental area but not within the sampling quadrats were collected. These were returned to the laboratory where the leaf petioles and stem of each plant was dissected and the number of CSFB larvae per plant counted.

At the time of pruning (late green bud), 20 main racemes were sampled from the experimental area avoiding the sample quadrats. The number of buds on each of these was counted to help estimate how many buds the pruning treatments were removing. This was later used to determine the 'pollen beetle equivalent' of the pruning treatments. For example, if 90 buds were removed, this would be equivalent the damage caused by ten pollen beetles as a single beetle has been shown to consume nine buds in our previous project (Ellis & Berry, 2012).

About two weeks before harvest of the field crop, the plants from each 1 m x 1 m quadrat were collected. These were cut off at soil level. Sub-samples were threshed then oven dried to 100% dry matter and the dry weights recorded.

3.3.2. Statistical analysis

Data were subjected to the parametric analysis of variance (ANOVA) using a single factor treatment structure. Where there was a significant treatment effect ($P < 0.05$) least significant difference values (LSD) are reported to allow comparisons between means.

3.4. Calibrate pollen beetle monitoring traps against field populations of the pest

Spray thresholds for pollen beetle are expressed as a mean number of beetles per plant. To use a monitoring trap to detect when populations of beetles exceed spray thresholds it is necessary to find a relationship between the mean number of beetles per plant with the numbers of beetles on the trap. In RD-2007-3394 (Project 504) a simple correlation between the numbers of pollen beetles in traps and on plants could not be found. However, the traps used in Project 504 were unbaited yellow sticky traps, and therefore different from those commercialised by Oecos (which have a larger trapping plane, a slightly different coloured yellow plastic and importantly, the addition of an attractive volatile bait. Also in Project 504 traps were changed infrequently (2-3 days minimum). A known limitation of the traps used in Project 504 and the commercialized trap is that, because the trapping plane is flat and angled at 45° (because previous studies found this the most effective orientation of a flat trap; see Blight & Smart, 1999), beetles are only trapped efficiently when the wind direction is near-to opposite the orientation of the trapping plane (as beetles use upwind anemotaxis to locate host plants (Evans & Allen Williams, 1994; Williams *et al*., 2007; Skellern *et al*., submitted). In this project we therefore (i) tested the relative performance of the Oecos commercialised baited trap with the unbaited yellow sticky traps used in Project 504 and a version of the unbaited yellow trap that spins around with the wind so that trapping efficacy is not influenced by wind direction and (ii) related trap catch of the commercial traps to the number of beetles in the crop.

Commercially-available baited pollen beetle monitoring traps provided by Oecos (Figure 5a) were put out on four edges of the crop on the NE (down-wind), SW (upwind), SE & NW (cross-wind) sides (aligned with an assumed SW prevailing wind direction), of three winter oilseed rape crops on Rothamsted farm a few days before the start of pollen beetle immigration (this date being determined using the Bayer Pollen Beetle Predictor on-line tool; see Objective 4). Unbaited yellow sticky traps as used in Project 504 (Figure 5b) were also placed out and 'spinning traps' were also set out (in 2014 on the NE downwind edges only). These had a light aluminum vane which caught the wind to spin the trap around to face the prevailing wind (Figure 5c). Traps were placed in the headlands, 3 m from the crop edge in a randomized row, 5 m apart from each other. The traps were changed regularly until one week after the end of migration (as predicted by the Bayer Pollen Beetle Predictor on-line tool); c. daily (2014) and daily Monday-Friday (2015 and 2016). When traps were changed, a transect was also walked following AHDB sampling recommendations (HGCA, 2013) to assess the mean number of beetles per plant on each side of the field (corresponding to trap positions). Each transect was 30m long and comprised 10 plants starting in the middle of the field and walking towards the headland. One plant was selected at random every 3 m (i.e. 30 m, 27 m, 24 m..- 3 m from crop edge) and its growth stage (BBCH; Lancashire *et al*., 1991) was assessed and recorded. The number of beetles per plant were assessed by beating it into a tray (see section 3.1.1). In mid-March the plant density was assessed using a 0.5 x 0.5 m quadrat, so that beetle numbers/plant in transects could be related to UK spray thresholds for pollen beetles, which is based on the mean no. beetles per plant at a given plant density (HGCA, 2013). In 2014, plant density/m^2 was calculated from four quadrat measures at 0-10 m, 10-20 m and 20-30 m into the transect and in 2015-2016, it was calculated from 10 quadrats, one for every 3 m along the transect.

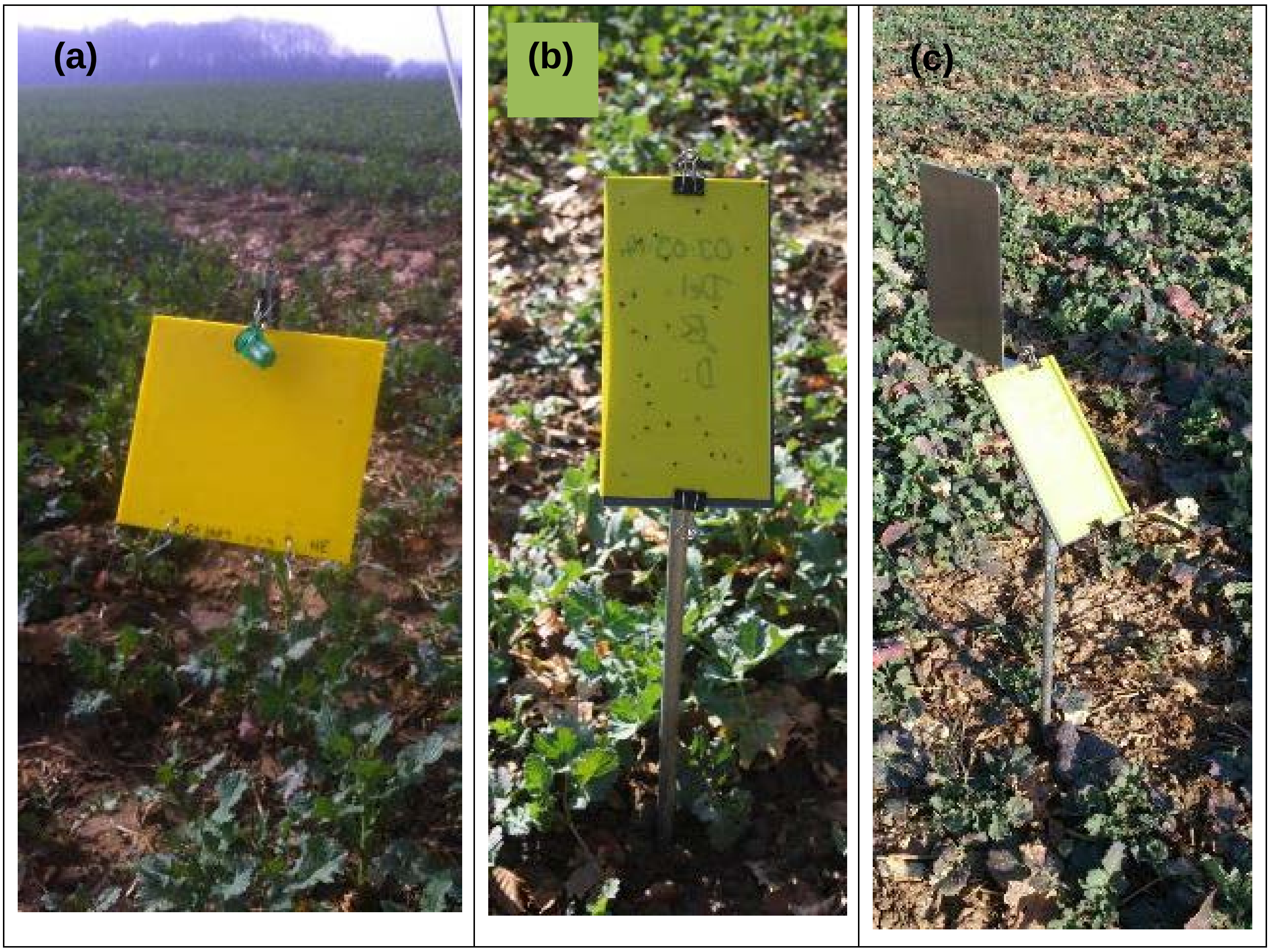


Figure 5. Pollen beetle monitoring traps tested in replicated experiments at Rothamsted 2014-16. (a) Commercial Oecos trap (baited with volatile lure); (b) unbaited yellow sticky trap as used in HGCA Project 504 (RD-2007-3394); (c) Spinning yellow sticky trap (unbaited) with aluminum vane to turn the trapping plane to face the prevailing wind.
Photos: Rothamsted Research

3.4.1. Differences in trapping efficacy between the three types of monitoring trap

Differences in trapping efficacy between the three types of trap were analysed using ANOVA for 2014 and a mixed model (REML) analysis for 2015/2016 (GenStat 18th Edition; VSN International, Hemel Hemptead, UK) where the data were transformed using log (x+1). An analysis was performed that accounted for the different sources of variation: i.e. variation associated with the transect position and field. Model terms were also included to assess differences between traps and their position within the field. In 2014 the NE side only of the field was analysed where the three different traps were present. Samples where all three traps contained no beetles were excluded from the analysis.

3.4.2. Monitoring trap calibration

To explore the relationship between the total number of beetles recorded in the trap and on plants in the transects, the correlation coefficient was calculated using trap and transect data collected at

Rothamsted from this experiment and using trap and transect data collected from volunteer farmers as described in Section 3.6. The data (total numbers of beetles per trap vs. the mean number of beetles per plant in the transect) were transformed using $\log_{10}$ +1 and the data were filtered to remove observations where beetles per transects and traps were both recorded as 0. Data were examined for all dates/sites and then further examined by restricting data to field side assessed (NE side for all sites and NW, SE, SW for Rothamsted sites). The data were restricted further to include only transects with plants within growth stages BBCH 50-59 (the susceptible stages of the crop) and then correlation coefficients were calculated for all sites, and then restricted to each side of the field as before.

To determine whether there was a simple linear relationship between the number of beetles caught in traps and the number per plant in a transect a linear regression was used. The data were restricted to only those observations on the NE side of the field and for the green-bud stage. The data were transformed using $\log_{10}$ and a grouping variable was used to investigate whether any relationship changed between the years. All analyses were performed using GenStat (Version 18, VSNi, Hemel Hempstead, UK).

3.5. Provide guidelines on how best to monitor pollen beetle numbers.

The advised procedure to determine whether or not spray thresholds have been exceeded involves assessing the number of plants per m^2 and pollen beetle numbers in the crop. To assess pollen beetle levels in the crop at least 10 plants are sampled along a transect 30 m minimum from the middle of the headland towards the centre of the crop (HGCA, 2013). The basis for this recommendation is that pollen beetles are more numerous at the crop edge than in its centre (e.g. Free & Williams, 1979) so a sampling method including plants from crop headlands and centre is important to get an accurate mean upon which to base spray decisions. However, both Projects 495 and 504 found that there was large variation in pollen beetle abundance and distribution in fields of OSR, and little evidence to support the hypothesis that pollen beetles are more abundant at the crop edge than in the centre. A better understanding the spatio-temporal distribution of immigration of pollen beetles could help inform improved monitoring methods.

3.5.1. Are pollen beetles more abundant at the crop edge than in the centre?

Data from HGCA Projects 495 (RD-2005-3242) 504 (RD-2007-3394) and from the current project (Objectives 4 and 6) on the number of pollen beetles per plant and the plant's growth stage and position in the crop (distance in metres along the transect from the crop edge in m) were drawn together and analysed.

To visually explore the data within the transects from the current project, shade plots of the number of beetles per plant were produced for the 10 plants along the length of the 30 m transect using

GenStat. The darker shades on the plot represent high counts of beetles and the lighter shades represent low counts. 'Visualised transect' shade plots were produced for each sample date on all sites and for each year of the project. For the Rothamsted sites, shade plots were produced for each of the four sides of the fields on which sampling took place (Section 3.4).

To assess differences between positions along the transect the total number of beetles recorded in the samples were combined into segments that represented 0-6 m, 7-12 m, 13-18 m, 19-24 m and 25-30 m from the edge of the field. Data were combined for all years in the current study and those conducted in Project 504. A linear mixed model (REML) was used; the data were transformed using $\log_{10}$ (x+1). The analysis accounted for the different sources of variation associated with the fields, side of the field, transect positions and sample dates. Model terms were included to assess differences between transect segments, side of the field and years. All analyses were done using GenStat (Version 18, VSNi, Hemel Hempstead, UK).

3.5.2. Spatio-temporal dynamics of pollen beetle immigration into OSR crops

The spatio-temporal distribution of pollen beetles during the immigration phase was assessed on three whole crops on Rothamsted Farm in 2015. Each of the fields was divided into 16.5 x 16.5 m squares 'zones' and the centre of each was marked using a flexicane. If the distance from a cane to the edge of the crop was 10 m or more then another cane was put on the crop edge to create another zone. The total number of sampling point zones for each field was: Little Knott = 73, Long Hoos = 117 and Great Harpenden = 187 (see Figure 15). Little Knott and Long Hoos fields were sampled about three times/week and Great Harpenden was sampled twice each week from 9th March – 27th April. On each sampling occasion, three plants were selected at random from each zone within 8 m of the cane; the growth stage of each plant was recorded (BBCH, Lancashire *et al*., 1991) as was the number of pollen beetles present on them (sampled by plant beating into a tray). The plant density of each zone was recorded in early March using a 0.5 m x 0.5 m quadrat; the number of plants per quadrat were counted and four quadrats per zone were assessed. At the same time pigeon damage was also assessed. Severe pigeon damage was recorded as being present when over half the plants in the transect had the terminal raceme pecked off by feeding damage.

The total number of pollen beetles on the three plants were used as a measure of the abundance of beetles per zone. These were mapped along with modal plant growth stage for each assessment date, plant density and areas of severe pigeon damage using Surfer software using Kriging (Version 13, Golden Software LLC, Colorado, USA).

3.6. Assess the accuracy of the on-line decision support tool for pollen beetle immigration and investigate effects of use on spray timing and control

In Project 504, the proPlant phenological model for pollen beetle migration was validated for UK conditions. A simplified version of this DSS tool, showing start of migration; risk of significant migration within the next few days and predictions of the completion of immigration is now available free on-line as the Bayer Pollen Beetle Predictor. Uptake of such tools by growers and advisors may improve if the online predictions are shown to be accurate at local sites across the UK and/or if clear advantages can be demonstrated through use of the tool e.g. reductions in monitoring effort, reductions in insecticide use, improved control and yield benefits.

3.6.1. Assess the accuracy of the on-line decision support tool for pollen beetle immigration

'Citizen Science' was used in the 'Pollen beetle trapping study' to generate data to address this Objective and also contribute to analyses described in Sections 3.4.2 and 3.5.1.

In each year of the current project, a call was put out for volunteers to participate in the 'Pollen beetle tapping study' using the network of volunteers built up in Project 504 and expanding it via requests for help posted on the AHDB, Rothamsted and ADAS web sites, via NFU and articles in the Farming press.

Each volunteer was sent a commercial Oecos monitoring trap and placed this on the NE side of an OSR crop, 3m from the crop edge. The trap was changed as frequently as possible (it was requested to do this a minimum of 2-3/week) and traps sent back to Rothamsted for processing (counting the number of pollen beetles caught). At each trap change, a monitoring transect was walked. On each transect, 10 plants were sampled along a 30 m transect starting 30 m mid-field and working towards the headland. One plant was selected at random every 3 m (i.e. 30 m, 27 m, 24 m..- 3 m from crop edge) and its growth stage (BBCH; Lancashire *et al*., 1991) was assessed and recorded. The number of beetles per plant were assessed by beating its head into a tray (see section 3.1.1). Traps and transects were started just prior to pollen beetle migration and were continued until flowering started (GS61) or in some cases beyond in an attempt to validate when migration was complete. At each site volunteers supplied the plant density of the crop so that the appropriate pollen beetle treatment threshold could be determined.

The location of each volunteer was matched to the nearest meteorological station (as the crow flies) used in the Bayer Pollen beetle Predictor (BPBP) www.bayercropscience.co.uk/pollenbeetlepredictor/ There are 92 meteorological stations in the UK used in the BPBP tool. As many of these as possible were tested, and we aimed for as wide a geographical spread as possible. The BPBP tool supplies a series of three maps showing predictions for (1) Start of pollen beetle migration, (2) Migration events and (3) End of migration. Predictions are shown on a traffic light warning scale with dark green indicating migration possible, lighter green migration more likely, yellow migration very likely and red migration conditions optimal. Grey areas where no dots are apparent relate to days when weather conditions are not condusive to pollen beetle migration. The system became live approximately one week before migration was expected to start and finished when most sites in the UK had migration complete. The system was checked daily during the 'live' period and the predictions (coloured dots) were recorded for each met station /site. The predictions given by the full proPlant version was also consulted daily so that the predictions between the two systems could be compared.

At the end of the season the trap and transect data were graphed and compared with the predictions given by the DSS tool. In particular we tested the accuracy of the predictions for the date of the start of migration, main migration peaks and end of migration with data returned by the volunteers.

3.6.2. Effects of using the on-line decision support tool for pollen beetle migration on spray timing and control

We hypothesised that use of the on-line tool would lead to more focussed (less frequent) monitoring, faster detection of threshold populations and therefore better control than in control systems without use of the tool. Previous work in Project 504 has shown that using the ProPlant DSS tool halved monitoring effort compared with strictly following rule-based advice (monitor when crop is green-yellow bud and when temperature exceeds 15°C; Ferguson *et al.*, 2014). However, most growers and advisors would never realistically monitor as frequently as rule-based advice suggests. After discussion with local growers and advisers, once-weekly monitoring was selected for use in the current project as a realistic frequency of monitoring to inform spray decisions.

Experimental set-up and approach

A replicated field trial was set up to compare four decision-making systems for pollen beetle control:

1) Insecticide applications applied prophylactically at GS 53 (green bud) and two weeks later.
2) Insecticide applied when threshold was exceeded and the threshold was detected via crop monitoring prompted by the on-line Bayer Pollen Beetle Predictor tool advice;
3) Insecticide applied when threshold was exceeded and the threshold was detected via weekly crop monitoring;
4) No insecticide applications.

Plots were 12 x 12 m and arranged in a Latin square design to account for possible directional bias. The experimental set up was repeated on two sites on Rothamsted/Woburn Farms in each of three years (2014-2016; sowing details see Table 6). Insecticide applications were Biscaya (thiacloprid) applied at the field recommended rate of 300ml/ha in the first instance (Treatments 1, 2 and 3), then Hallmark Zeon (lambda-cyhalothrin) applied at the full field rate of 75 ml/ha in the case of prophylactic control system (1) and if thresholds were exceeded again in systems involving spraying to threshold (2 and 3). In threshold systems (2 and 3) plots were treated as soon as possible after the threshold had been exceeded.

Table 6. Sowing details of experimental oilseed rape crops 2014-2016, Rothamsted Research Farm

Year	Field	Cultivar	Sowing date	Seed rate /m^2	Previous crop
2014	Drapers	Compass*	20/08/13	60	Winter wheat
2014	Great Knott 3	Compass*	23/08/13	60	Winter Barley
2015	Delafield	Quartz	22/08/14	80	Winter wheat
2015	Far Field **	Charger	5/09/14	30	Winter Wheat
2016	Great Knott 1	DK Exalte	21/08/15	50	Spring Barley
2016	Osier	DK Exalte	22/08/15	50	Spring Barley

* Dressed with Cruiser neonicotinoid seed treatment

** Rothamsted Research at Woburn Farm

Plots were treated as a grower would a whole field so as to test *system* differences, rather than *treatment* differences *per se*. Thus if a given plot assigned to a system using thresholds exceeded the treatment threshold then an insecticide application was made on that plot as soon as possible thereafter, but the other plots assigned to that system were not treated if they did not exceed the threshold.

Thresholds

To avoid the situation of the UK control threshold never being exceeded, which would result in no system differences between those requiring sprays to threshold (2, 3) or no sprays (4), the threshold was artificially lowered. Each year this was based on the number of pollen beetles present early in the season and was selected using the list of European thresholds by Williams (2010). In 2014 the artificial threshold was based on the German threshold system for backward crops which also considers crop growth stage: GS 50-51 2/plant; GS 52-53 3/plant; GS55-61 >4/plant. In 2015 the threshold was again based on that used in Germany; this time on that for normal crops: GS 50-51 4/plant; GS 52-53 7/plant; GS55-61 >8/plant. In 2016 the Polish threshold was used GS 50-51 1/plant; GS 52-53 3/plant; GS55-61 >3/plant.

Assessments

Plant density: The number of plants/m^2 was determined in early March using a 0.5 m x 0.5 m quadrat; the number of plants per quadrat were counted at four locations randomly selected within each plot. During this assessment, any pigeon damage was also noted.

Pollen beetle abundance. The number of pollen beetles were counted (by tray beating method) from the main raceme of 20 plants per plot, taken at random in a W-shaped transect across the plot. The mean number of pollen beetles/plant was calculated.

Plant growth stage. Growth stage (GS) on the BBCH scale (Lancashire *et al*., 1991) was assessed whenever a pollen beetle count was done. The minimum, maximum and modal GS were recorded for each plot as a whole.

Assessments were done weekly (or on the first dry day thereafter if raining) starting from when the crop reached GS 50 (flower buds present) until flowering GS 62 (20% flowers on main raceme; beyond which the crop cannot be treated with Biscaya) and whenever monitoring was prompted by the DSS tool. A monitoring event was said to have been returned whenever a red dot was given or when three yellow dots were given on consecutive days (Ferguson, 2014). The monitoring period was 10th March – 9th April 2014, 1-30th April 2015 and 1st March – 17 April 2016. All plots were assessed on weekly monitoring days and whenever a monitoring event was prompted by the DSS tool. However, insecticide treatments were only applied if the threshold was exceeded through sampling according to the appropriate system (i.e. an application would not be made to a plot assigned to a threshold via weekly monitoring system (3) if the assessment had been promoted by use of the DSS; equally an application would not be made to a plot assigned to a threshold via DSS system (2) if detected on a weekly sampling event that was not also prompted by the DSS system.

Bud damage:

As a measure of direct pollen beetle damage, 20 primary racemes were collected at random from a W-shaped transect across the plot at the end of the experiment at each site when the crop had reached GS 62. Racemes were maintained in pots of water in the fridge (5°C) until assessment in the lab; for each raceme, the numbers of buds and blind stalks were recorded, and the numbers of buds showing feeding or oviposition damage, and whether or not they contained pollen beetle eggs or larvae.

Yield:

Yield was taken by plot combine from each plot at harvest and grain weight recorded at 91% dry weight.

Performance of the control systems

The number of monitoring events, breaches of thresholds (noting the system) and number of spray applications was recorded for each plot and for each control system 'treatment'. The total number of times thresholds were exceeded in each plot was calculated and whether this was appropriately detected by the control system or not was noted. The number of days delay (if any) between the first experimental detection of the threshold and detection by the system was also calculated. These were compared between systems along with the total number of missed treatments and number of treatments applied.

Statistics

Differences in plant density at the start of the experiment were analysed between the four systems for each field in each year by ANOVA. The number of blind stalks and the proportion of buds with oviposition damage were analysed using a linear mixed model for each field in 2014 and analysis of variance for the fields in 2015 and 2016. The no. blind stalk data were transformed using $\log_{10}(x+1)$ and the proportion of oviposition damage data were transformed using a logit with an adjustment to avoid zero values. Each analysis accounted for the source of variation within the fields and included a term to assess the difference between the different systems.

Yield data (tonnes/hectare at 91% dry weight) were analysed by ANOVA.

4. Results

4.1. Insecticide experiments

WOSR Boxworth and High Mowthorpe 2014

There was no significant effect of insecticide treatment on the yield of OSR crops at Boxworth or High Mowthorpe in 2014 (Table 7). Plant numbers in March were 55 plants/m^2 at Boxworth and 63 plants/m^2 at High Mowthorpe, equating to a threshold of 11 beetles per plant at both sites. The green area index (GAI) measured at insecticide application was 1.6 at Boxworth and 1.5 at High Mowthorpe, respectively. At Boxworth, following insecticide application, the pollen beetle numbers decreased naturally in the untreated plots from 1.8 to 0.4/plant. There was also no significant effect of insecticide application on the number of beetles per plant or on the percentage change in the number of beetles per plant following insecticide application. Similarly, despite a significant treatment effect at High Mowthorpe, there was no significant difference in the number of beetles per plant between the untreated control and any of the insecticide treatments. The number of beetles was highest in the Biscaya treatment which was significantly higher than any of the other insecticide treatments, but not the untreated control. At High Mowthorpe the average beetle number per plant before application was 1.5 and this decreased naturally to 0.2 in the untreated plots two days later. In addition, the percentage change in the number of beetles per plant after insecticide treatment was significantly different between treatments. None of the insecticide treatments were significantly different from the untreated control but Biscaya did not reduce beetle numbers as much as the other insecticide treatments.

Table 7. Pollen beetle insecticide results from Boxworth and High Mowthorpe sites in 2014. Values followed by the same letter are not significantly different (*P* < 0.05).

	Boxworth			High Mowthorpe		
Treatment	Yield (t/ha)	Beetles/plant (after treatment) (pre-treat: 1.8)	% change in beetles/plant after treatment	Yield (t/ha)	Beetles/plant (after treatment) (pre-treat: 1.5)	% change in beetles/plant after treatment
Untreated	4.03	0.4	-86	3.41	0.2[ab]	-82[ab]
Rumo	4.19	0.4	-77	3.57	0.1[a]	-94[a]
Hallmark	4.04	0.3	-85	3.83	0.1[a]	-96[a]
Plenum	4.21	0.0	-98	3.69	0.0[a]	-96[a]
Biscaya	3.95	0.3	-82	3.53	0.4[b]	-66[b]
Grand Mean	4.08	0.3	-85	3.60	0.15	-87
P	0.801	0.320	0.269	0.261	0.013	0.006
SED	0.243	0.17	8.8	0.182	0.08	7.5
LSD	0.529	0.38	19.19	0.405	0.18	16.37

WOSR Terrington and High Mowthorpe 2015

There was no significant effect of insecticide treatment on the yield of WOSR crops at Terrington or High Mowthorpe in 2015 (Table 8). Plant numbers in spring 2015 were 17 plants/m^2 at Terrington and 49 plants/m^2 at High Mowthorpe. The pollen beetle thresholds for these sites were therefore 25 beetles per plant at Terrington and 18 beetles per plant at High Mowthorpe. The GAI at insecticide application was 2.4 at Terrington and 1.5 at High Mowthorpe. At Terrington there were very similar beetle numbers recorded pre- (4.8) and post- (4.5) insecticide treatments in the untreated plots. There were significantly lower numbers of beetles per plant following the application of all four insecticides when compared to the untreated control at Terrington, although there was no significant effect of insecticide treatment on beetle numbers at High Mowthorpe, despite a trend for insecticide application to reduce beetle numbers, particularly by Plenum. There was a natural decline in the pollen beetle numbers at High Mowthorpe from 3.4 to 1 beetle per plant in the untreated plots following insecticide application. There was, however, a significantly larger decrease in the percentage change in number of beetles per plant following application of

Rumo, Hallmark and Plenum at Terrington in comparison with Biscaya and the untreated control. At High Mowthorpe, there was a significantly larger decrease in the percentage change in the number of beetles per plant following the application of Hallmark, Plenum and Biscaya in comparison Rumo and the untreated control.

Table 8. Pollen beetle insecticide results from Terrington and High Mowthorpe winter oilseed rape (WOSR) sites in 2015.

	Terrington WOSR			High Mowthorpe WOSR		
Treatment	Yield (t/ha)	Beetles/plant (following treat) (pre-treat:4.8*	% change in beetles/plant after treatment	Yield (t/ha)	Beetles/plant (following treat) (pre-treat: 3.4*)	% change in beetles/plant after treatment
Untreated	4.70	4.5^{a}	4^{a}	3.87	1.0	-53^{a}
Rumo	5.51	2.7^{b}	-49^{b}	3.86	0.8	-66^{a}
Hallmark	5.41	2.6^{b}	-47^{b}	3.96	0.5	-83^{b}
Plenum	5.36	2.2^{c}	-49^{b}	4.15	0.1	-99^{b}
Biscaya	4.98	2.7^{b}	-24^{a}	4.09	0.4	-85^{b}
Grand Mean	5.19	2.9	-33	3.99	0.55	-77
P	0.203	<0.001	<0.001	0.363	0.081	0.038
SED	0.355	0.17	10.41	0.171	0.31	13.4
LSD	0.792	0.36	22.68	0.37	0.68	29.1

*Pre-treatment means of pollen beetle numbers are across all plots to give an indication of background levels of pest infestation

WOSR Terrington and High Mowthorpe 2016

There was a significant effect of insecticide treatment on yield at Terrington in 2016 following application of Hallmark or Biscaya when compared with the untreated control. Prior to insecticide application there were 36 plants/m^2, therefore the threshold was 18 pollen beetles per plant. The GAI at the time of insecticide application was 2.3. There was a natural increase in the number of pollen beetles per plant following insecticide application in the untreated plots at Terrington from 1.6 up to 2.1. There was a significant reduction in the number of beetles per plant when treated with any of the insecticides. There was no significant effect of insecticide treatment on the percentage change in the number of beetles per plant at P = 0.05, but there was a significant effect at P = 0.1 with Rumo and Plenum both reducing beetle numbers.

There were 25 plants/m^2 in April 2016 at High Mowthorpe, equating to a threshold of 25 pollen beetles per plant. The GAI was 0.96. There was a significant reduction in the number of beetles per plant when treated with all four insecticides. Prior to insecticide application the number of beetles per plant was 0.9, post-treatment application the mean beetles per plant in the insecticide treated plots was 0.6 compared with a natural increase to 2.1 beetles per plant in the untreated plots. There was no significant effect of insecticide application on the percentage change in beetle number per plant at High Mowthorpe in 2016. Yield data were not available for the experiment at High Mowthorpe in 2016 due to problems with the weighing mechanism on the plot combine such that yields were available for less than 50% of plots.

Table 9. Pollen beetle insecticide results from the Terrington and High Mowthorpe winter oilseed rape (WOSR) sites in 2016.

	Terrington WOSR			High Mowthorpe WOSR		
Treatment	Yield (t/ha)	Beetles/plant (after treatment) (pre-treat: 1.6*)	% change in beetles/plant after treatment	Yield (t/ha)	Beetles/plant (after treatment) (pre-treat: 0.9*)	% change in beetles/plant after treatment
Untreated	3.96[ac]	2.1[a]	69	NA	2.1[a]	376
Rumo	3.93[a]	1.1[b]	-50	NA	0.5[b]	20
Hallmark	4.13[b]	1.4[b]	11	NA	0.6[b]	-26
Plenum	4.04[bc]	0.9[b]	-55	NA	0.5[b]	-49
Biscaya	4.07[b]	0.9[b]	-12	NA	0.7[b]	3
Grand Mean	4.03	1.3	-7	-	0.9	65
P	<0.01	0.015	0.089	-	<0.001	0.141
SED	0.0445	0.33	44.5	-	0.19	170.9
LSD	0.097	0.72	97.0	-	0.42	372.4

* Pre-treatment means of pollen beetle numbers are across all plots to give an indication of background levels of pest infestation

WOSR Cross site analysis

Across the five WOSR sites for which yield data were available, there was no significant effect of insecticide treatment on yield (P = 0.714) and no interaction between site and treatment (P = 0.982), but there was a significant difference in the yield between sites (P <0.01; *Figure*).

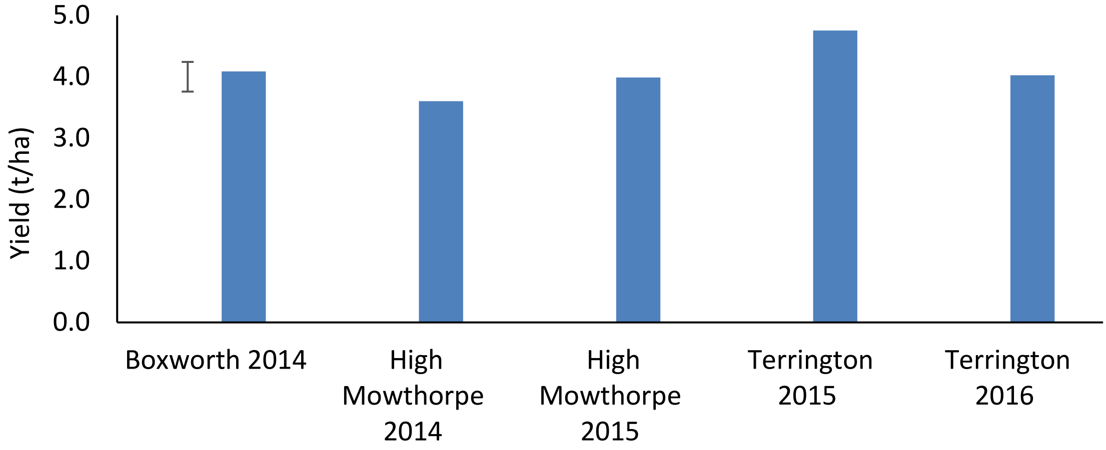


Figure 6. Yield at 91% dry matter (t/ha) for each of the insecticide experimental sites. Error bar represents one LSD.

Across the six winter OSR sites, there was a significant difference between sites in the number of beetles present before insecticide application (P < 0.001; Figure 7). There was a significant interaction between insecticide treatment and site for the number of beetles post insecticide application (P < 0.001; Figure 8). This was predominantly due to greater decreases in pollen beetle numbers in response to insecticide application in years where there were pest numbers were highest (e.g. Terrington 2015), whereas in lower risk years there was a lower effect of insecticide application.

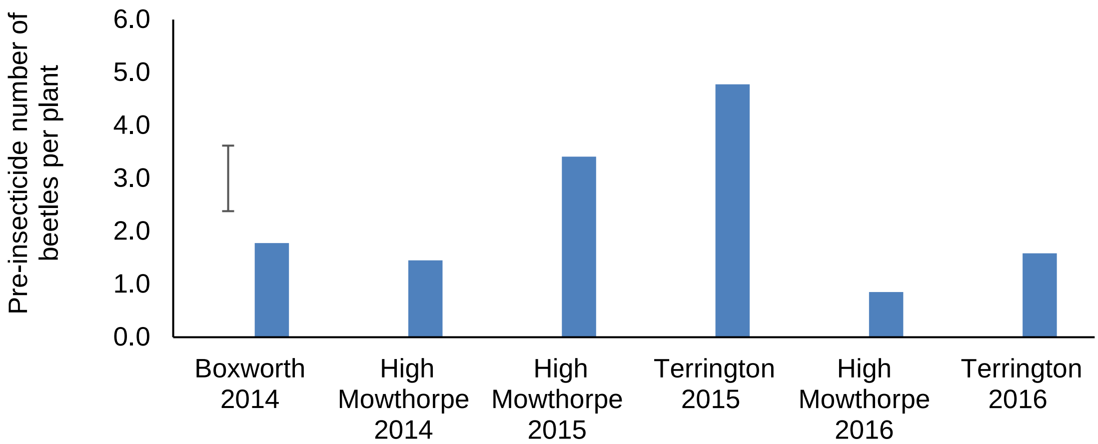


Figure 7. Mean number of pollen beetles per plant before insecticide application for each experimental site. Error bar represents one LSD.

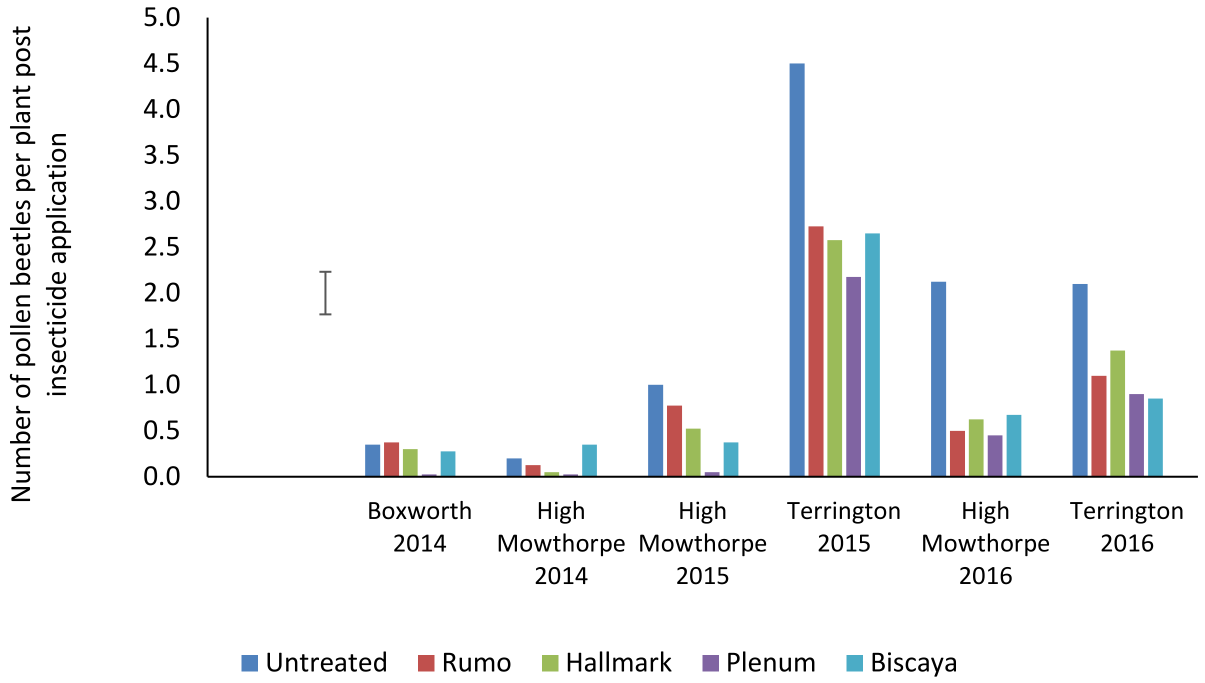


Figure 8. Mean number of pollen beetles per plant after insecticide application for each experimental site. Error bar represents one LSD.

There was also a significant interaction between site and insecticide treatment in the percentage change in beetle numbers after insecticide application (*P* <0.05). This was mostly driven by the large increase (376%) in pollen beetle numbers in the untreated plots following insecticide application at High Mowthorpe in 2016. This may have been a result of the second beetle count falling on a particularly sunny day, increasing the chance of catching active individuals. There may also have been further pest migration after treatments were applied. If the data from High Mowthorpe in 2016 were excluded from the analysis, there was still a significant interaction, but the LSD decreased (*P* <0.05, Figure 9), making it easier to assess differences between insecticide treatments. In this case, Hallmark was significantly more effective at reducing pollen beetle numbers at Boxworth 2014, High Mowthorpe 2014, High Mowthorpe 2015 and Terrington 2015 than at Terrington 2016. Similarly, Biscaya was not as effective at reducing beetle numbers at Terrington 2016 compared with Boxworth 2014, High Mowthorpe 2014 and High Mowthorpe 2015.

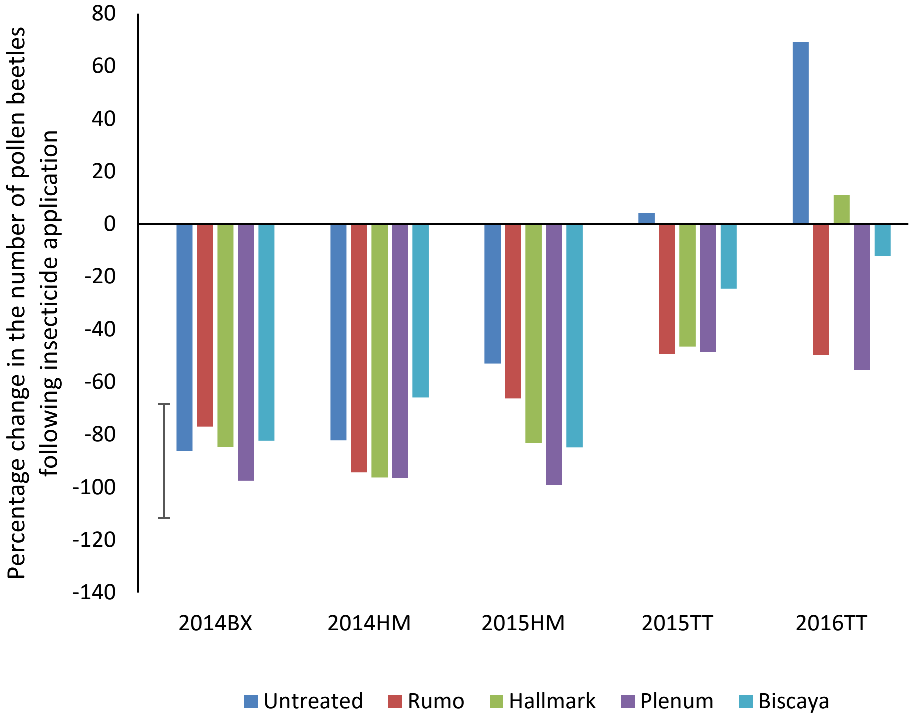


Figure 9. Percentage change in the number of pollen beetles two days after insecticide application. Insecticides included Rumo, Hallmark, Plenum and Biscaya. Error bar represents one LSD. (BX = Boxworth, HM = High Mowthorpe, TT = Terrington)

SOSR High Mowthorpe 2015

There was no significant effect of insecticide application on the yield of SOSR plants at High Mowthorpe in 2015. Prior to insecticide application (16th June) there were 35 plants/m^2, this equates to a threshold of 18 pollen beetles per plant. The GAI at the time of insecticide application was 2.5. The number of beetles decreased naturally from 2.7 to 0.9 in the untreated plots after the date of the insecticide. Insecticides decreased the pollen beetle numbers to 0.1 /plant which was a significantly greater decrease than occurred naturally in the untreated plots (Table 10).

Table 10. Pollen beetle insecticide results from the High Mowthorpe spring oilseed rape (SOSR) site in 2015.

	High Mowthorpe SOSR		
Treatment	Yield (t/ha)	Beetles/plant (after treatment) (pre-treat: 2.67)	% change in beetles/plant after treatment
Untreated	2.84	0.9[a]	-61[a]
Rumo	2.95	0.1[b]	-96[b]
Hallmark	2.86	0.1[b]	-95[bc]
Plenum	2.85	0.1[b]	-97[b]
Biscaya	2.73	0.3[c]	-89[c]
Grand Mean	2.85	0.3	-88
P	0.745	<0.001	<0.001
SED	0.162	0.05	3.1
LSD	0.353	0.11	6.8

4.2. Simulated pollen beetle and pigeon damage experiments

Rosemaund 2014

Plant number was significantly affected by seed rate (P<0.001). The 30 seeds/m^2 treatment averaged 21.4 plants/m^2 whilst the 120 seeds/m^2 treatment averaged 50.2 plants/m^2. Seed yield measured on the 12 m x 3 m plots using the small plot combine showed a significant effect of defoliation on yield (P<0.001), with defoliation reducing yield by 0.54 t/ha (Table 11). Seed rate had no significant impact on yield and there was no significant interaction between the two parameters. There was no significant impact of bud pruning, although yield was reduced by 0.47 t/ha and 0.35 t/ha when 50% and 100% of the buds were removed, respectively (Table 12). Yield was significantly reduced by 1.0 t/ha when the crop was defoliated when measured from the 1 m x 1 m quadrats. There was no significant interaction between pruning, seed rate or defoliation.

Table 11. Combine seed yield (t/ha) for the Rosemaund 2014 experiment.

	Defoliation		
Seed rate (seeds/m2)	Defoliation	No Defoliation	Grand Mean
30	3.22	3.73	3.48
120	3.10	3.66	3.38
Grand Mean	3.16	3.70	3.43
	P	SED	LSD
Seed rate	0.331	0.094	0.213
Defoliation	<.001	0.094	0.213
Seed rate*Defoliation	0.813	0.133	0.302

Table 12. Quadrat seed yield (t/ha) for the Rosemaund 2014 experiment.

Treatment		Pruning treatment			
Seed rate (seeds/m^2)	Defoliation treatment	0%	50%	100%	Grand Mean
	Defoliation	4.22	3.64	3.32	3.73
30	No Defoliation	5.05	4.10	4.74	4.63
	Defoliation	3.74	3.64	3.90	3.76
120	No Defoliation	5.04	4.76	4.69	4.83
30 mean		4.63	3.87	4.03	4.18
120 mean		4.39	4.20	4.30	4.30
Defoliation mean		3.98	3.64	3.61	3.74
No Defoliation mean		5.04	4.43	4.72	4.73
Grand Mean		4.51	4.04	4.16	4.24
	P	SED	LSD		
Seed rate	0.407	0.122	0.389		
Defoliation mean	<0.001	0.127	0.311		
Pruning	0.167	0.25	0.517		
Seed rate*Defoliation	0.519	0.176	0.405		
Seed rate* Pruning	0.463	0.314	0.645		
Defoliation* Pruning	0.789	0.316	0.645		
Seed rate*Defoliation*Pruning	0.393	0.445	0.909		

High Mowthorpe 2014

Defoliation of the crop resulted in a significant 0.17 t/ha decrease in seed yield from 3.94 t/ha to 3.76 t/ha (P = <0.01) as measured in the 12 m x 3 m plots using the small plot combine. The 1 m x 1 m quadrat yields showed a consistent 0.16 t/ha reduction in yield due to defoliation, although in this case the difference was not significant. There was no significant effect of pruning on quadrat yield, and no significant interaction with defoliation (Table 13).

Table 13. Quadrat seed yield (t/ha) for the High Mowthorpe 2014 experiment.

	Pruning treatment			
Defoliation treatment	0%	50%	100%	Grand Mean
Defoliation	3.39	3.11	3.33	3.27
No Defoliation	2.90	2.99	3.43	3.11
Grand Mean	3.15	3.05	3.38	3.19
	P	SED	LSD	
Defoliation	0.231	0.134	0.286	
Pruning	0.147	0.164	0.351	
Defoliation* Pruning	0.225	0.233	0.496	

Rosemaund 2015

Plant number was significantly affected by seed rate (P<0.001). The 30 seeds/m^2 treatment averaged 18.9 plants/m^2 whilst the 120 seeds/m^2 treatment averaged 48.7 plants/m^2. Seed yield measured by the small plot combine showed a borderline significant impact of defoliation on yield (P=0.055), with yield being reduced by 0.26 t/ha (Table 14). GAI was measured following mowing, and defoliation and decreased from 2.16 to 0.36 for the low seed rate and from 3.21 to 0.38 for the high seed rate. On average, defoliation reduced the GAI by 2. There was no significant effect of seed rate on yield and no significant interaction between seed rate and defoliation (Table 14). There was no significant impact of pruning on yield as measured by 1 m x 1 m quadrats (Table 15).

Table 14. Combine seed yield (t/ha) for the Rosemaund 2015 experiment.

	Defoliation		
Seed rate (seeds/m^2)	Defoliation	No defoliation	Grand mean
30	5.78	5.85	5.81
120	5.69	6.13	5.91
Grand Mean	5.73	5.99	5.86
	P	SED	LSD
Seed rate	0.423	0.118	0.267
Defoliation	0.055	0.118	0.267
Seed rate*Defoliation	0.144	0.167	0.377

Table 15. Quadrat seed yield (t/ha) for the Rosemaund 2015 experiment.

	Treatment	Pruning treatment			
Seed rate (seeds/m2)	Defoliation treatment	0%	50%	100%	Grand mean
	Defoliation	5.78	6.96	6.18	6.31
30	No Defoliation	7.43	7.40	7.47	7.43
	Defoliation	6.36	7.05	6.33	6.58
120	No Defoliation	6.14	6.92	7.42	6.83
30 mean		6.61	7.18	6.83	6.87
120 mean		6.25	6.99	6.87	6.70
Defoliation mean		6.07	7.01	6.25	6.44
No Defoliation mean		6.79	7.16	7.45	7.13
Grand Mean		6.43	7.08	6.85	6.79
	P	SED	LSD		
Seed rate	0.604	0.289	0.919		
Defoliation mean	0.127	0.388	0.95		
Pruning	0.363	0.457	0.944		
Seed rate*Defoliation	0.301	0.484	1.095		
Seed rate* Pruning	0.907	0.602	1.243		
Defoliation* Pruning	0.532	0.655	1.346		
Seed rate*Defoliation*Pruning	0.634	0.890	1.810		

High Mowthorpe 2015 WOSR

Plant number was significantly affected by seed rate ($P < 0.01$). The 30 seeds/m^2 treatment averaged 36.7 plants/m^2 whilst the 120 seeds/m^2 treatment averaged 72.7 plants/m^2. The 30 seeds/m^2 seed rate treatment resulted in more than 30 plants/m^2 due to volunteer plants. Seed yield measured by the small plot combine revealed no significant effect of defoliation or seed rate on yield (Table 16). Following mowing, GAI decreased from 1.39 to 0.34 for the high seed rate and from 0.83 to 0.31 for the high seed rate. On average defoliation reduced the GAI by 0.8. There was a significant interaction between pruning and seed rate. For the low seed rate, yield increased by 0.37 t/ha in response to 100% removal of the buds, whilst for the high seed rate, yield was reduced by 0.89 t/ha. When 50% of the buds were removed, yield was reduced by 1.00 t/ha at the low seed rate and just 0.28 t/ha for the higher seed rate.

Table 16. Combine seed yield (t/ha) for the High Mowthorpe 2015 WOSR experiment.

	Defoliation		
Seed rate (seeds/m^2)	Defoliation	No Defoliation	Grand Mean
30	3.84	3.86	3.85
120	4.01	3.87	3.94
Grand Mean	3.92	3.87	3.90
	P	SED	LSD
Seed rate	0.473	0.122	0.276
Defoliation	0.647	0.122	0.276
Seed rate*Defoliation	0.511	0.172	0.390

Table 17. Quadrat seed yield (t/ha) for the High Mowthorpe 2015 WOSR experiment.

Treatment		Pruning treatment			
Seed rate (seeds/m^2)	Defoliation treatment	0%	50%	100%	Grand Mean
	Defoliation	5.02	3.65	4.73	4.35
30	No Defoliation	4.43	3.54	5.28	4.42
	Defoliation	3.94	4.07	2.81	3.61
120	No Defoliation	4.89	4.22	4.26	4.45
30 mean		4.63	3.60	5.00	4.35
120 mean		4.42	4.14	3.53	4.42
Defoliation mean		4.30	3.86	3.77	3.61
No Defoliation mean		4.66	3.88	4.77	4.45
Grand Mean		4.51	3.87	4.27	4.39
	P	SED	LSD		
Seed rate	0.183	0.277	0.882		
Defoliation mean	0.228	0.247	0.604		
Pruning	0.058	0.314	0.652		
Seed rate*Defoliation	0.082	0.371	0.869		
Seed rate* Pruning	0.015	0.457	0.969		
Defoliation* Pruning	0.208	0.439	0.902		
Seed rate*Defoliation*Pruning	0.416	0.633	1.298		

High Mowthorpe 2015 SOSR

Plant number was significantly affected by seed rate ($P < 0.001$). The 30 seeds/m^2 treatment averaged 16.8 plants/m^2 whilst the 120 seeds/m^2 treatment averaged 58.8 plants/m^2. Seed yield measured using a small plot combine revealed a significant impact of seed rate on yield, with the lower seed rate of 30 seeds/m^2 yielding less than the higher seed rate of 120 seeds/m^2 by 0.42 t/ha (Table 18). There was no significant effect of pruning on yield, although pruning 50% of buds yielded 0.91 t/ha more than the unpruned treatment (*P*=0.098) (Table 19). Seed rate yields from the quadrat area were 2.17 t/ha for the low and 3.76 t/ha for the high seed rate, the difference was much greater than that obtained from the plot yields.

Table 18. Combine seed yield (t/ha) for the High Mowthorpe 2015 SOSR experiment.

Seed rate		
30 seeds/m^2	120 seeds/m^2	Grand Mean
2.16	2.58	2.37
P	<0.001	
SED	0.08	
LSD	0.17	

Table 19. Quadrat seed yield (t/ha) for the High Mowthorpe 2015 SOSR experiment.

	Pruning treatment			
Seed rate (seeds/m$^{2)}$	0%	50%	100%	Grand Mean
30	2.3	2.32	1.88	2.17
120	2.76	4.57	3.68	3.67
Grand Mean	2.53	3.44	2.78	2.92
	P	SED	LSD	
Seed rate	<.001	0.33	0.704	
Pruning	0.098	0.404	0.862	
Seed rate* Pruning	0.105	0.572	1.219	

Pruning experiments cross site analysis.

Across the seven experiments, on average there was no statistically significant impact of pruning 50% or 100% of the buds from the terminal raceme (simulated pollen beetle damage), although there was a trend for yield to decrease by 0.2 t/ha on average when 100% of the buds were removed.

4.3. Simulated pollen beetle damage under high and low cabbage stem flea beetle pressure.

Boxworth 2016

The mean plant number in mid-April was 16 plants/m^2 and there were an average of 6.6 CSFB larvae per plant, exceeding the threshold of five larvae per plant. There was an average of 60 buds per main raceme at the time of pruning. Therefore the pruning treatments of 0, 50 and 100% of main raceme buds was equivalent to a minimum of 0, 30 and 60 buds being removed per plant, assuming one pollen beetle can consume about nine buds per plant if present during the green/yellow bud growth stages (Ellis & Berry, 2012) this damage was equivalent to damage from

0, 3.3 and 6.7 pollen beetles per plant. Despite a trend for lower yields in the pruning treatments, there was no significant difference in the quadrat yields (Table 20).

High Mowthorpe 2016

The mean plant number at the end of April was 34.8 plants/m^2, and there were an average of 3.4 CSFB larvae per plant (below threshold). There was an average of 42 buds per main raceme at the time of pruning. This means that 0, 21 and 42 buds were removed per plant in the 0, 50 and 100 % pruning treatments, respectively; equivalent to a minimum of 0, 2.3, and 4.6 pollen beetles respectively, if it is assumed that one pollen beetle can consume about nine per plant (Ellis & Berry, 2012). However, there was no significant effect of pruning treatment on the quadrat yields at High Mowthorpe 2016 (Table 20).

Table 20. Cabbage stem flea beetle and pollen beetle interaction pruning experiment - results from Boxworth and High Mowthorpe in 2016.

	Boxworth	**High Mowthorpe**
Pruning treatment	**Quadrat yield (t/ha)**	**Quadrat yield (t/ha)**
0%	5.08	1.90
50%	4.37	2.28
100%	3.59	1.91
Grand Mean	4.35	2.03
P	0.266	0.273
SED	0.861	0.253
LSD	1.876	0.550

4.4. Calibrate pollen beetle monitoring traps against field populations of the pest

Plant density varied between the position within a crop and between fields both within year and between years leading to large variation in the possible pollen beetle threshold values applied to these crops according to the position in the field where they were sampled (Tables 21-23).

Table 21 Plant density (plants/m^2) and pollen beetle threshold (in parentheses) in field experiments on Rothamsted Farm, 2014

Field	Position	Plants/m^2			Transect mean Plants/m^2
		0-10 m	10-20 m	20-30 m	
Great Knott3[1]	NE	71 (7)	53 (11)	49 (18)	57.7 (11)
	SE	52 (11)	61 (11)	46 (18)	53.0 (11)
	SW	75 (7)	64 (11)	57 (11)	65.3 (11)
	NW	42 (18)	92 (7)	43 (18)	59.0 (11)
	Whole field average				58.8 (11)
Pastures[2]	NE	62 (11)	90 (7)	55 (11)	69.0 (11)
	SE	89 (7)	93 (7)	61 (11)	81.0 (7)
	SW	84 (7)	66 (11)	67 (11)	72.3 (7)
	NW	57 (11)	69 (11)	71 (7)	65.7 (11)
	Whole field average				72.0 (7)
Delharding[3]	NE	49 (18)	56 (11)	61 (11)	55.3 (11)
	SE	41 (18)	55 (11)	42 (18)	46.0 (18)
	SW	52 (11)	45 (18)	68 (11)	55.0 (11)
	NW	45 (18)	35 (18)	39 (18)	39.7 (18)
	Whole field average				49.0 (18)

[1] Great Knott 3 sowing details: cv Compass, dressed with Cruiser, drilled at 60 seeds/m^2 on 23/8/2013

[2] Pastures sowing details: cv Quartz, dressed with Cruiser, drilled at 60 seeds/m^2 on 5/9/2013

[3] Delharding sowing details: cv Quartz, dressed with Cruiser, drilled at 60 seeds/m^2 on 28/8/2013

Table 22. Plant density (plants/m²) and pollen beetle threshold (in parentheses) in field experiments on Rothamsted Farm, 2015

Field	Position	Plants/m² Distance from crop edge 1-10 m	10-20 m	20-30 m	Transect mean
Great Harpenden[1]	NE	27 (25)	33 (18)	36 (18)	32.0 (18)
	SE	22 (25)	26 (25)	25 (25)	24.3 (25)
	SW	27 (25)	25 (25)	30 (18)	27.3 (25)
	NW	22 (25)	32 (18)	32 (18)	28.7 (25)
	Whole field average				28.1 (25)
Long Hoos[2]	NE	29 (25)	6 (25)	44 (18)	26.3 (25)
	SE	61 (11)	11 (25)	38 (18)	36.7 (18)
	SW	30 (18)	11 (25)	39 (18)	26.7 (25)
	NW	58 (11)	10 (25)	36 (18)	34.7 (18)
	Whole field average				31.1 (18)
Little Knott 1[3]	NE	35 (18)	44 (18)	17 (25)	32.0 (18)
	SE	40 (18)	39 (18)	30 (18)	36.3 (18)
	SW	60 (11)	54 (11)	45 (18)	53.0 (11)
	NW	32 (18)	31 (18)	38 (18)	33.7 (18)
	Whole field average				38.8 (18)

[1] Great Harpenden sowing details: cv Charger, drilled at 60 seeds/m² on 24/8/2014

[2] Long Hoos sowing details: cv Quartz, drilled at 80 seeds/m² on 22/8/2014

[3] Little Knott 1 sowing details: cv Quartz, drilled at 80 seeds/m² on 22/8/2014

Table 23. Plant density (plants/m^2) and pollen beetle threshold (in parentheses) in field experiments on Rothamsted Farm, 2016

Field	Position	Distance of sample from edge of crop										
		30 m	27 m	30 m	27 m	30 m	27 m	30 m	27 m	30 m	27 m	30 m
Great Knott 3[1]	NE	24 (25)	24 (25)	12 (25)	28 (25)	24 (25)	24 (25)	24 (25)	24 (25)	20 (25)	28 (25)	23.2 (25)
	SE	28 (25)	20 (25)	24 (25)	24 (25)	28 (25)	24 (25)	24 (25)	28 (25)	20 (25)	28 (25)	24.8 (25)
	SW	24 (25)	32 (18)	16 (25)	12 (25)	8 (25)	12 (25)	20 (25)	24 (25)	24 (25)	32 (18)	20.4(25)
	NW	24 (25)	28 (25)	28 (25)	24 (25)	24 (25)	20 (25)	28 (25)	28 (25)	12 (25)	40 (18)	25.6 (25)
	Whole field average											23.5 (25)
Sawyers 2[2]	NE	40 (18)	32 (18)	32 (18)	40 (18)	24 (25)	32 (18)	24 (25)	20 (25)	25 (25)	16 (25)	28.5 (25)
	SE	27 (25)	32 (18)	28 (25)	36 (18)	32 (18)	32 (18)	24 (25)	28 (25)	28 (25)	40 (18)	30.7 (18)
	SW	4 (25)	20 (25)	28 (25)	40 (18)	52 (11)	8 (25)	12 (25)	24 (25)	8 (25)	16 (25)	21.2 (25)
	NW	32 (18)	28 (25)	28 (25)	16 (25)	28 (25)	36 (18)	40 (18)	32 (18)	24 (25)	48 (18)	31.2 (18)
	Whole field average											27.9 (25)
Osier[3]	NE	20 (25)	28 (25)	12 (25)	28 (25)	8 (25)	20 (25)	20 (25)	20 (25)	20 (25)	24 (25)	20 (25)
	SE	24 (25)	24 (25)	24 (25)	16 (25)	16 (25)	24 (25)	24 (25)	28 (25)	16 (25)	20 (25)	21.6 (25)
	SW	20 (25)	16 (25)	24 (25)	32 (18)	12 (25)	24 (25)	16 (25)	24 (25)	16 (25)	44 (18)	22.8 (25)
	NW	20 (25)	16 (25)	20 (25)	12 (25)	20 (25)	24 (25)	32 (18)	12 (25)	28 (25)	20 (25)	20.4 (25)
	Whole field average											21.2 (25)

[1] Great Knott 3 sowing details: cv DK Exalte, dressed with Cruiser, drilled at 50 seeds/m^2 on 21/8/2015

[2] Sawyers 2 sowing details: cv DK Exalte, dressed with Cruiser, drilled at 50 seeds/m^2 on 22/8/2015

[3] Osier 1 sowing details: cv DK Exalte, drilled at 50 seeds/m^2 on 22/8/2015

4.4.1. Differences in trapping efficacy between the three types of monitoring trap

There was a significant difference between the numbers of pollen beetles found in the three types of traps for years 2014 (Figure 10a) and 2015 (Figure 10b) ($P<0.001$ in each case); the commercial trap caught the most beetles and the spinning trap caught the least. In 2016 (Figure 10c) there was a significant difference between the traps and an effect due to the side of the field ($P<0.001$ in each case). Significantly more beetles were caught in the commercial trap compared to the experimental and spinning traps except on the NW side where there appeared to be very little difference.

4.4.2. Monitoring trap calibration

There was some evidence of a positive correlation between the numbers of pollen beetles caught in the commercial pollen beetle traps and the mean number of beetles per plant in the crop. The correlation coefficient was 0.46 (n=1065) for the transformed numbers of beetles in traps vs numbers on plants with no data restrictions. When field side was considered the improvement (i.e. got closer to 1) in correlation coefficients was variable (NE = 0.41, n=449; SE = 0.49, n=210; SW = 0.54, n=215 and NW = 0.41, n=191). When the data were restricted to green-yellow bud growth stage, the correlation coefficient was slightly improved (r = 0.58, n=448). The best correlations were returned when data were restricted by both GS 50-59 growth stage and field side: correlation coefficients as follows NE = 0.57, n=165; SE = 0.53, n=99; SW = 0.60, n=105; NW = 0.70, n=79 (Figure 11).

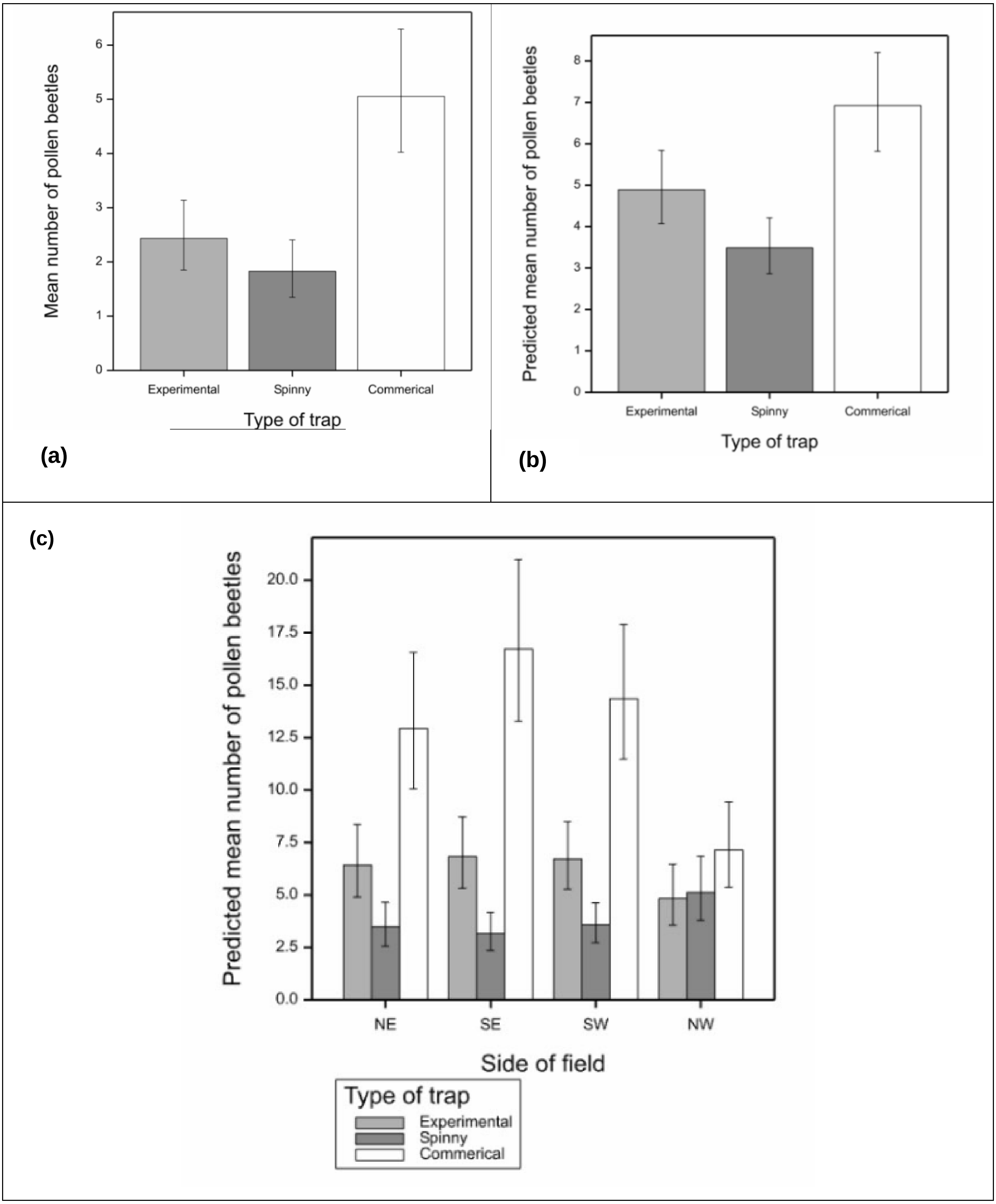


Figure 10. Numbers of adult pollen beetles caught on three types of monitoring trap (Commercial Oecos Pollen Beetle Monitoring trap baited with volatile lure, Experimental yellow sticky trap (unbaited) used in HGCA Project 504 (RD-2007-3394) and a Spinning version of the Experimental trap) during immigration into oilseed rape crops on Rothamsted Farm in 2014 (a), 2015 (b) and 2016 (c).

4.4.3. Monitoring trap calibration

There was some evidence of a positive correlation between the numbers of pollen beetles caught in the commercial pollen beetle traps and the mean number of beetles per plant in the crop. The correlation coefficient was 0.46 (n=1065) for the transformed numbers of beetles in traps vs numbers on plants with no data restrictions. When field side was considered the improvement (i.e. got closer to 1) in correlation coefficients was variable (NE = 0.41, n=449; SE = 0.49, n=210; SW = 0.54, n=215 and NW = 0.41, n=191). When the data were restricted to green-yellow bud growth stage, the correlation coefficient was slightly improved (r = 0.58, n=448). The best correlations were returned when data were restricted by both GS 50-59 growth stage and field side: correlation coefficients as follows NE = 0.57, n=165; SE = 0.53, n=99; SW = 0.60, n=105; NW = 0.70, n=79 (Figure 11).

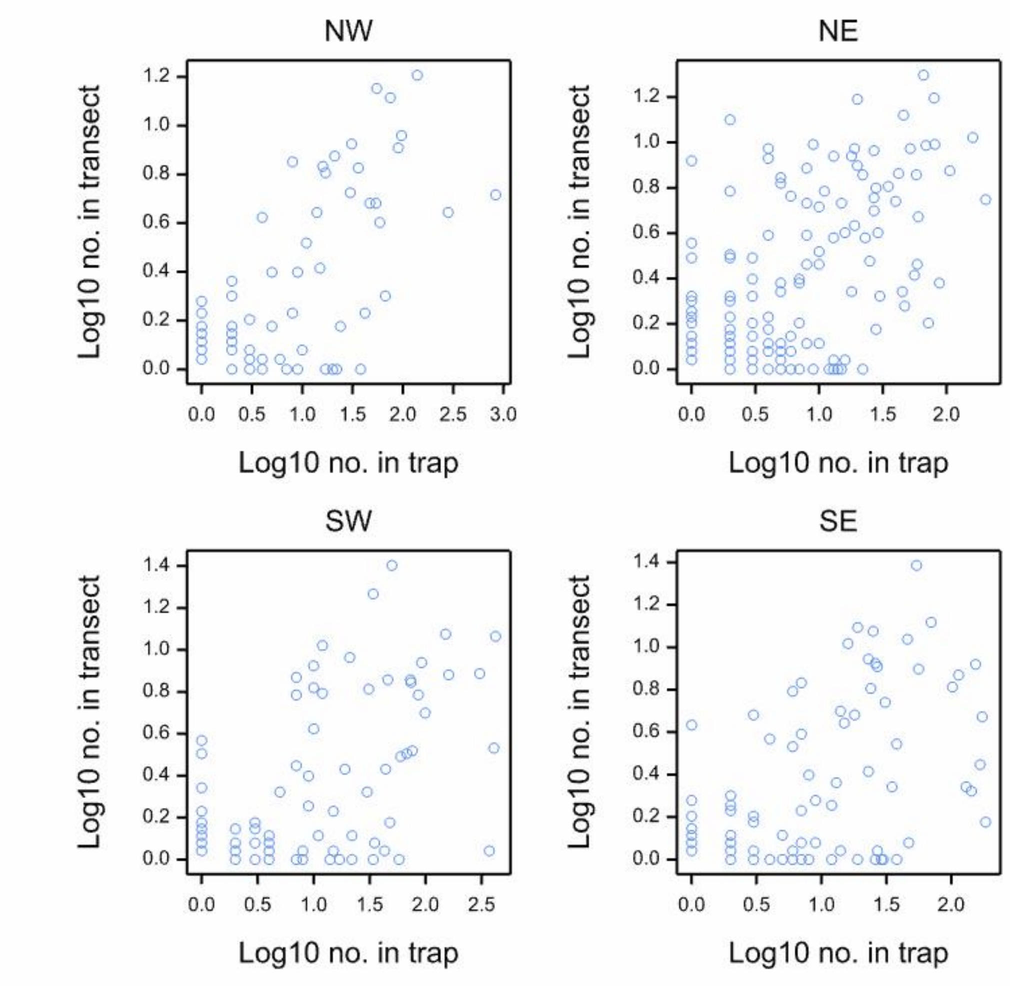


Figure 11. Correlation of number of pollen beetles per trap and number of pollen beetles per plant in the transects. NE represents sites from across the UK (including Rothamsted); NW, SW and SE traps represents those from Rothamsted only. Correlation coefficients as follows NE = 0.57, n=165; SE = 0.53, n=99; SW = 0.60, n=105; NW = 0.70, n=79.

An analysis of parallelism found the model that best described the data to be where separate lines were fitted for each of the years. This model explains approximately 38% of the variability in the number of beetles per plant in a transect (adjusted R^2-=37.9; Figure 12).

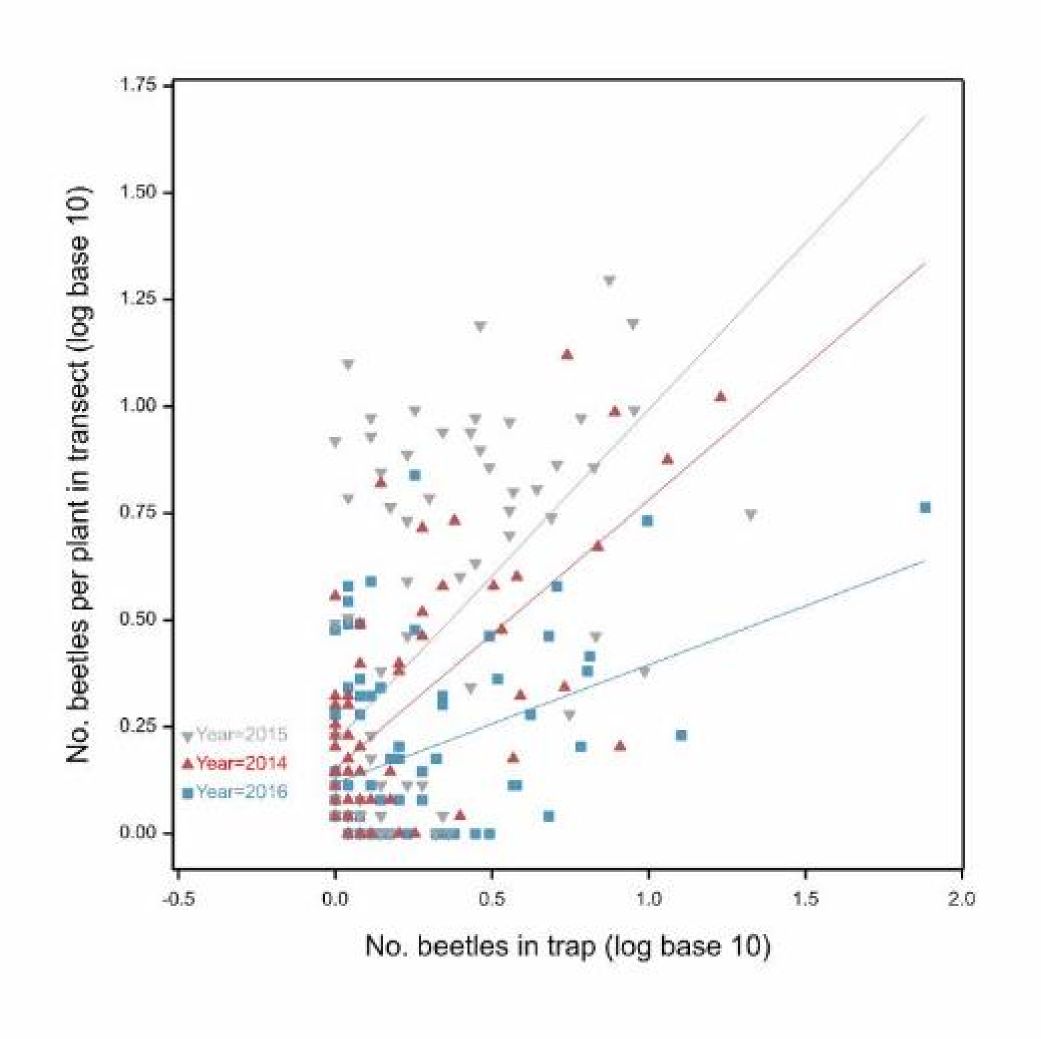


Figure 12. Relationship between the number of beetles caught in sticky traps and the mean number per plant in an adjacent transect.

4.5. Guidelines on how best to monitor pollen beetle numbers

4.5.1. Are pollen beetles more abundant at the crop edge than the centre?

Shade plots showing the number of pollen beetles per plant in monitoring transects for all sites in the current project are presented in full in Appendix 1. Changes in the number of pollen beetles in space (distance from crop edge) and in time (date) can be visualised. For most of the sites there seems to be a gradual rise in pollen beetle numbers early in the season as migration progresses then an obvious influx of the main migration. There does not appear to be any clear patterns displayed within the data regarding edge distribution of the beetles. In some sites, such as Great Harpenden 2015, there appears to be an edge effect with the density of beetles being greater at the crop edge than towards the centre (SE and NE; Figure 13) but this pattern was rather more the exception than the rule.

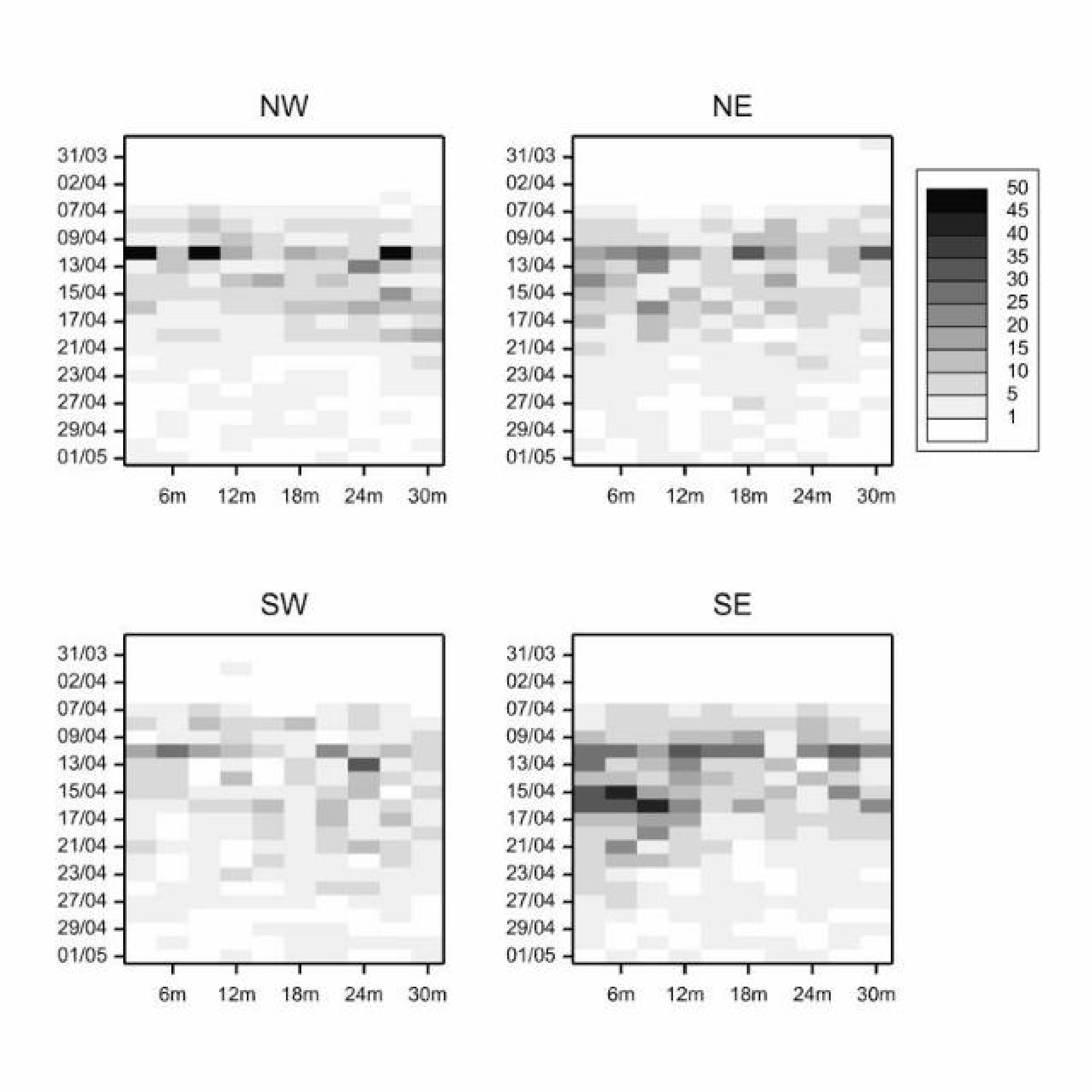


Figure 13. Shade plots showing the number of pollen beetles per plant and distance of plants from the crop edge on 10 plants sampled along 30 m transects from the crop edge into the crop (X-axis) on various sampling dates throughout the season (Y-axis): Great Harpenden Field, Rothamsted Research, 2015.

The analysis to explore how pollen beetle numbers change with distance into the crop found a significant difference between the number of beetles in the transect segments between the years and sides of the field ($P<0.001$). The profiles in Figure 14 show that the difference is mainly due to the result from 2016 on the SW side of the crop where a larger number of beetles were seen at 0-6 m and 25-30 m as compared to other years and the NE side. Otherwise there were no clear differences between the numbers of beetles across the transect.

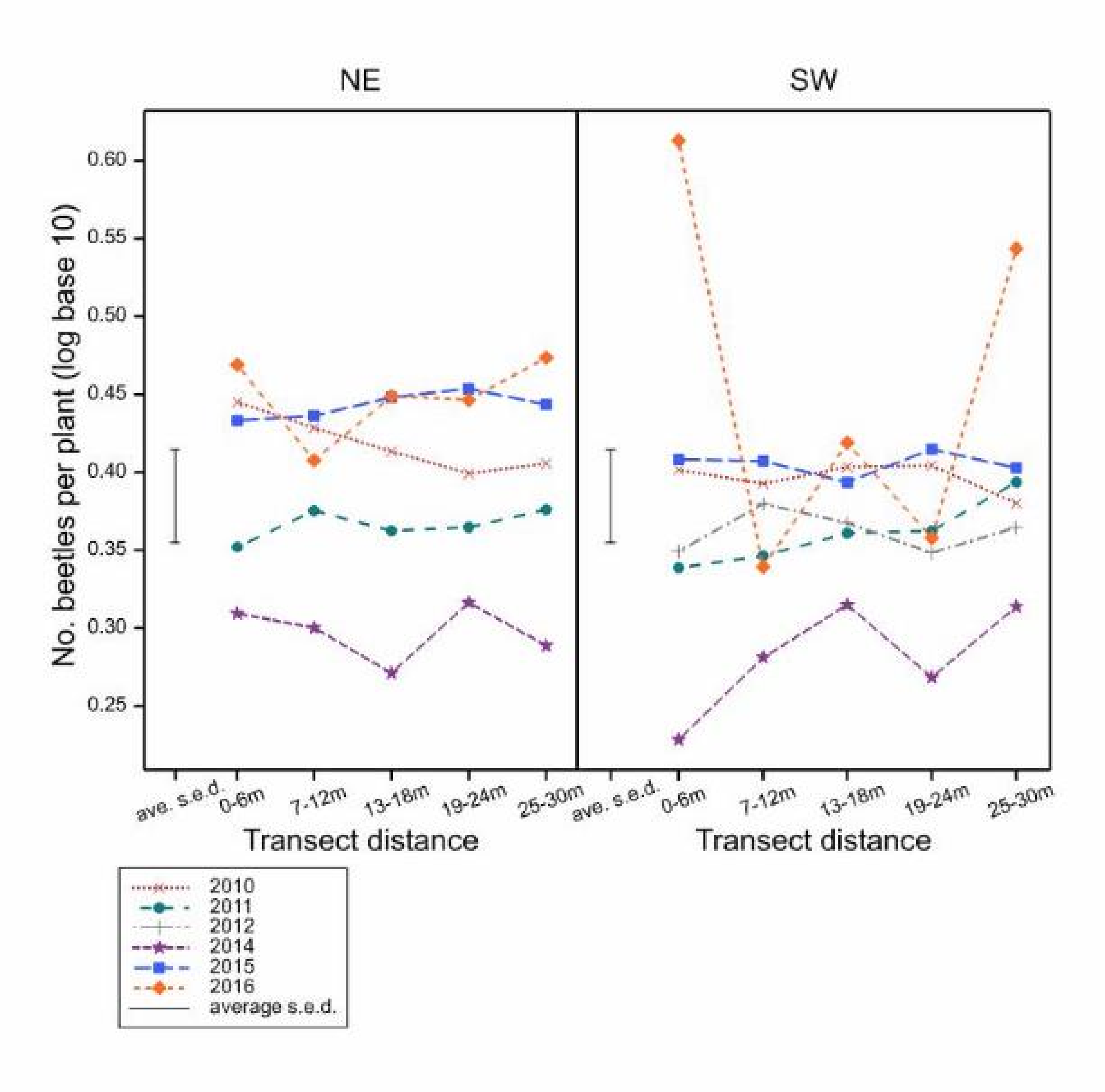


Figure 14. Relationship between numbers of beetles on oilseed rape plants at various distances from the edge of the crop on the north-east (NW) and south-west (SE) sides of the field, relative to down-wind and upwind, respectively of an assumed SW prevailing wind. Error bars shows average standard error of the difference.

4.5.2. Spatio-temporal dynamics of pollen beetle immigration into OSR crops

Plant density was variable within and between each field. Long Hoos varied between 18-79 plants/m^2; mean 39.8 plants/m^2; Great Harpenden 7-45 plants/m^2, mean 24.9 plants/m^2 and Little Knott 6-86 plants/m^2; mean = 40.3 plants/m^2 (Figure 15). The threshold values for pollen beetle control based on plant density could therefore range between 7-25 beetles/plant for Long Hoos and Little Knott, and 18-25 beetles/plant for Great Harpenden, depending on the position of the sample. Areas of severe pigeon damage were absent from Little Knott. Areas present in Long Hoos and Great Harpenden are shown in Figure 16.

The spatial distribution of pollen beetles in each of the three crops is shown throughout time (sampling date) along with relative plant growth stage in Appendix 2. Sampling started on 9th March 2015 before the pollen migration had started. The first beetles were recorded on 11th March for crops in both Great Harpenden and Long Hoos and 16th March for Little Knott; the first pollen beetle was found at the crop edge on only one of the three sites (Long Hoos) (Figure 17a). In all sites the next few pollen beetles were observed in patches throughout the crop (Figure 17b) until the first major migration occurred on all sites on 7 April. On this date 'hotspots' of beetles were observed on each site, generally concentrated in a discreet patch or patches located on one or two sides of the field (Figure 17c). The field sides on which this main immigration started were around the NE side for all three sites. Hotspots tended to be located in the less developed areas of the crop and were not apparently related to crop plant density or areas of severe pigeon damage.

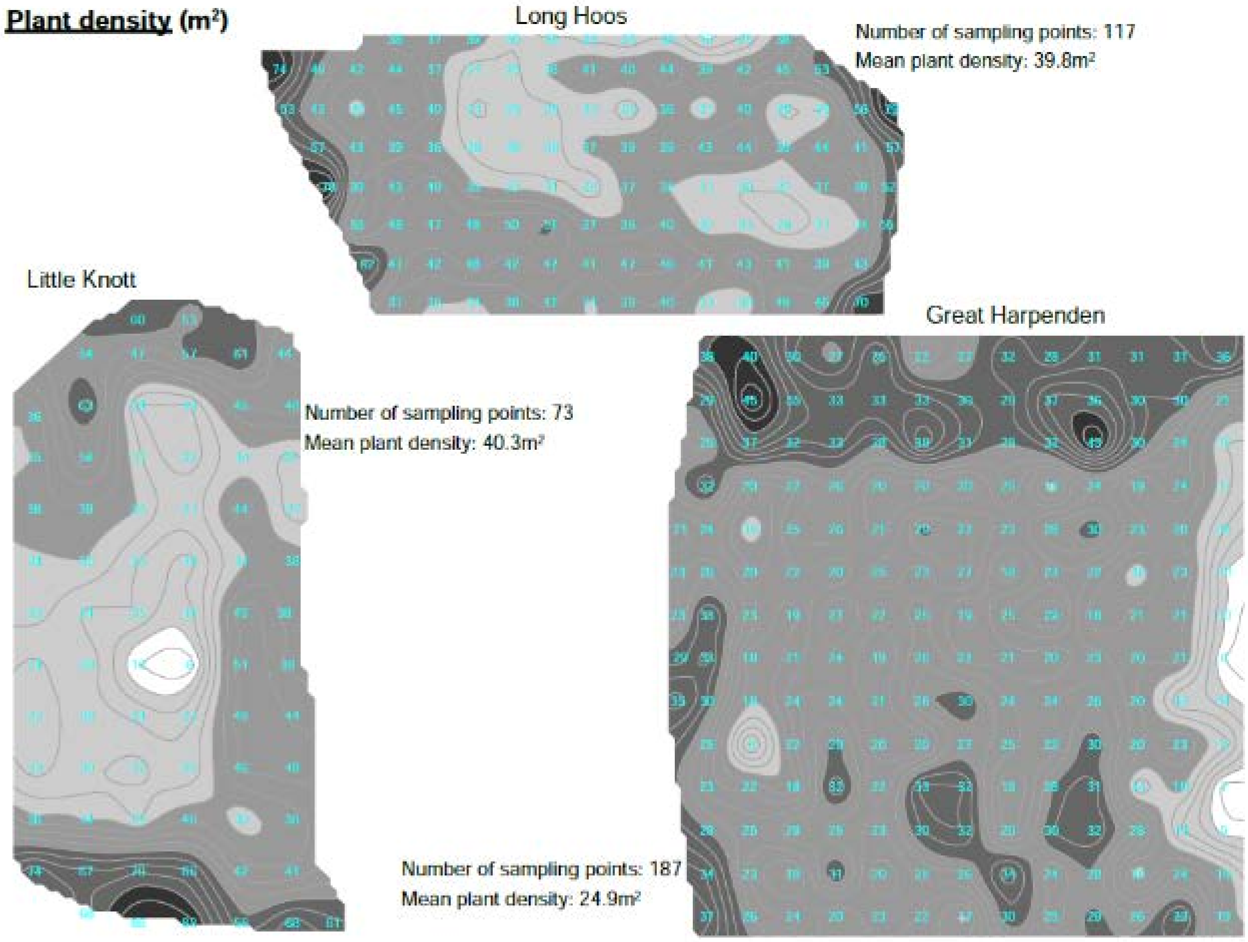
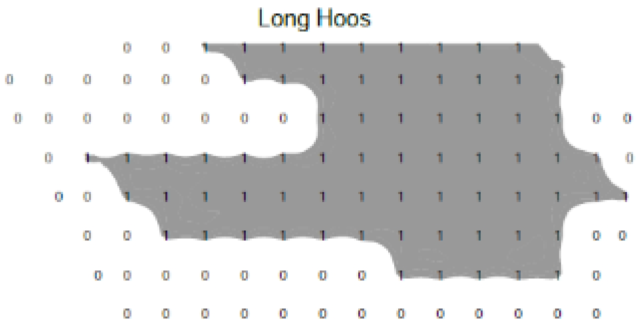


Figure 15. Plant density (plants/m^2) of oilseed rape plants in the experimental fields, Rothamsted Research 2015. Greyscale indicates plant density with the darkest areas being most dense and lighter areas less dense, scaled to enable comparison between sites. Numbers in blue represent the actual plant density recorded at each of the sampling points in the crop.

Severe pigeon damage



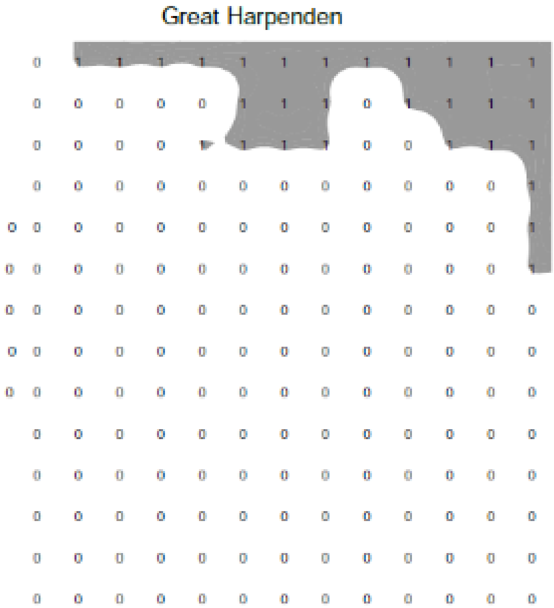


Figure 16. Areas of severe pigeon damage (terminal raceme bitten off by feeding damage) in crops of oilseed rape, Rothamsted Research, 2015.

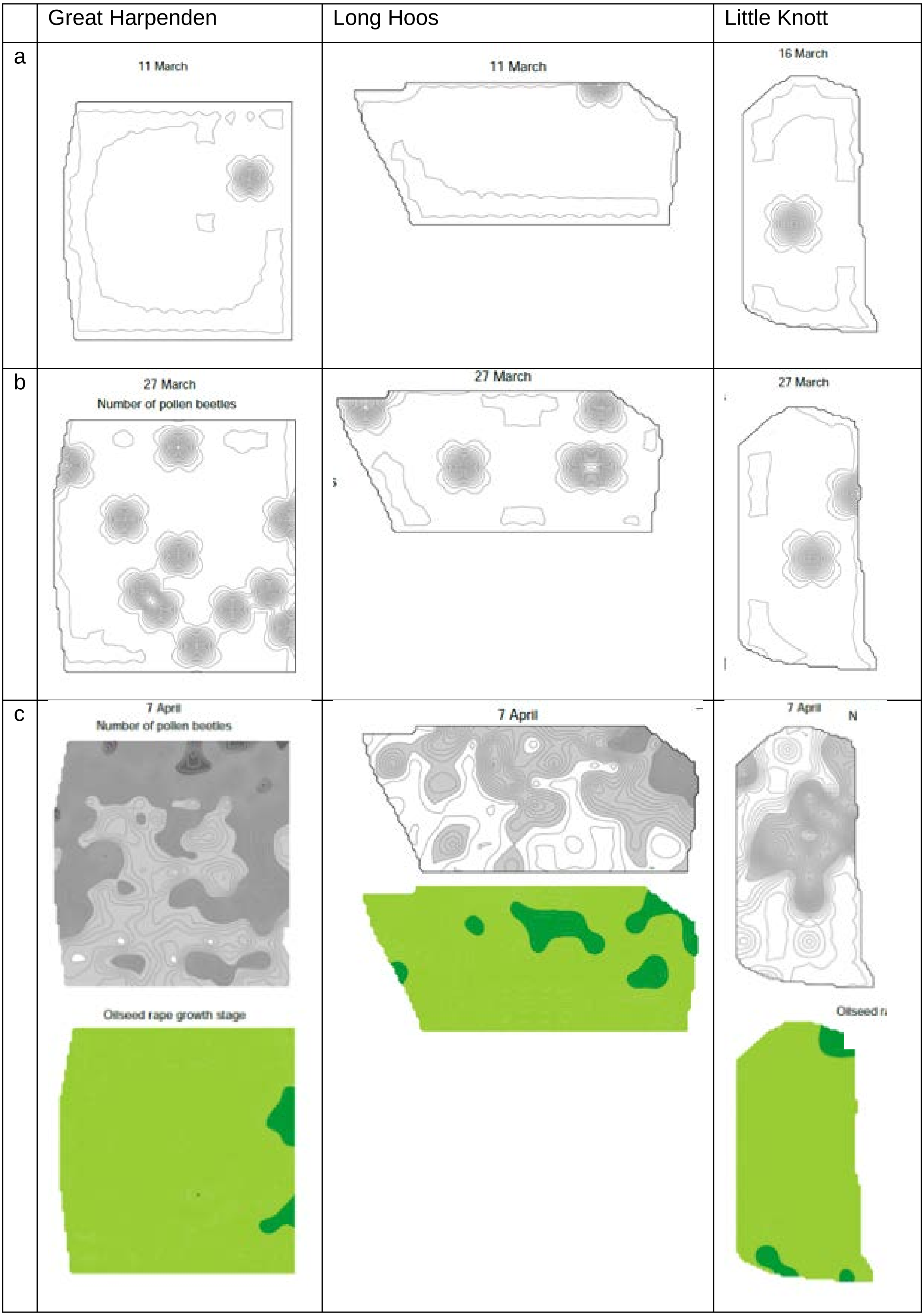


Figure 17. Spatio-temporal distribution of pollen beetles (grey scale) and OSR crop development (green/yellow colour) in three fields at Rothamsted Research, 2015. (a) First beetle recorded (b) next few pollen beetles arriving in patches throughout the crop(c) first main migration of pollen beetles showing discreet 'hot spot' areas of high density beetles (dark grey).

4.6. Assess the accuracy of the on-line decision support tool for pollen beetle immigration and investigate effects of use on spray timing and control

4.6.1. Assess the accuracy of the on-line support tool for pollen beetle immigration

The number of pollen beetles recorded on Oecos Pollen Beelte Monitoring Traps from each sampling date for each site in each year is shown in Appendix 4 together with with the daily predictions from the Bayer Pollen Beetle Predictor for migration start, new migration and percent completion of migration for the meterological station closest to that site. Site details are given in Appendix 5.

Overall, data were collected from 25 of the 92 met stations in the UK (including England, Wales and Scotland). Almost all sites were run by volunteers who responded to requests for help in this Project and are gratefully acknowledged (Section 9). In 2014, data were collected from sites associated with six met. stations: Grantham (Notts), Glastonbury (Somerset), Beverley (N Yorks), Lincoln (Lincs), Dereham (Norfolk) and Rothamsted (Welwyn Garden City (Herts; three sites). In 2015 nine additional sites were assessed: Selby (Yorks), Gainsborough (Lincs), Boston (Lincs), Aylsham (Norfolk), Worcester (Worcestershire), Leamington Spa (Warwicks), Chipping Norton (Oxfordshire), Shelford (Cambs) and Faversham (Kent). Two separate sites were run in association with met data from Faversham (in Lenham and Tilmanstone) and three sites were run at Rothamsted (Welwyn Garden City (Herts) for comparison with 2014. In 2016, ten additional sites were assessed associated with the following met stations: Haddington (Fife, Scotland), Brigg (Lincs), Louth (Lincs), Peterborough (Northants), Bungay (Suffolk), Haverfordwest (Ceredigion, Wales), Bedford (Beds), Bury St Edmunds (Suffolk), Tetbury (Glous), Plymouth, (Cormwall), Dorchester (Dorset). As in previous years sites associated with weather stations assessed in other years were assessed to provide comparisons between years: Beverley, (N Yorks), Selby (Yorks), Boston (Lincs), Worcester (Worcestershire), Chipping Norton (Oxfordshire), and Welwyn Garden City (Herts) (sites at Rothamsted and Knebworth).

Start of migration

The BPBP system predicted a start of pollen beetle migration for several sites as early as 26th February in 2014 (Figure 18). This is the earliest start to migration ever recorded to date and no sites in these areas had traps out early enough to validate this. Start of migtation in 2015 was more ususal, with sites in the south (Wimborne and Newport) starting on 4th March but no sites in our trials were near these met stations. In 2016 another early start to migration was predicted for Alysham (Norfolk) on 22/2/16 but none of the experimental sites were in this region that year.

Figure 18. Bayer Pollen Beetle Predictor ‘Migration Start’ map of UK showing red warnings for ‘migration started’ for several regions.

Comparing trap catches with BPBP predictions for the sites that had traps running early enough to validate the start of migration predictions, yellow dots ‘migration to start in the next few days’ were accurate to within 3 days of the recorded start of migration (first positive trap catch) on only 29.5.4% of occasions (n=17) rising to 65.0% (n=20) for accuracy within 7 days. Of the inaccuracies, the majority gave the warning too early, rather than late (respectively, 11 vs 1 occasion for accuracy within 3d, and 6 vs 1occasion for accuracy within 7d; see Appendix 5). Red dots (prediction for migration to have started in that area) were accurate to within 3 days for 66.7% of sites (n=30). Of the sites that were inaccurate, red warnings also tended to come early, rather than late (6 vs 4, respectively; see Appendix 5).

New migration events

Migration events were generally extremely well predicted by the BPBP system with most trap catches being being clearly associated with yellow or red predictions from the system for good or optimal conditions for migration (Appendix 4). Of equal importance is that periods predicted by the BPBP to be poor conditions for migration (green dots) were almost always associated with very low (or zero) catches of pollen beetles on traps in the field (Appendix 4).

End of Migration

In all years the end of migration was predicted to occur after the crop had reached GS61 when trapping ceased so the end of migration could not be validated on most sites. In 2014 the BPBP predicted migration would be complete between mid April and mid May. Five sites (100%) were able to validate the end of the migration around mid April. In 2015 and 2016 end of migration for some sites occurred mid May however no sites trapped long enough to be able to validate this. In 2015 the BPBP system shut down on 31st May and several sites had not reached 100% by this date; one site (Skegness, Boston) was only 28% complete by this date. In 2016 the BPBP system was shut down on 23rd May and again several sites had not reached 100% migration complete by this time.

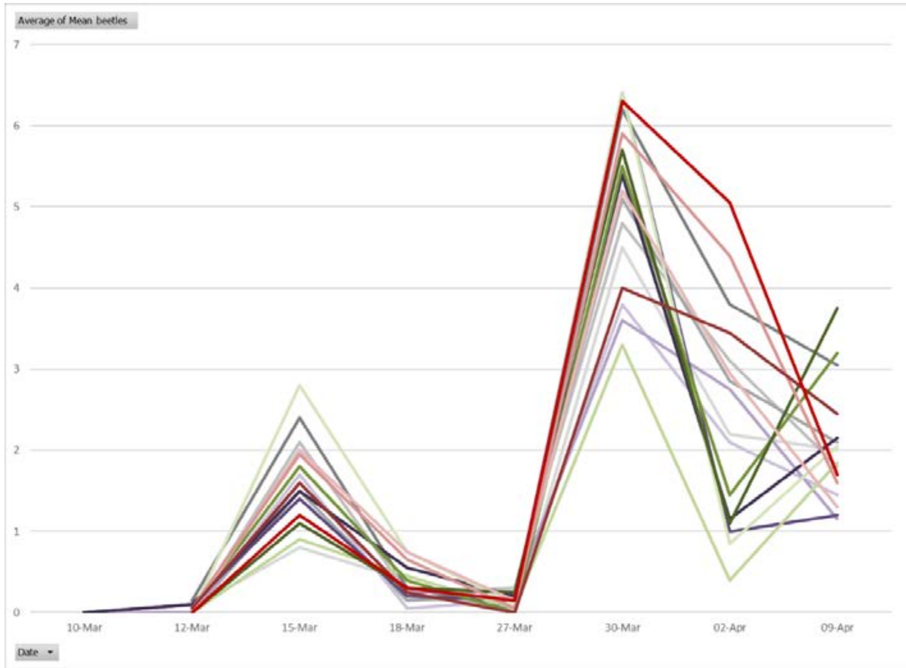
4.6.2. Effects of using the on-line decision support tool for pollen beetle migration on spray timing and control

Control systems were analysed from five crops in total (in 2015 the crop at Woburn farm failed). Plant density varied between fields and between years, ranging between 20-80 plants/m^2 over the five crops in three experimental years, however, the plant density in plots for each of the four systems were not significantly different at the start of the experiment (see Table 24).

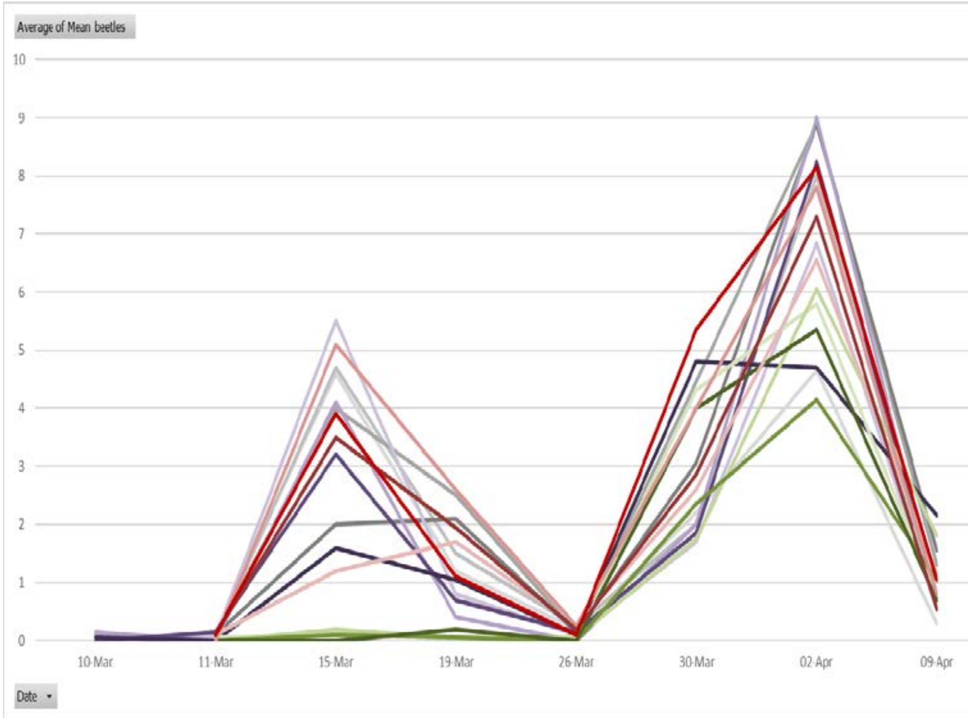
Table 24. Plant density per m^2 (mean ±SE) in plots of four control systems used to control pollen beetles in winter oilseed rape

Year	Field	No spray	Prophylactic spray	Spray to threshold – weekly monitoring	Spray to threshold – DSS	$F_{3,9}$	*P*-value
2014	Great Knott 3	71.25 (2.32)	81.75 (5.72)	84.25 (2.93)	80.50 (7.14)	1.06	0.415
2014	Drapers	47.25 (4.35)	42.50 (5.24)	42.50 (4.77)	51.50 (3.30)	1.26	0.345
2015	Delafield	26.00 (1.16)	27.00 (1.92)	26.00 (1.16)	30.00 (2.58)	1.59	0.258
2016	Great Knott 1	22.25 (1.32)	21.75 (0.75)	24.25 (1.18)	22.25 (1.11)	0.86	0.498
2016	Osier	23.75 (1.65)	21.00 (0.41)	22.75 (1.32)	20.75 (0.63)	1.45	0.292

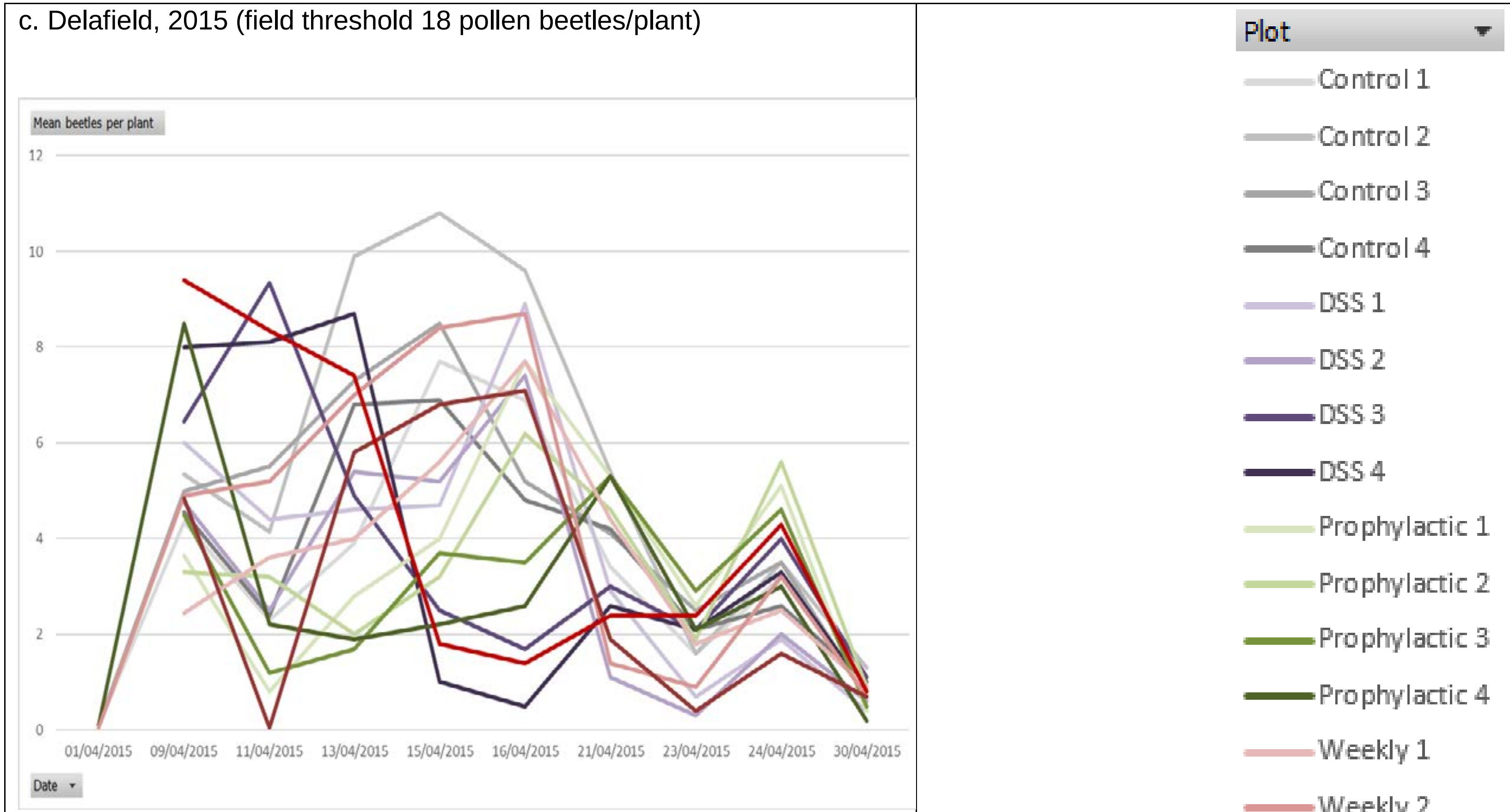
a. Great Knott, 2014 (field threshold 7 pollen beetles/plant)



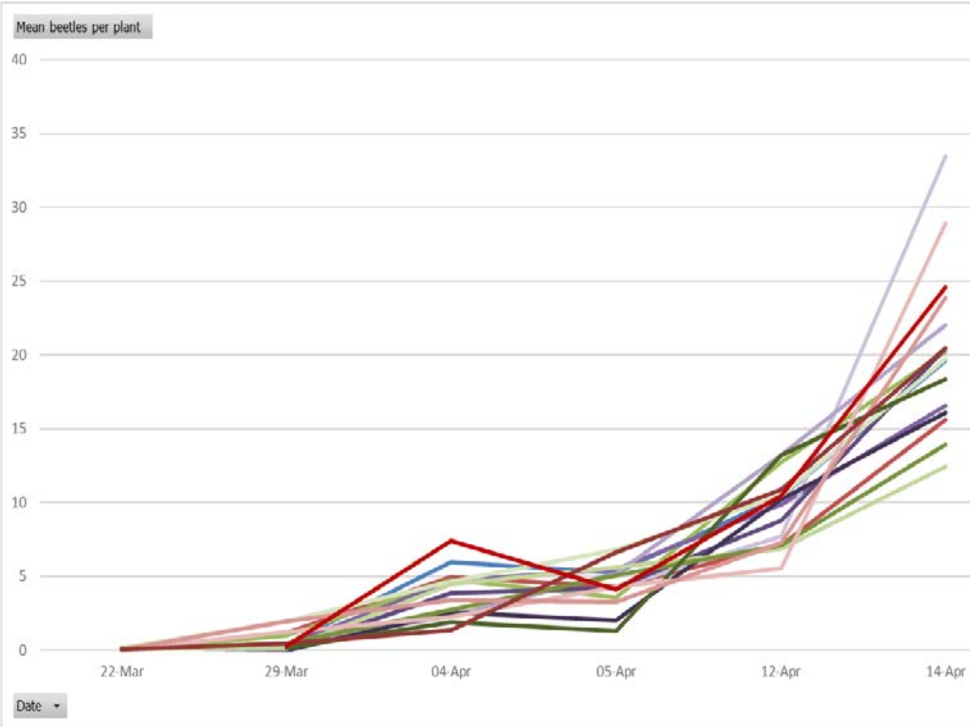
b. Drapers 2014 (field threshold 18 pollen beetles/plant)



c. Delafield, 2015 (field threshold 18 pollen beetles/plant)



d. Great Knott, 2016 (field threshold 25 beetles/plant)



e. Osier, 2016 (field threshold 25 beetles/plant)

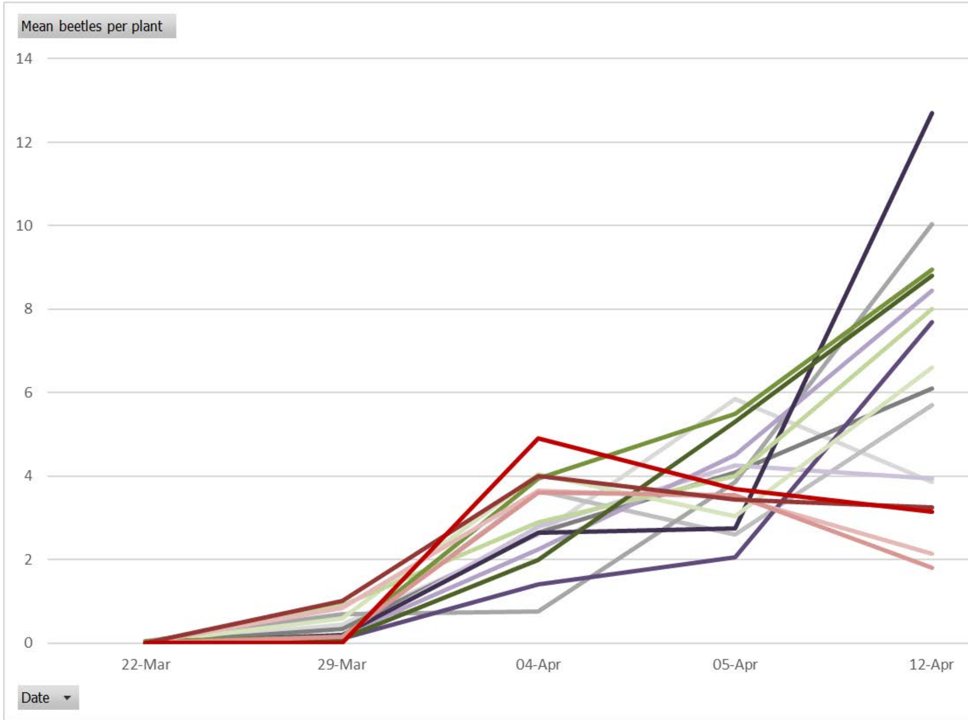


Figure 19. The mean no. pollen beetles/plant on plots of oilseed rape in five field experiments (a-e) over three years (2014-2016) using control systems for pollen beetles as follows: Control (no insecticide spray), Prophylactic (spray at greed bud stage and two weeks after), Weekly (spray to threshold with weekly monitoring), DSS (spray to threshold with monitoring prompted by the Bayer Pollen beetle Predictor on-line tool. The spray threshold expressed as no. beetles/plant, based on mean plant density is given in parenthesis next to the field name. X-axis shows date; Y-axis mean no. pollen beetles/plant

The mean number of pollen beetles per plant in each plot according to treatment system is shown throughout the monitoring period on each site/year in Figure 19; the whole-field threshold was not beached on any of the sites.

There was no significant difference found between the number of blind stalks (Table 25) nor the proportion of damaged buds (Table 26) in any of the systems in any of the experiments. Although Drapers in 2014 had a borderline significant difference in the proportion of damaged buds between treatments this result should be treated with caution as the model did not fit the data well and there were a lot of zero observations.

Table 25. Mean number of blind stalks (±SE) per main raceme in plots of four control systems (using artificially lowered thresholds) for control of pollen beetles in winter oilseed rape

Year	Field	No spray	Prophylactic spray	Spray to threshold – weekly monitoring	Spray to threshold – DSS	$F_{3,9}$	*P*-value
2014	Great Knott 3	2.38(0.313)	3.19(0.34)	2.56(0.32)	2.81(0.4)	2.03*	0.196
2014	Drapers	1.33(0.28)	1.07(0.21)	1.63(0.36)	1.75(0.3)	0.43**	0.738
2015	Delafield	3.63(0.36)	3.51(0.36)	3.45(0.43)	3.78(0.46)	0.09	0.966
2016	Great Knott 1	1.33(0.36)	1.08(0.19)	0.95(0.24)	0.675(0.19)	1.54	0.271
2016	Osier	0.55(0.2)	1.13(0.32)	0.775(0.23)	0.85(0.26)	0.64	0.606

*denominator degrees of freedom (ddf) = 7.2, **ddf = 10.8

Table 26. Proportion of buds with oviposition damage (mean ±SE) in plots of four control systems (using artificially lowered thresholds) for control of pollen beetles in winter oilseed rape

Year	Field	No spray	Prophylactic spray	Spray to threshold – weekly monitoring	Spray to threshold – DSS	$F_{3,9}$	*P*-value
2014	Great Knott 3	0.018(0.003)	0.008(0.0025)	0.019(0.0036)	0.017(0.005)	2.75*	0.109
2014	Drapers	0.01(0.004)	0.001(0.004)	0.004(0.003)	0.001(0.0007)	3.44**	0.052
2015	Delafield	0.22(0.02)	0.37(0.024)	0.4(0.027)	0.25(0.026)	1.01	0.431
2016	Great Knott 1	0.174(0.02)	0.18(0.02)	0.18(0.02)	0.177(0.02)	0.71	0.572
2016	Osier	0.32(0.03)	0.36(0.03)	0.32(0.036)	0.29(0.04)	1.47	0.287

*ddf = 8.5, **ddf = 12

There was no difference in yield between any of the control systems in any of the experiments done in 2015 and 2016 but there were significant differences in yield in 2014 (Table 27).

Regardless of system, when comparing the yield of plots that were insecticide treated and untreated, apart from Drapers in 2014, there were no significant differences (Table 28).

Table 27. Yield (at 90% dry matter, tonnes/hectare) of oilseed rape from plots of four control systems (using artificially lowered thresholds) for control of pollen beetles in winter oilseed rape

Year	Field	No spray	Prophylactic spray	Spray to threshold – weekly monitoring	Spray to threshold – DSS	$F_{3,6}$	s.e.d.	*P*-value
2014	Great Knott3	5.21[b]	5.41[a]	5.13[b]	5.05[c]	6.56	0.088	0.025*
2014	Drapers	4.462[c]	4.81[a]	4.71[b]	4.63[c]	5.37	0.052	0.039*
2015	Delafield	4.42	4.44	4.46	4.58	0.35	0.169	0.789
2016	Great Knott1	4.02	3.88	3.94	3.96	0.43	0.130	0.740
2016	Osier	3.85	3.88	4.18	4.00	2.18	0.143	0.191

*Treatments with different letters are significantly different from each other

Table 28. Yield (at 90% dry matter, tonnes/hectare) of oilseed rape from plots which received insecticide treatments and those that did not (regardless of of four control systems used to control pollen beetles)

Field site	Year	Mean Yield (n)		s.e.d.	$F_{1,8}$	P
		Spray	No Spray			
Drapers	2014	5.342 (n=8)	5.048 (n=8)	0.099	8.47	0.018
Great Knott 3	2014	4.717 (n=7)	4.673 (n=9)	0.071	0.39	0.548
Delafield	2015	4.494 (n=11)	4.436 (n=5)	0.127	0.21	0.659
Great Knott 1	2016	3.911 (n=11)	4.030 (n=5)	0.091	1.71	0.227
Osier	2016	4.029 (n=8)	3.926 (n=8)	0.121	0.72	0.422

The performance of the four control systems for pollen beetle is presented for each site in each year of the experiment in Appendix 3. Summarisng the data across the whole experiment there were clear differences in some of the measures used to compare performance of the pollen beetle control systems tested in this experiment (Table 29). In general a weekly monitoring system was a more labour-intensive method of identifying spray thresholds than using the DSS (an average of 5.6 times/season compared with 3.6 times/season, respectively) although this was not evident in each year of the study The proportion of occasions when the threshold was exceeded identified by the DSS system was 83% compared with 52% when monitoring was done on a weekly basis. The DSS system detected when a threshold was exceeded generally earlier than the weekly monitoring system, with a delay of 0.17 days between the first experimental threshold detection and detection by the system compared with a delay of 1.15 days for the weekly monitoring system. When no monitoring was done (in the no-spray and prophylactic spray treatments), there were more occasions when the threshold was exceeded that were missed completely, resulting in a missed treatment, than in the control systems involving monitoring; fewer treatments were missed when using the DSS than when treatment was prompted by a weekly monitoring system. Most insecticides were applied in the prophylactic treatment followed by the treatment where sprays were applied to threshold as prompted by the DSS. Least were used following the weekly monitoring system.

Table 29). Performance of four control systems (using artificially lowered thresholds) for control of pollen beetles in winter oilseed rape; Summary of five experiments done between 2014-2016 at Rothamsted Research (for details of each individual experiment see Appendix 3).

Assessment	System			
	Spray to threshold - Weekly monitoring	Spray to threshold - DSS-prompted monitoring	Prophylactic spray	No spray
Mean No. monitoring events/site	5.6	3.6	0	0
Mean No. plots (from four) with thresholds exceeded/site	3	3	2.4	3.6
Mean Total no. times threshold reached/site	5	3.6	2.6	5.4
Total no. times threshold exceeded (all sites)	25	18	13	27
Proportion of times threshold exceeded and identified by system	0.52	0.83	0	0
Proportion of times threshold exceeded but missed by system	0.48	0.17	1	1
Mean no. days delay between 1st experimental detection and system detection	1.15	0.17	NA	NA
Total No. missed treatments	3	2	7	19
Mean no. treatments applied	2.4	2.6	6.4	0

5. Discussion

5.1. Insecticide experiments

The number of pollen beetles pre-insecticide treatment varied between the sites, with the highest numbers at Terrington in 2015 (4.8 beetles per plant). However, when considered alongside the number of plants/m^2 the sites with the highest relative pollen beetle pressure were High Mowthorpe and Boxworth in 2014. This is because they had the highest plant numbers (55 and 63 plants/m^2, respectively) and therefore the lowest threshold of 11 beetles per plant. The pollen beetle thresholds of the six WOSR sites and one SOSR site over the past three years ranged from 11 to 25 beetles per plant. However, the number of beetles per plant only ranged from 0.9/plant to 4.8/plant across the seven sites, thus no site exceeded the threshold recommended for treating with insecticide. This is in agreement with the FERA pollen beetle survey data from 2004 to 2014. This survey found that there were between 0.9 and 5.0 pollen beetles per plant on average across the UK. When broken down into regions (East, Midlands, North East, North West, South East, South West and Yorkshire), the mean beetle number per plant ranged from 0 to 9.1. Over the 11 years of sampling, only 16 sites exceeded the original 15 beetles per plant threshold out of a total of 462 studied (3.5%), and five of these were in 2004. Therefore the numbers of beetles observed in the this experiment can be considered typical and representative of the vast majority of UK sites.

At five of the six sites where insecticides were compared for pollen beetle control there was no significant impact of treatment on yield. This result suggests that the thresholds calculated for these sites, based on plant populations, are a good indicator of the requirement for insecticide treatment. The lack of a yield response was despite insecticide application reducing beetle number compared with the untreated control at six out of seven sites.

The only site at which there was a significant effect of insecticide application on yield was Terrington in 2016. In this experiment Hallmark and Biscaya treated plots had a higher yield than the untreated control. If the insecticides were killing beetles this would be reflected in the % change in numbers/plant after treatment. This was not the case with no significant difference between insecticide treatments and the untreated control.There was also was no relationship between the number of beetles or change in number of beetles following insecticide application and crop yield. Thus the significant yield increases at Terrington in 2016 are unlikely to be a consequence of insecticidal control of pollen beetle. It is possible that the insecticide treatments may have affected other pests. For example there were diamond back moths and mealy cabbage aphids observed at the site. These pests were not thought to be at damaging levels and so numbers were not assessed, but it is possible that the effect of their combined feeding together with that of low numbers of pollen beetle resulted in lower yields in the untreated control.

Overall, it can be concluded that across the six WOSR sites and one SOSR site, the application of insecticides did not significantly increase yields, despite often reducing pollen beetle numbers. These experiments therefore provide validation of the new threshold scheme (AHDB 2013) as treating pollen beetle populations below the threshold did not result in significant yield increases. The levels of pollen beetle were representative of those typically observed in commercial crops which regularly receive insecticide treatments (Figure 1). Therefore this work should give growers confidence not to treat unless thresholds are exceeded.

It was not possible to determine whether canopy size could be used as an indicator of crop tolerance to pollen beetle damage in this study, as there was insufficient pollen beetle pressure to cause a reduction in yield. Previous work has found that the relationship between GAI and excess flowers per plant was inconsistent (Ellis and Berry, 2012), but that there was a more consistent negative relationship between the number of plants/m^2 and excess flowers per plant.

Despite there being no significant effect on yield, the data from this project can be used to comment on the efficacy of insecticide treatment as beetle numbers were significantly reduced in response to insecticide application in most experiments. This may help to decide which insecticide is most likely to control pollen beetle populations in an above threshold year when treatment is warranted. Hallmark was less effective at controlling beetle at Terrington in 2016 than any of the other sites. As the active ingredient of this insecticide is a pyrethroid, this could have been due to an increased proportion of pyrethroid resistant beetles at this site than other sites, but pyrethroid susceptibility was not assessed in these experiments. Biscaya was also significantly less effective at controlling beetle numbers at Terrington in 2016 than at High Mowthorpe in 2014 or 2015 or Boxworth in 2014. In contrast, the other insecticides were relatively consistent in their efficacy between sites.

5.2. Simulated pollen beetle and pigeon damage experiments

Four defoliation experiments were done in WOSR over the course of the project to simulate severe pigeon damage. In two of the four experiments, yield was significantly reduced by defoliation. When all four sites were combined in a cross site analysis, yield (as measured in 12 m x 3 m plots by a small plot combine) was reduced by 0.23 t/ha by defoliation but this effect was not statistically significant. The greatest yield loss of 0.54 t/ha occurred at Rosemaund in 2014. Spring rainfall was below average, meaning that the dry conditions may have restricted compensatory growth. At High Mowthorpe in 2014, the defoliation occurred later in the season and the growing point was removed which may explain the significant but small yield loss in this experiment. In the Rosemaund and High Mowthorpe WOSR 2015 experiments, the impact of defoliation on green area index (GAI) was measured. Defoliation reduced GAI by 2 on average across the two seed rates at Rosemaund and by 0.8 on average at High Mowthorpe. There was a greater yield reduction in response to defoliation at Rosemaund in comparison to High Mowthorpe, which may be attributed to the significant reduction in crop N content by reducing the canopy size by 2 GAI units i.e. 100 kg N/ha. It is also worth noting that the high seed rate is likely to have had a super optimal canopy size at Rosemaund (GAI of 3.2) and it is therefore possible that a less severe defoliation treatment may have had a positive effect on yield by optimising canopy size at flowering. The defoliation treatment was very effective at simulating pigeon damage, with leaf material stripped away. Given the high severity of the defoliation, it was surprising that yield losses were not greater and provides evidence to suggest that OSR is extremely tolerant of severe pest damage when conditions allow compensatory growth. In both Australia and Canada, dual-purpose OSR are grown for forage and seed production in sheep-grazing systems. This practice was reviewed by Dove & Kirkegaard (2014), who concluded that when sown early and grazed in winter before stem elongation, later-maturing wheat and OSR crops can be grazed with little impact on grain yield. Maintaining seed yield depends upon the timing and extent of defoliation in relation to plant development and the seasonal conditions for recovery and regrowth (Kirkegaard *et al*., 2012). The results of defoliation studies in this project support findings in the Australian and Canadian work and could have practical implications for other pests. For example, it is possible that the impact of pigeon grazing on crop yield is over estimated sometimes, although the impact of the distribution of damage on compensatory ability requires further investigation. It is also possible that mowing or grazing by farm animals offers an opportunity to control CSFB larvae, particularly where they are predominantly located in the leaf petioles. Where crops are defoliated the larvae will be lost in the mown/grazed plant material and are unlikely to be able to re-invade, particularly if the mown crop is removed. This option could be particularly valuable where high larval populations and insecticide resistant CSFB are recorded.

Overall there was little, evidence to suggest that simulated pollen beetle damage (bud pruning) in which up to 100% of buds on the main raceme were removed had any impact on the yield of the crop. In order to calculate the number of pollen beetles that would have been equivalent to the bud pruning treatments, the number of buds on the terminal raceme were counted at High Mowthorpe in 2015. On average across the two seed rate and two defoliation treatments, 74 buds on the terminal raceme were removed in the 100% pruning treatment. If it is assumed that a single pollen beetle can damage about nine buds during green/yellow bud growth stages (Ellis & Berry, 2012 then the removal of 74 buds by pruning simulates the damage that would be caused by a minimum of eight pollen beetles. It should be recognised that the estimate of nine buds destroyed by a pollen beetle represents the maximum number of buds that can be destroyed by a beetle that is not competing for food with other beetles. Ellis and Berry (2012) showed that when 10 beetles were introduced together the number of buds destroyed per beetle decreased to six. It is likely that this reduction was due to competition for food resources given that the beetles in this experiment were confined to a single plant. This is also likely to occur under field conditions, so the estimate of how many pollen beetles were equivalent to the pruning may be too conservative. In the pruning experiment at High Mowthorpe 2015, the two seed treatments had average plant populations of 37 and 73 plants/m^2, giving pollen beetle thresholds of 23 and 9 per plant respectively. Therefore the damage imposed in the pruning experiments would have been equivalent to a sub-threshold pollen beetle population for the low seed rate and close to threshold for the high seed rate. Since no significant yield losses were observed from this level of pruning this is good evidence that pollen beetle numbers below the current thresholds are unlikely to require control measures. The Fera pollen beetle survey suggests that high pollen beetle numbers are the exception rather than the norm. However, under conditions where there are above threshold levels of the pest which are not controlled, continued feeding pressure may affect the compensatory ability of the plant. Addressing this possibility was beyond the scope of our experiments but requires further work. Overall there was no significant effect of bud pruning on yield representing a partial validation of the threshold by confirming that beetle numbers below threshold do not need to be controlled.

In calculating pollen beetle numbers equivalent to the numbers of buds from plants we have used the data of Ellis & Berry (2012) which suggests that a single beetle can destroy up to nine oilseed rape buds during the green/yellow bud stage of the crop. Other workers (Ekbom & Borg, 2006 and Ferguson *et al*, 2015 have suggested that the level of damage from one beetle may be much higher. Ferguson *et al*., (2015) investigated feeding and oviposition damage to a cut raceme of glasshouse-grown spring OSR (cv.Heros) with its stem inserted into the floral foam and onto which a single female beetle was introduced. Racemes presented were selected to be as uniform as possible, with a minimum of ten buds of optimum size for oviposition (2–3mm long), together with the terminal rosette of smaller developing flower buds, but no larger buds. The studies were done in controlled environment cabinets at temperatures ranging from 12-20^{o}C. The total number of damaged buds increased with temperature with the majority of buds being injured by feeding. Three-quarters of all buds that were fed upon were ‘small buds’ ranging from 0.5 mm to < 2 mm. Increasing numbers were fed upon at higher temperatures. All eggs were laid into buds 2–3mm long, and separate feeding damage lesions were not observed in buds with eggs. Both the number of buds with eggs and the total number of eggs laid increased with temperature. The maximum number of buds damaged was seven and the maximum in which eggs were laid was six. The level of damage occurred over 20 hours (approximately one day) whereas in the work of Ellis & Berry (2012) beetles were exposed to buds over about 11 days. If each beetle consumed seven buds per day then over 11 days a total of 77 buds would be consumed which would significantly decrease the calculated threshold. However, the experiments of Ellis & Berry were conducted in a poly-tunnel in which the sides wert raised and the doors left open so beetles were exposed to ambient temperatures. Mean temperatures ranged from 6.4-15.4^{o}C and minimum temperatures were as low as 0.8^{o}C over two nights. These variable temperatures would have affected beetle feeding and overnight it is possible that there would have been no feeding at all. Also in controlled environment studies racemes were selected with buds that were suitable for feeding or oviposition whereas in the semi-field study the size of buds will have changed over the period of the experiment so thaty at some point some may have become less preferred for feeding or oviposition. This may go some way to accounting for the differing levels of damage recorded in controlled environment and semi-field studies.

It would be possible to test what happens with more severe bud removal on both terminal raceme and primary secondary and tertiary branches to simulate exceeding the pollen beetle threshold by a substantial amount. Damage to the secondary and tertiary branches will be affected by plant population. Branching is most likely to occur in low plant populations which will also have a high pollen beetle threshold due to high numbers of excess buds. Pollen beetles pierce the perianth to access pollen in the developing anthers inside the buds. There is no evidence that entire buds are eaten, and the amount of damage needed to cause bud abortion is unknown. Therefore it may be that complete removal of buds on a single occasion as employed in this study has a more severe impact on the plant than natural pollen beetle feeding. Pollen beetle feeding is known to be affected by bud size, with buds that are 2-3 mm long being preferred (Ekbom & Borg, 2006; Ferguson *et al.,* 2015). It is therefore unlikely that they would focus their feeding on the terminal raceme if buds of a preferred size are available on other branches. The growth stage of the plant at which pollen beetle damage occurs may also affect the ability of the plant to compensate for damage. This was not studied in our experiments but is acknowledged by the threshold system in many European countries being based on crop growth stage (Williams, 2010). This also requires further investigation. The impact of removing a small number of buds from many branches is unknown. However, it should be acknowledged that Fera Crop Monitor data and assessments made during this project have rarely recorded pollen beetle numbers above threshold. Therefore whilst it would be expected that pest numbers above the threshold would have an impact on crop yield this is likely to be the exception rather than the norm and in no way justifies the level of insecticides currently used that are specifically targeted at this pest (see Figure 1)

5.3. Simulated pollen beetle damage under high and low cabbage stem flea beetle pressure.

This experiment investigated whether exposure to CSFB larval feeding affects the ability of an oilseed rape crop to compensate for pollen beetle damage as simulated by bud pruning. Two sites were selected, one in north Yorkshire where larval numbers were below the 5/plant threshold (3.4/plant) and one in Cambridgeshire where larval numbers were above threshold (6.6/plant). At neither site was there any impact of bud pruning on crop yield. The most severe pruning treatment was calculated to be the equivalent of 6.7 pollen beetles/plant suggesting that up to this level of bud loss CSFB larval populations of up to 6.6/plant had no impact on the ability of the crop to compensate for pollen beetle damage.

In the east of England very high levels of CSFB larval infestation have been recorded. White (2015) recorded up to 27.8 larvae/plant in Cambridgeshire which is significantly above the five larvae per plant threshold and almost four times higher than the level recorded in the bud pruning experiment in Cambridgeshire reported in this project. It is likely that such a high level of CSFB infestation would affect the ability of the crop to compensate for subsequent pollen beetle damage and this is something that is worthy of further investigation.

5.4. Calibrate pollen beetle monitoring traps against field populations of the pest

Plant density varied between the position within a crop and between fields within year and between years. Variation in plant density within a crop led to large variation in the pollen beetle threshold values. If threshold for a crop was based on a single count of plant density, values could have ranged widely (e.g. between 7-18, Great Knott, 2014 or 11-25, Long Hoos 2015 and Sawyers 2, 2016). It is recommended in the AHDB monitoring guidelines that plant density should be estimated at several positions within a field (HGCA, 2013). However, even if plant density was averaged across several samples along a transect, the threshold returned for transects on different sides of the field often varied from that of the whole-field average. It is questionable whether a sampling strategy to return a relatively accurate estimate of plant density over a whole field is practical for growers; as plant density varied between fields on the same farm within year this suggests that each crop on the farm should be assessed. As plant density varied for the same field between years the position within a crop and between fields within year and between years it also doesn’t follow that high risk fields one year will be high risk in another year, based on this assessment.

5.4.1. Differences in trapping efficacy between the three types of trap

The commercial monitoring traps were consistently significantly more effective (i.e. caught more pollen beetles) than unbaited yellow sticky traps (spinning and static). This is likely to be due to the increased attraction of beetles to traps due to the phenylacetaldehyde lure. Phenylacetaldehyde is a common floral volatile known to be attractive to pollen beetles in the quantities released by the bait (Cook *et al*., 2007; Cook *et al*., 2013). Increased trapping efficiency means that the start of migration is more likely to be detected and abundance is less likely to be under-estimated compared with use of non-baited traps. We therefore recommend the use of these traps for monitoring pollen beetle movement and for estimates of abundance.

We hypothesise that if the traps were always facing into the wind (to catch pollen beetles as they fly upwind using anemotaxis) more beetles would be caught than in traps which are in a fixed position. However, the spinning traps caught significantly fewer beetles than the fixed traps. This is likely to be because the aluminium plane did not have the desired effect; traps were often observed spinning continuously in high wind and sudden gusts of wind often left them in the wrong position with respect to following prevailing wind direction. It is possible that further engineering of the traps would improve performance but this was beyond the scope of the current project.

5.4.2. Calibration of the pollen beetle monitoring trap

There was a moderate correlation between the numbers of pollen beetles caught in commercial monitoring traps (changed every 2-3 days) with the mean number of pollen beetles per plant in monitoring transects, especially when side of the field was considered and data restricted to transects walked when the crop was at green-yellow bud stage. This is precisely when the crop is at its most susceptible and when growers would be monitoring for threshold numbers of beetles. However, although the correlations were significant, this is quite common when there are a lot of data and there was much unexplained variability. The linear relationship between the number of beetles in the trap and the mean number of beetles per plant from transect monitoring was positive in each of the three years in this study. However, the relationship varied between years so it is not currently possible to relate the number of beetles caught on a trap to an equivalent number per plant to determine if the threshold has been exceeded. The data suggests that the calculated number per plant would be correct on only 38% of occasions and this is insufficiently accurate for growers and advisors. Further modelling work using other variables known to affect trap catch i.e. temperature and wind speed/direction (Cook *et al*., 2013; Skellern *et al,* in press) is being done (beyond the scope of this project) and may explain this difference and improve the ability to predict numbers per plant from trap catches.

From Figure 11 it is clear that threshold numbers of beetles were rarely exceeded (also see Appendix 6) , supporting experiments conducted in Objectives 1-3, 5 and data from Fera, indicating that pollen beetle populations rarely merit control.

5.5. Provide guidelines on how best to monitor pollen beetle numbers

5.5.1. Are pollen beetles more abundant at the crop edge than in the centre?

The pollen beetle monitoring procedure suggests that at least 10 plants should be sampled in a transect from the headland into the crop. This is because it is believed that pollen beetles initially infest the headland so that assessments confined to this area are likely to over estimate numbers. Samples from a transect from the headland towards the crop centre therefore ensures that a representative sample of plants are assessed.

This procedure still represents best practice although we found little evidence to support the assumption that pollen beetles more abundant in the crop headland than in the centre. This could be because the 30 m transects used did not truly represent the crop centre: indeed field size was not taken into account in our analyses. It could also be because the transects missed hotspots with high beetle numbers at the crop edge (see section 5.5.2).

5.5.2. Spatio-temporal dynamics of pollen beetle immigration into OSR crops

The spatio-temporal maps of pollen beetle density and crop growth stage showed that pollen beetle immigration tended to begin on the NE side of the crop, supporting previous work that pollen beetles use upwind anemotaxis to locate the crop (Williams *et al*., 2007; Skellern *et al*, 2017) and would therefore arrive on the NE side of a crop given a SW prevailing wind. Monitoring effort (i.e. placement of traps and monitoring transects) should therefore be focussed on this area if time is limited as this is where the migration is likely to begin and where abundance of beetles is likely to be greatest. There was some limited evidence to suggest abundance of beetles was influenced by plant growth stage with most beetles occurring on plants in the green bud stages when the rest of the crop was at yellow bud or early flowering; however more work is needed to investigate this relationship.

Pollen beetle abundance was highly variable in both space and time. They tended to occur in hot-spots in different areas of the crop, with other areas being largely uninfested. It is clear that if thresholds are exceeded, they often only relate to localised areas and not to the whole crop. This calls into question the validity of a whole-field based threshold, especially when related to crop plant density which is also highly variable within a crop. A greater understanding of pollen beetle spatio-temporal dynamics and the relationship with plant growth stage, plant density, landscape features and meteorological factors could enable prediction of hotspot areas and lead to targeted treatment of these in the crop without having to spray the whole crop. In the meantime, the more plant counts that can be done and the more transects that can be walked the more likely it is that the areas of the field requiring (and not requiring) treatment will be identified. It may also be possible to use plant counts to effectively 'shut the gate' on some OSR crops well before pollen beetle migration begins. Monitoring data indicates that mean pollen beetle numbers rarely exceed the old 15/plant threshold (Figure 1, Appendix 6). If plant counts indicate that the threshold is likely to be in excess of this value or even 10 beetles/plant it is very unlikely that it will be reached and farmers/agronomists could concentrate their monitoring effort on parts of the crop or other crops on the farm which are likely to be more susceptible to the pest.

If just a single transect is to be done, does it matter if it is done along the headland or from the headland towards the crop centre? Further work using the data generated by the spatio-temporal study is being done, outside the scope of the current project to compare the 'spatio-temporal' field average number of pollen beetles per plant with that generated by the transects on each side of the field on the same date. Simulations will also be run using data from the spatio-temporal study to compare the result of conducting a transect along the crop edge compared with a transect running from the edge towards the centre.

5.6. Validation of the on-line decision support tool

5.6.1. Assess the accuracy of the on-line support tool for pollen beetle immigration

Predictions for the start of migration were 65% accurate to within 7 days, which is less accurate than observed by Ferguson et al., (2016) who used the full proPlant.expert model. It could be that the averaging technique used to produce a single dot on a given date in the BPBP tool makes the BPBP system slightly less accurate compared to the ProPlant.expert tool where predictions are visible for 3 days in advance. However, these predictions still represent a useful tool to ‘get ready’ for the start of the season; to get monitoring traps in place and to start to keep and eye on the weather and the crop so that main migrations (and possibility of exceeding the threshold) will not be missed. Where inaccuracies occurred, the system tended to return early warnings which would allow any migration events to be re-predicted accurately at a later date; warnings were rarely given too late. The BPBP predicted well the main periods of pollen beetle migration – and the periods when migration was unlikely to occur. Use of this map would therefore help to time monitoring efforts to when it is most needed (see also section 5.6.2). If migration were to be complete before the end of the damage susceptible stage of the crop (GS 61) then knowing this would save monitoring effort and possibly unnecessary insecticide applications. However, in the three years duration of this study, migration continued well into the flowering phase of the crop and so validating this was not possible.

5.6.2. Effects of using the on-line decision support tool for pollen beetle migration on spray timing and control

If growers base spray decisions on thresholds to decide on the need to spray, they can monitor fields regularly (e.g. whenever temperatures exceed 15° C when the crop is at green-yellow bud stage, or on a weekly basis) or when prompted to do so by the on-line Bayer Pollen Beetle Predictor (BPBP) DSS tool which predicts risk of pollen beetle migration (and therefore risk of thresholds being exceeded). The accuracy of using the BPBP tool in comparison with weekly monitoring varied from year-to year based on the weather conditions. In 2014 and 2015 the system predicted several periods of weather conducive to pollen beetle migration which often coincided with the weekly monitoring schedule. Consequently there was little difference in the number of monitoring events between the use of the DSS and regular crop monitoring. However, in 2015 when the weather was cooler, the BPBP predicted only one or two migration events which vastly reduced monitoring effort in comparison with weekly assessments. Overall, using the on-line BPBP tool reduced average monitoring effort by about 35% (two monitoring events).

Missing a threshold could represent yield loss to a grower. The BPBP tool identified more occasions when the (artificially lowered) threshold was exceeded than the weekly monitoring system (except in 2016). Overall the tool identified 83% occasions when the threshold was exceeded compared with 52% using the weekly monitoring system. In total over the whole experiment this related to two missed treatments for the DSS system and three for the weekly monitoring system.

The time taken to detect a threshold was faster using the DSS than weekly monitoring, resulting in an average of 0.17 and 1.15 days' delay, respectively between the first experimental detection of a threshold and the system-detection of that threshold (as experimentally plots were sampled more regularly than the weekly or DSS-prompt control systems used). The DSS was more effective at detecting thresholds than the weekly monitoring. As a result, more sprays were applied in response to using the DSS (2.6)) than for the weekly monitoring (2.4). Both systems recommended treatment on average one third less than where prophylactic sprays were used (and if the current UK thresholds had been used then this difference would have been even greater). This is clear evidence that using monitoring systems can reduce the amount of unnecessary insecticide applied.

In our experiments we artificially lowered the pollen beetle threshold to give the best chance of detecting differences in the number and timing of insecticide applications between systems. However, there were no clear yield differences between the four control systems tested, and only in 2014 did spraying have any effect on yield. This was regardless of treatment and is difficult to explain. These data support the results of other experiments in the project which indicate that if pollen beetle populations are below threshold they have no significant impact on yield as well as providing supporting evidence for the validity of the current UK threshold scheme. This experiment also provides further evidence that UK populations of pollen beetles rarely exceed threshold.

This begs the question, is monitoring worth the effort? In our experiments the pollen beetle populations reached threshold numbers (regardless of plant density) at 19 sites across the UK given a 7 beetle/plant threshold; at 11 sites for the 11 beetle/plant threshold and only five sites for the 18 beetle/plant threshold (at Rothamsted and one at Grantham). Only three crops sampled on Rothamsted farm in 2016 exceeded populations of 25 beetles/plant (see Appendix 6 and it is known that Rothamsted has unusually high numbers of pollen beetles, Skellern *et al*., 2017). There is strong evidence that the number of pollen beetles fluctuates from year to year. The DSS tools cannot predict at present if a season is going to be a 'bumper beetle year'. Methods to predict the relative abundance of the population with respect to the last season are urgently needed so that growers and advisors know whether or not they need to be vigilant if they are in areas with traditionally high beetle abundance. There is also evidence from Rothamsted suction traps that populations of pollen beetles are generally increasing with time, so thresholds are potentially more likely to be exceeded in future. However, in the short term most growers in the UK are unlikely to need to spray against pollen beetle. The results of this project will hopefully improve grower confidence in the current threshold scheme and confirm that treatment is only justified if the threshold is exceeded and that the freely available DSS tool can help them to accurately monitor pollen beetle levels.

6. Conclusions

- Pollen beetle numbers rarely exceed threshold and rarely justify insecticide treatment. In three years of study and in historical data from Fera Crop Monitor sub-threshold populations of the pest are the norm rather than the exception.
- Insecticide treatments generally reduced pollen beetle numbers but this did not affect crop yield, and yet may still drive resistance.
- The efficacy of different insecticides varied across sites and might be due to the local population of pyrethroid resistant beetles.
- Overall this project has confirmed the significant resilience of the OSR crop to loss of green leaf area in late winter (simulated pigeon damage) or loss of buds at the green/yellow bud stage (simulated pollen beetle damage).
- Overall there was no significant effect of bud pruning on yield. This represents a partial validation of the threshold by confirming that beetle number below threshold do not need to be controlled.
- There was limited evidence to suggest that simulated pigeon damage (mowing/defoliation) had significant impact on the yield of the crop. On average across all sites yields were reduced by 0.23 t/ha but this was not significantly different from plants that were not defoliated. Yield was significantly reduced by 0.17 and 0.54 t/ha at two out of the four sites. Considering the severity of the defoliation treatment, these reductions in yield are relatively low and may have been partly caused by plants being mown after they had started to extend.
- Crops with lower plant populations are no more at risk to simulated pollen beetle damage than crops with high plant populations.
- There was no interaction between simulated pigeon damage and simulated pollen beetle damage indicating that crops that were mown were no more susceptible to bud pruning than those that were not mown. Extrapolation from plot scale to whole field scale would suggest that pigeon damaged crops are not more susceptible to pollen beetle attack than undamaged crops at simulated pollen beetle populations of up to 8/plant.

- Although only two sites were studied, there was no evidence to suggest that the crop with above threshold numbers of CSFB larvae was any more susceptible to simulated pollen beetle damage than the crops with sub-threshold population of the pest.
- Mowing and bud pruning were effective means of simulating pigeon and pollen beetle feeding respectively and were probably more severe than would be experienced in the field. Although the threshold was not exceeded, a simulated population of eight beetles per plant is higher than is commonly observed in the field.
- A pollen beetle monitoring trap baited with an attractive lure was developed by Project 504. This trap is now commercially available via Oecos and was shown to be more effective at trapping pollen beetles than unbaited yellow sticky traps.
- The number of beetles in the Oecos pollen beetle monitoring trap is positively related to the number of beetles per plant in the crop, so the trap can be used to detect local pollen beetle movement and relative abundance between sites.
- The relationship between the number of pollen beetles on Oecos pollen beetle monitoring traps and the mean no./plant in the crop varied between years so we cannot currently calibrate the trap to reliably relate to threshold numbers of beetles in the crop. Further work currently in progress may improve the predictive ability of our models.
- Plant density is variable within fields making whole-field thresholds based on plant density innacurate. Ideally multiple assesssments of plant population would be made across the field to give a more precise estimate of the threshold. However, this will need to be balanced against the time required to make these assessments and relative gains of this increased precision.
- Pollen beetle immigration is greatest on the NE side of the field (downwind of an assumed SW prevailing wind). Traps and monitoring transects should be focussed on this side to minimise the chances of missing a threshold
- After the first major influx beetles occurred in 'hotspot' areas throughout the field. This makes estimation of beetle numbers per-field difficult. Multiple transects would be preferable to identify hotspot areas at most risk (and to potentially identify areas of the crop which will not need treatment).
- The Bayer Pollen beetle predictor accurately predicts the main pollen beetle migration events, helping to focus monitoring effort to when it is most needed.
- Use of the Bayer Pollen Beetle Predictor can reduce monitoring effort needed to detect pollen beetle counts above threshold and the likelihood that they are missed in comparison with weekly monitoring.
- Crop monitoring significantly reduces the number of insecticide treatments applied compared with prophylactic spraying ensuring that growers spray only when necessary.

7. Future Research

- Validate thresholds with more severe simulated pruning to represent above threshold pollen beetle attacks and consider the effect of pruning primary and secondary branches as well as main raceme buds to determine the impact upon yield.
- Investigate the effect of pollen beetle damage at different growth stages; is there a need for different thresholds at key growth stages, as with many other European countries?
- Develop ways to predict the relative size of the population (beetle abundance) to identify 'bumper beetle years' when extra vigilance will be required.
- Develop better ways to assess beetle numbers. Current crop beating is onerous, time consuming and potentially inaccurate as beetles fly away before they can be counted. Monitoring traps to detect thresholds are still in development, however, the potential to remotely sense numbers of beetles should be investigated. Smartphone apps have been used to assesss GAI and it is possible that they could be used to count pollen beetles using a digital photo. This could be combined with plant population estimates to allow growers to rapidly assess thresholds at multiple locations within a field.
- Consider interactions of pollen beetles with other key pests – e.g. CSFB, diamond back moth, aphids. Are cumulative effects of lower levels of damage by each likely to result in yield losses? How can this be tackled using integrated pest management methods to avoid unnecessary insecticide use?
- Better understand the spatio-temporal patterns pollen beetle immigration into crops in particular identification and prediction of hot-spot areas that could allow precision input of insecticides
- Consider how the spatial distribution of beetles is likely to affect the ability of the crop to compensate for pest damage.

8. References

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9. Acknowledgements

Objectives 1-3 were conducted by ADAS who are most grateful to the farmers involved in this project for their continued enthusiasm and incurrence of hassle. Thank you to Mark Wood of Fawley Court Farm, Mark Panniers of Middle House Farm, A.L.Legge and Son Ltd of Further Fen Farm, Ray Gadsby of Sharpes Bank Farm, Graham Desborough of Summerlin Farm, John Kilby of Church Farm, Robert Taylor of Grange Farm and Dave Lee of Corner Farm. We are grateful to field staff at ADAS Boxworth, High Mowthorpe, Rosemaund and Terrington and Boxworth for managing the experiments in this project.

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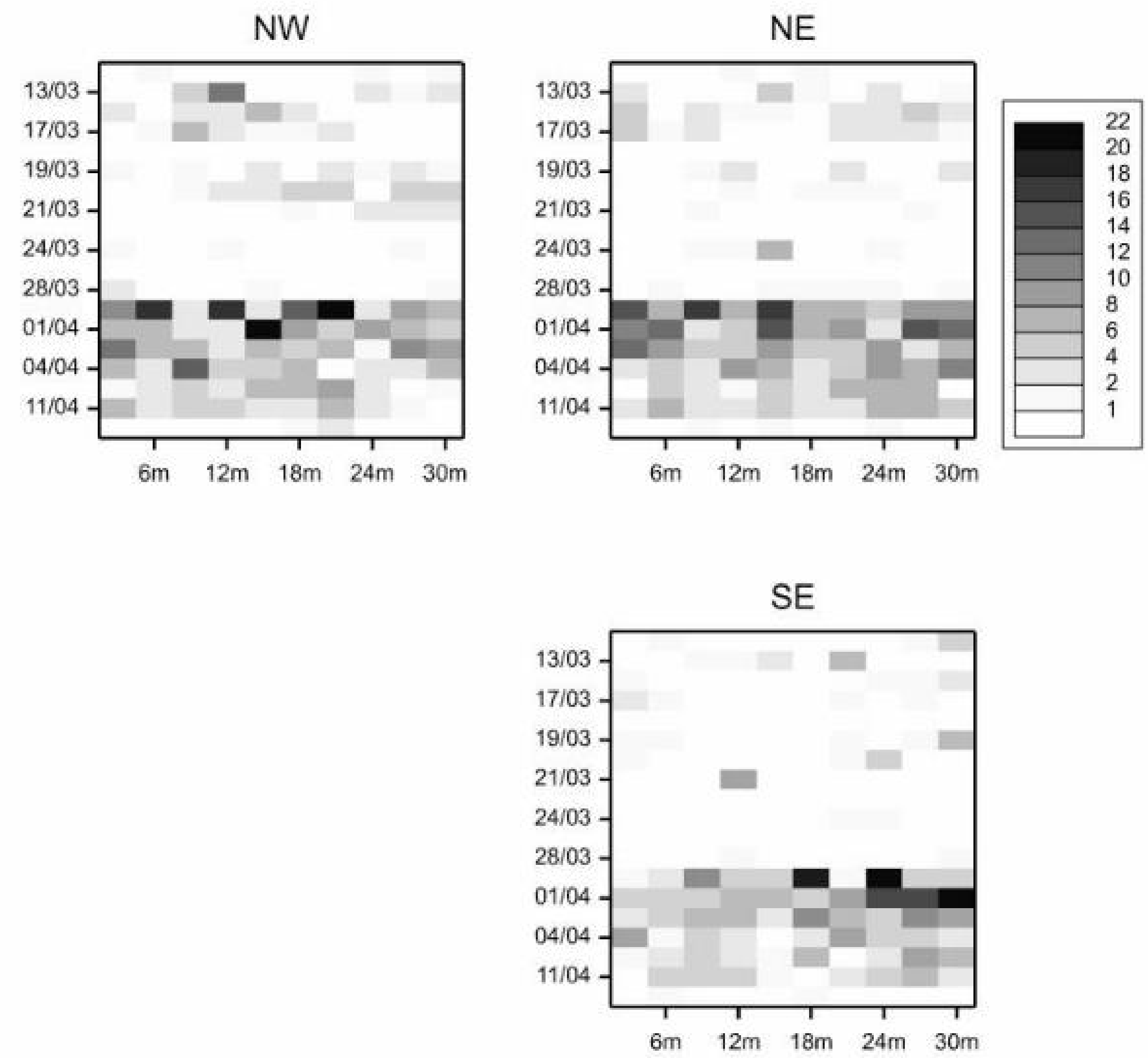
10. Appendices

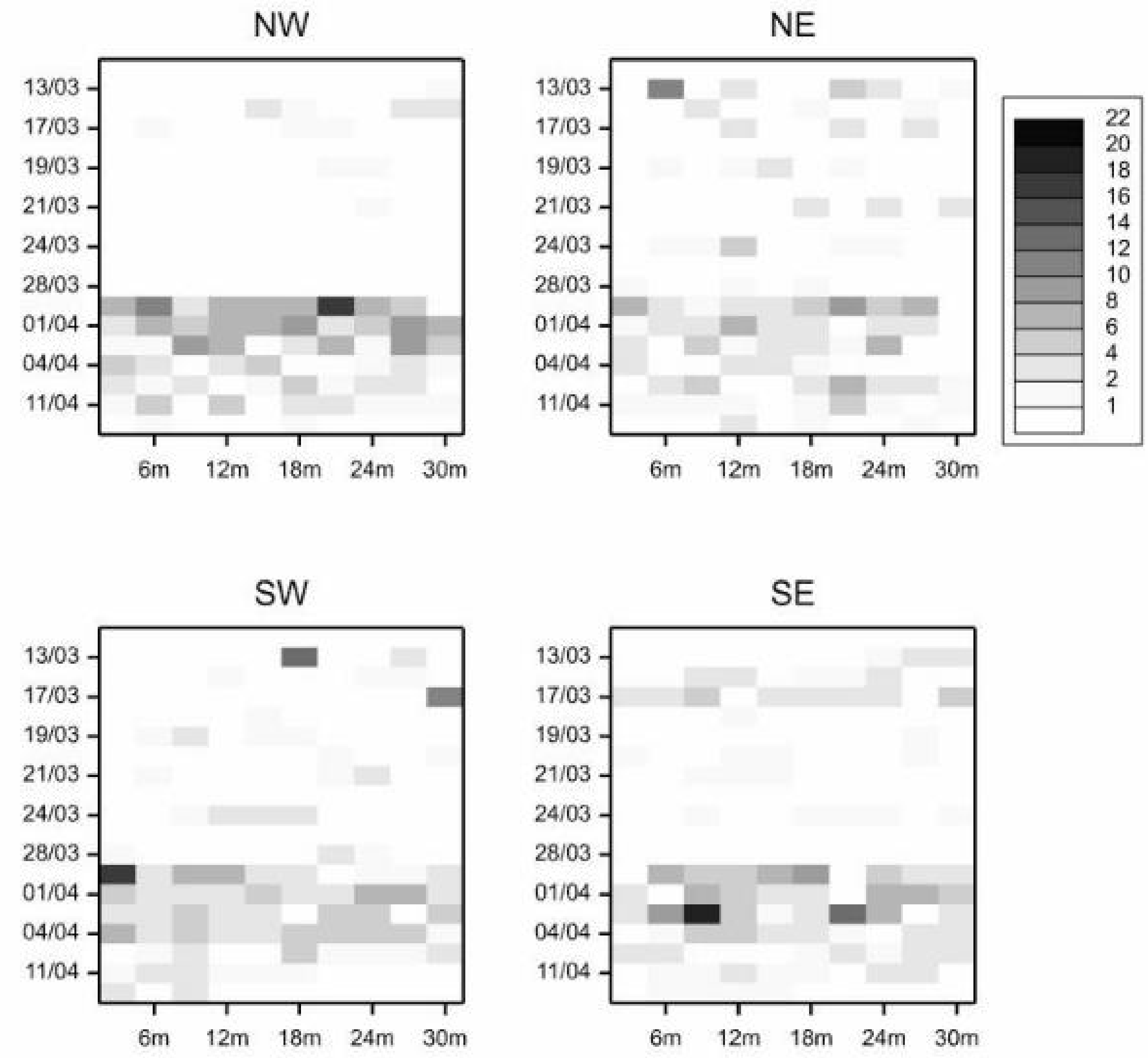
Appendix 1.

Shade plots representing 'visualised transects' of the number of pollen beetles per oilseed rape plant with respect to distance from the edge of the crop (m) and date, site and year (2014-2016). The darker shades represent high counts of beetles and the lighter shades represent lower counts. The rows show the number of counts for each sample in date order over the experiment. The columns show the number of counts for each of the sample positions. For the Rothamsted sites shade plots are shown for each of the four sides of the fields; at other sites only the NE field side was assessed.

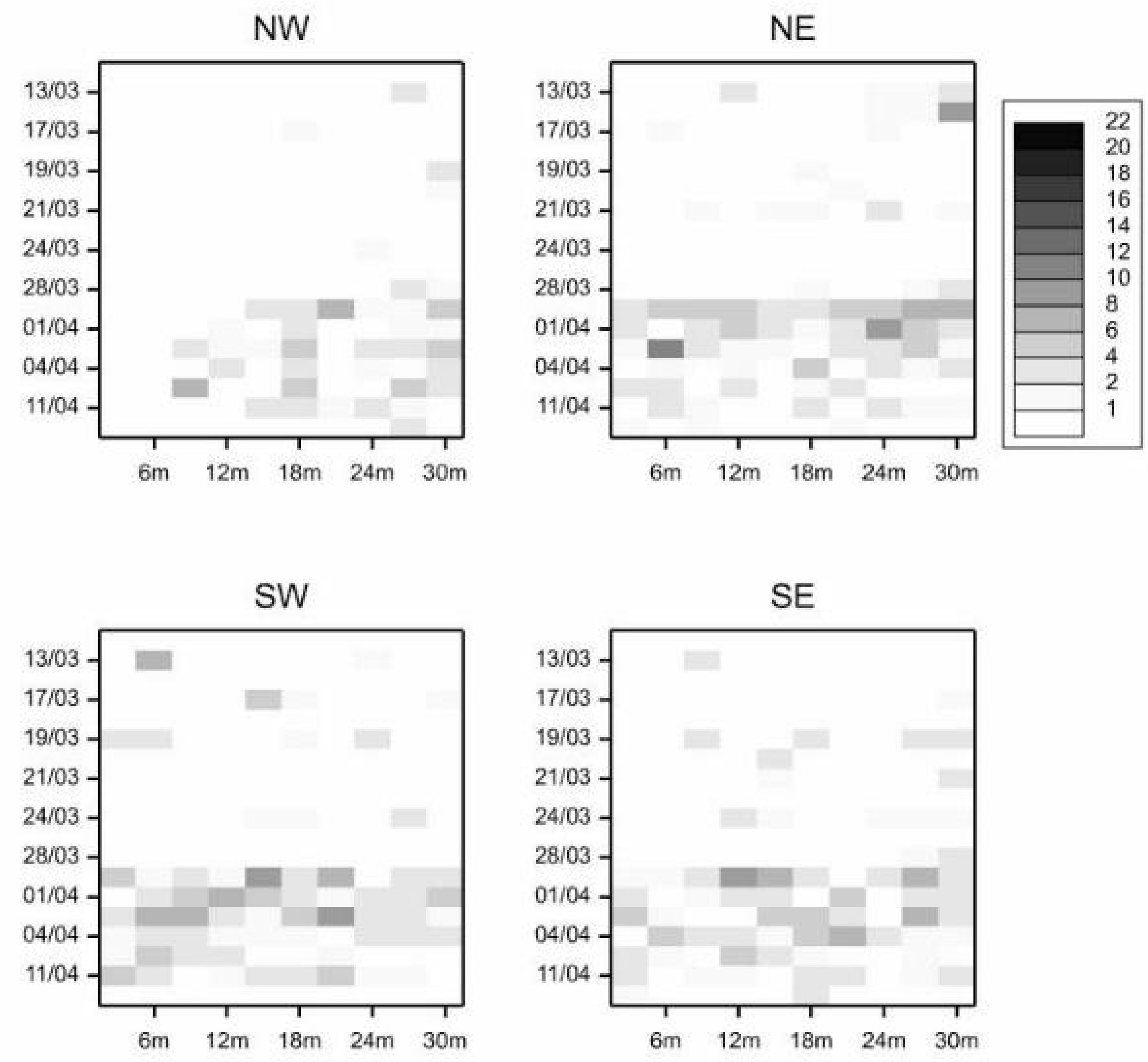
Appendix 1. 2014 Delharding Field, Rothamsted Research



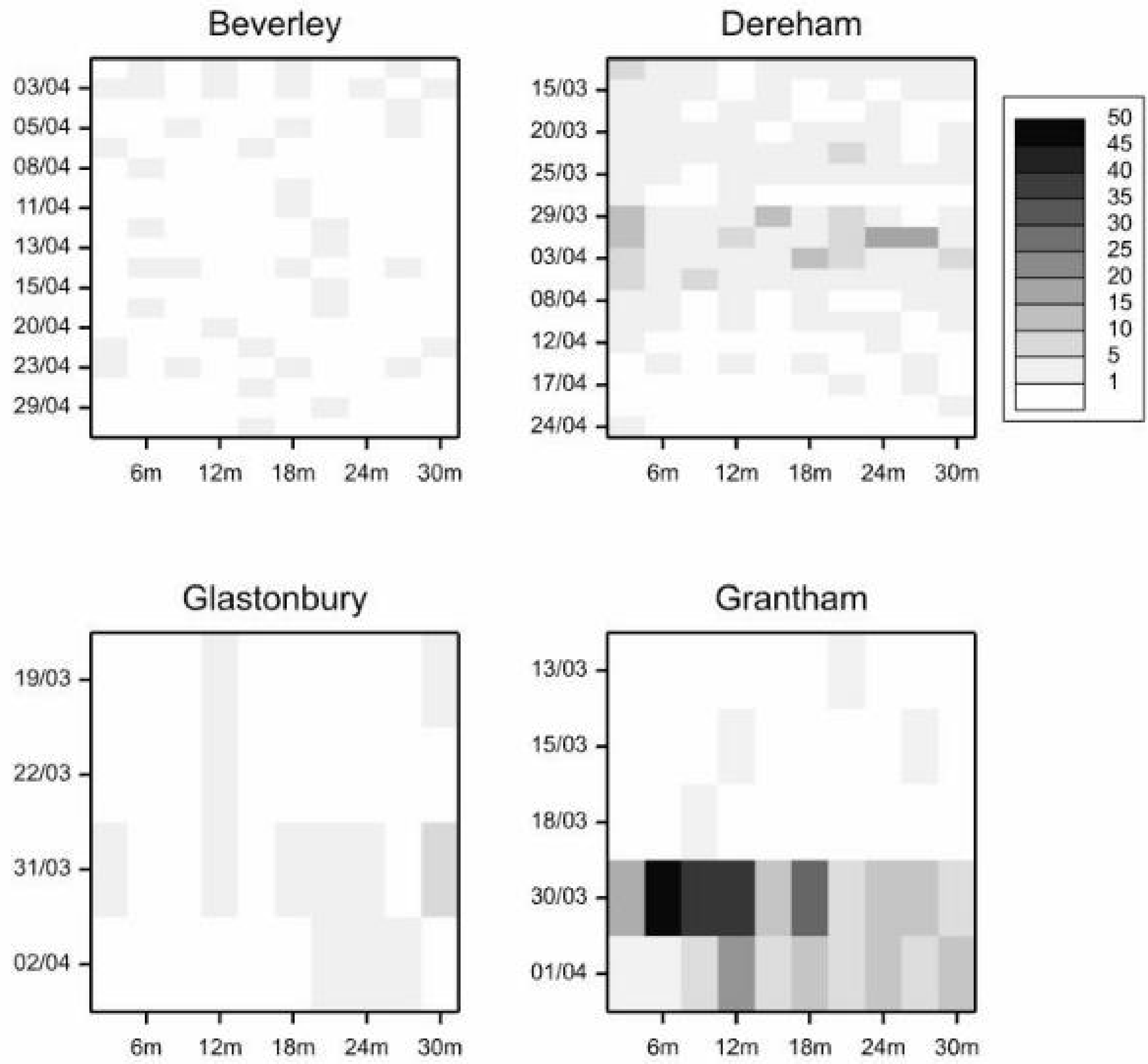
Appendix 1. 2014 Great Knott 3 Field, Rothamsted Research



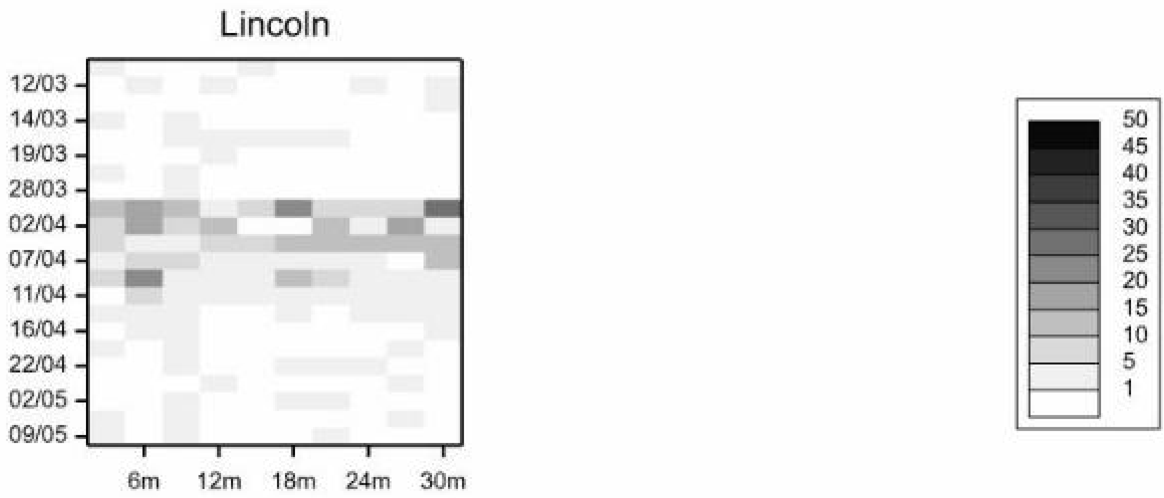
Appendix 1. 2014 Pastures Field, Rothamsted Research



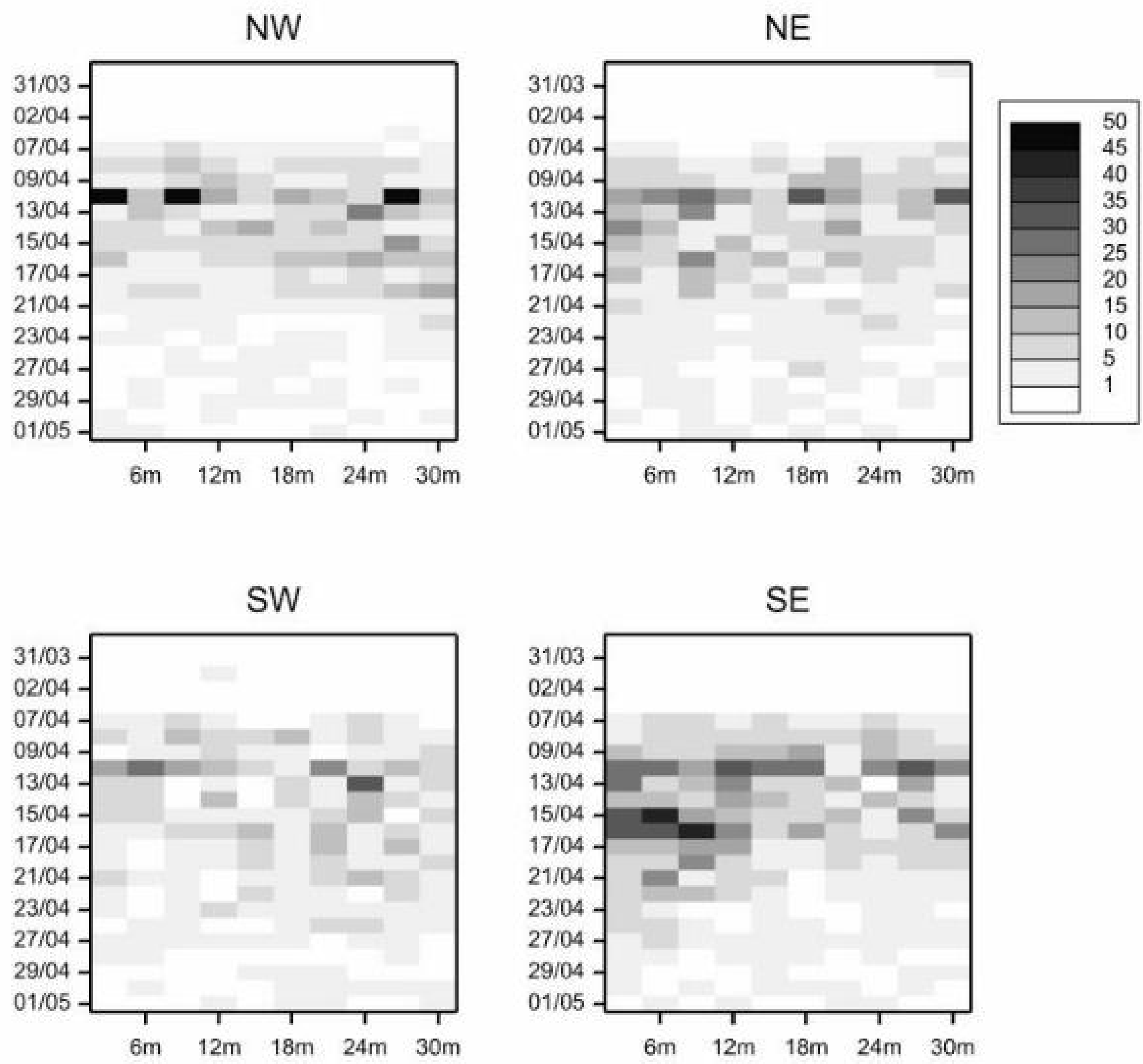
Appendix 1. 2014 Other sites



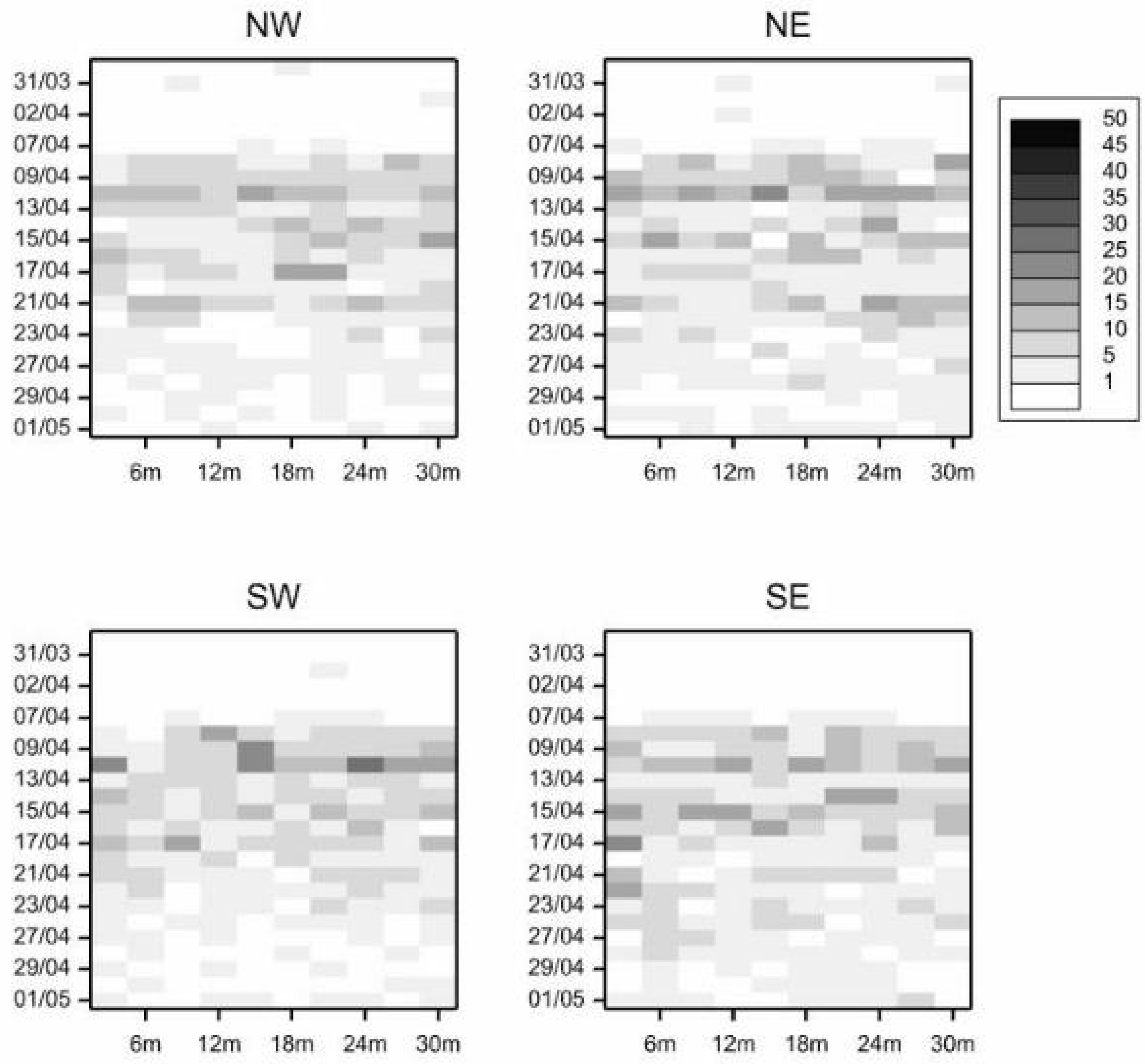
Appendix 1. 2014 Other sites



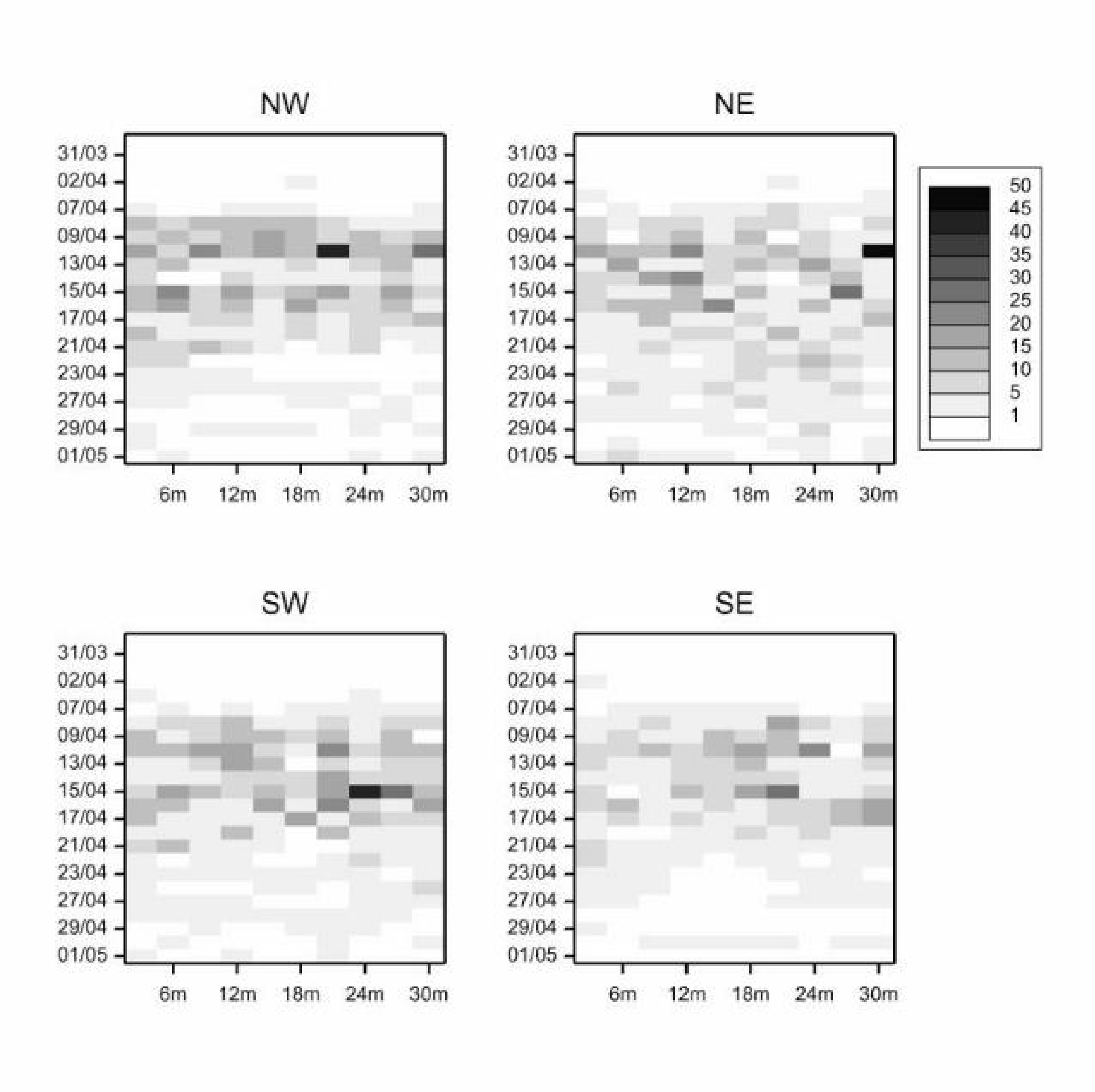
Appendix 1. 2015 Great Harpenden Field, Rothamsted Research



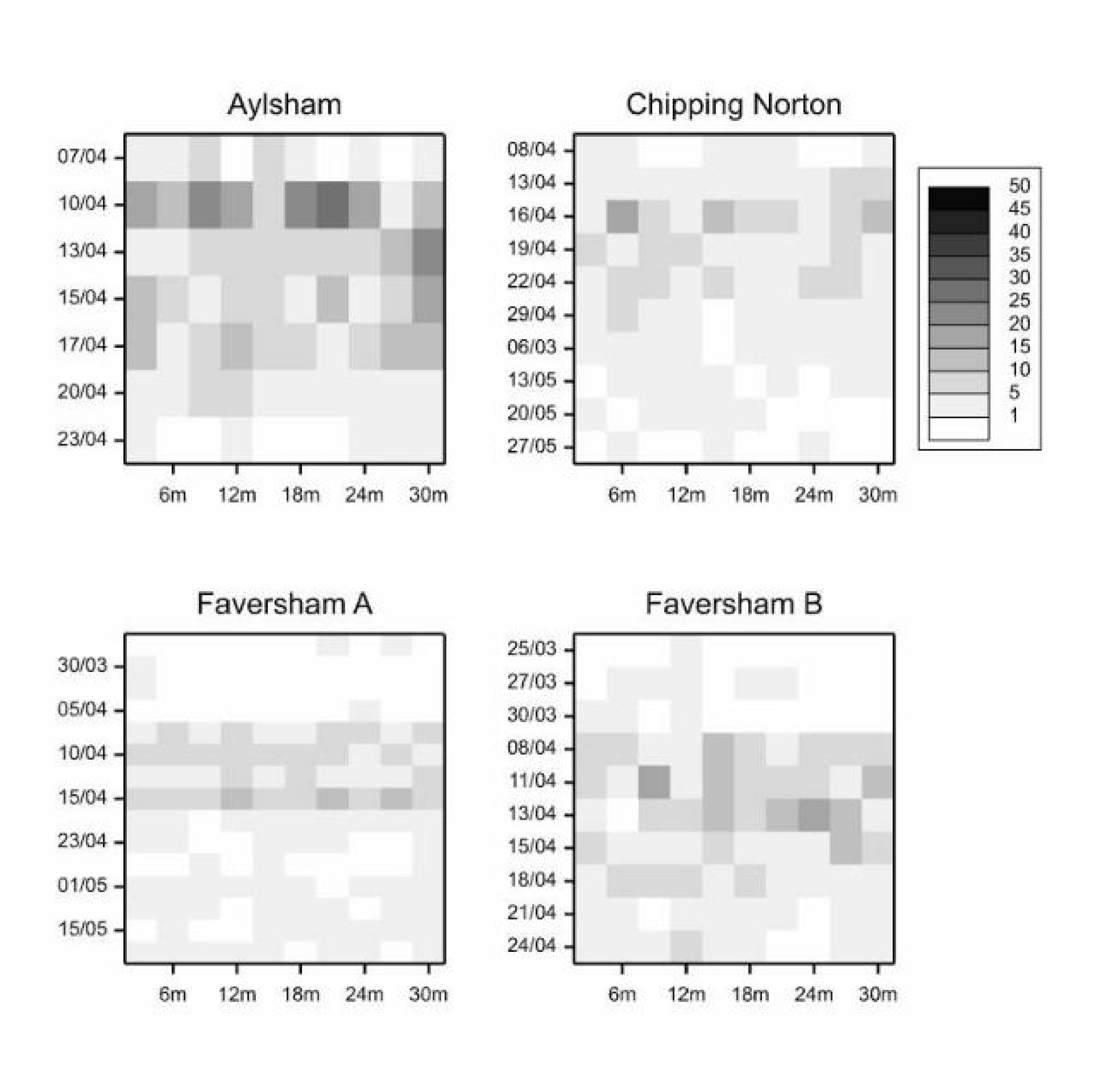
Appendix 1. 2015 Little Knott Field, Rothamsted Research



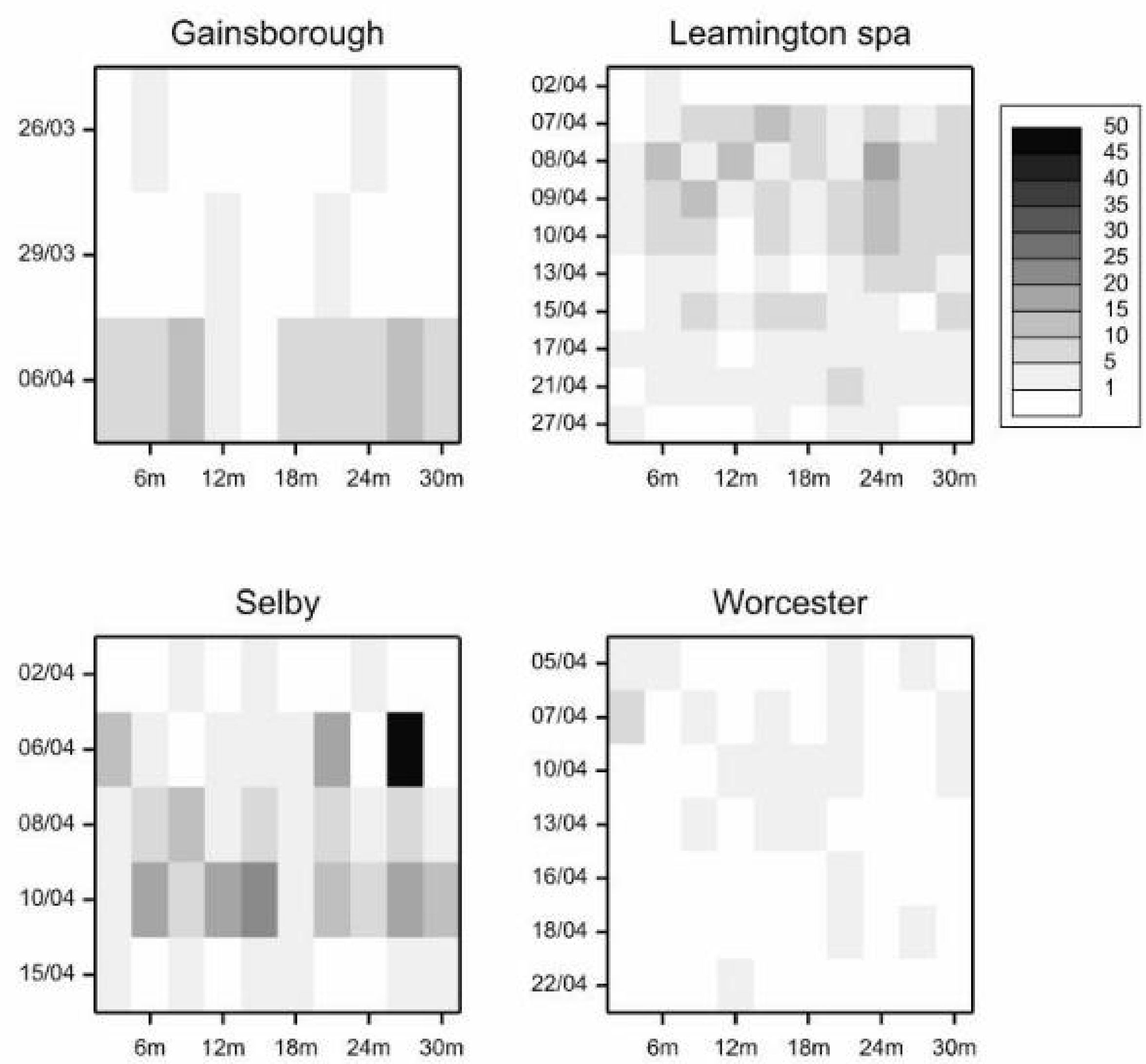
Appendix 1. 2015 Long Hoos Field, Rothamsted Research



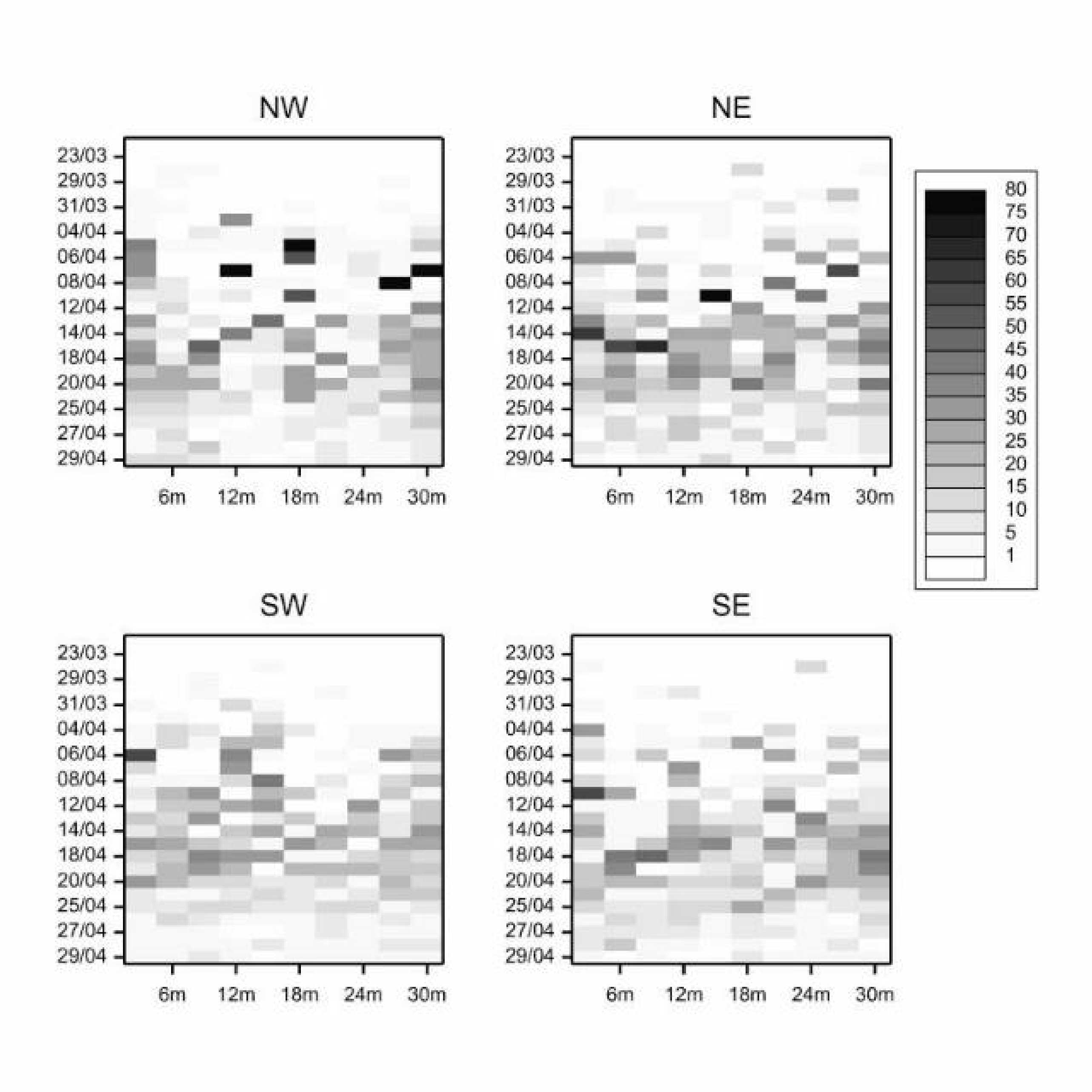
Appendix 1. 2015 Other sites



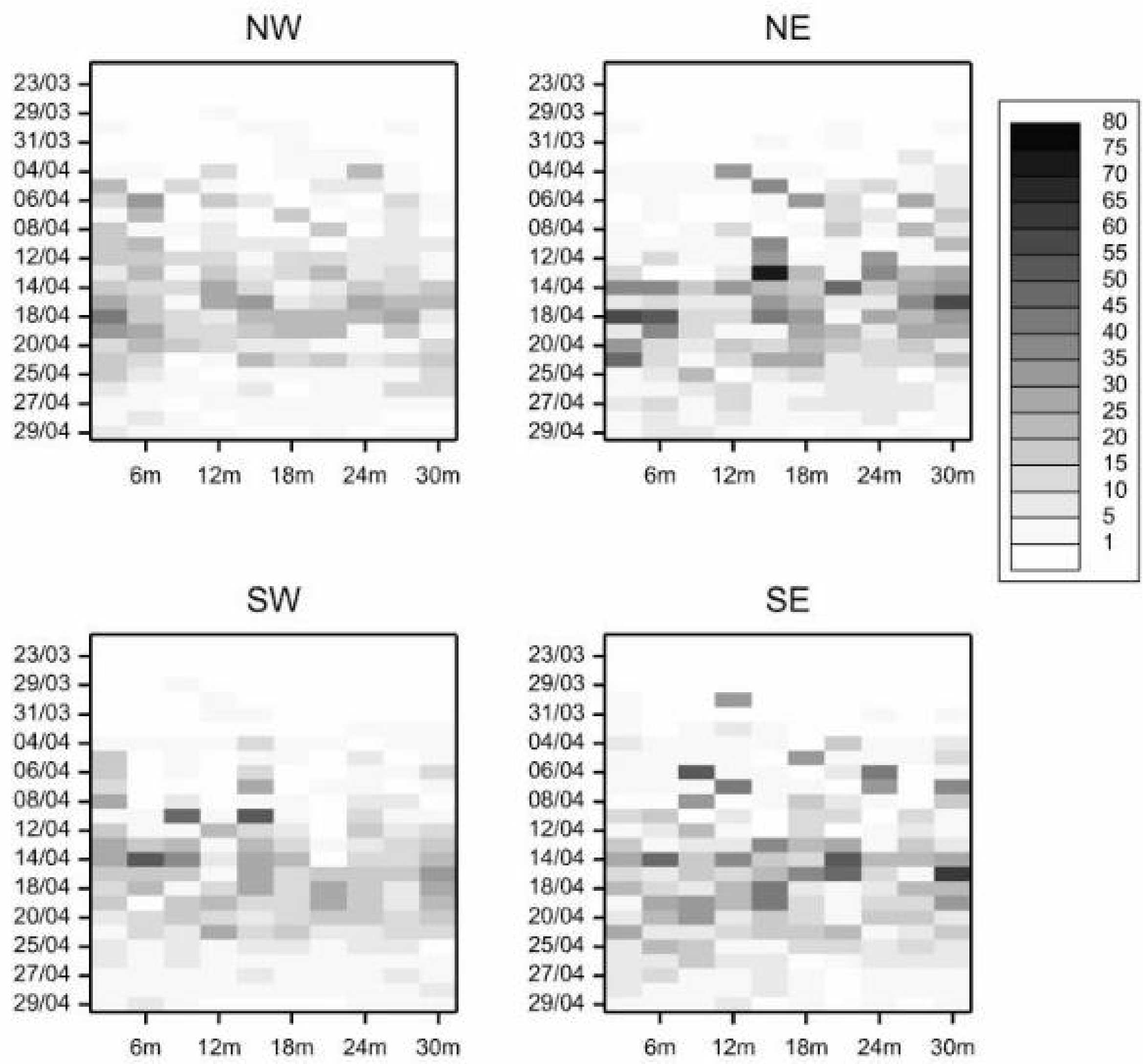
Appendix 1. 2015 Other sites



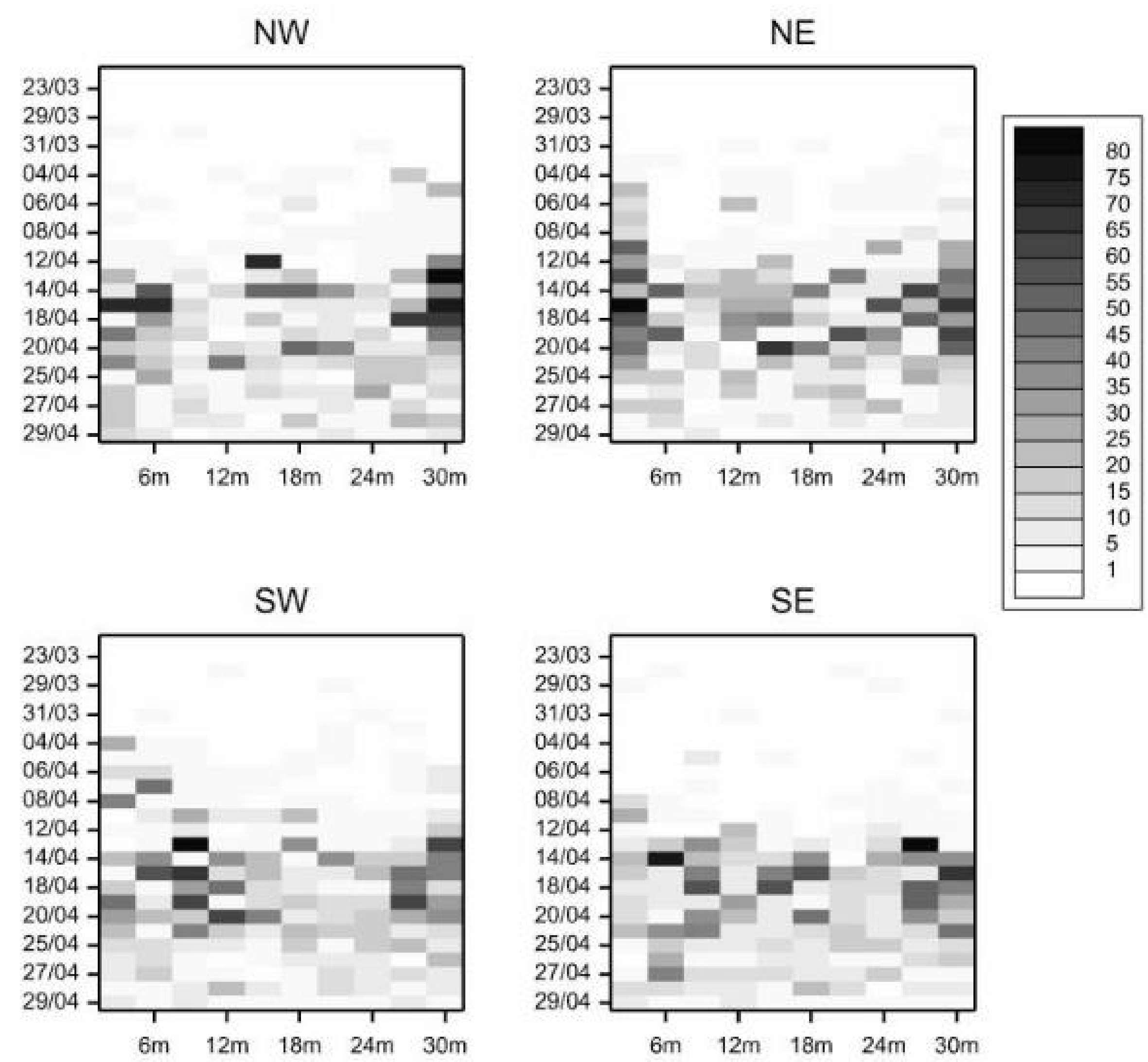
2016 Great Knott Field, Rothamsted Research



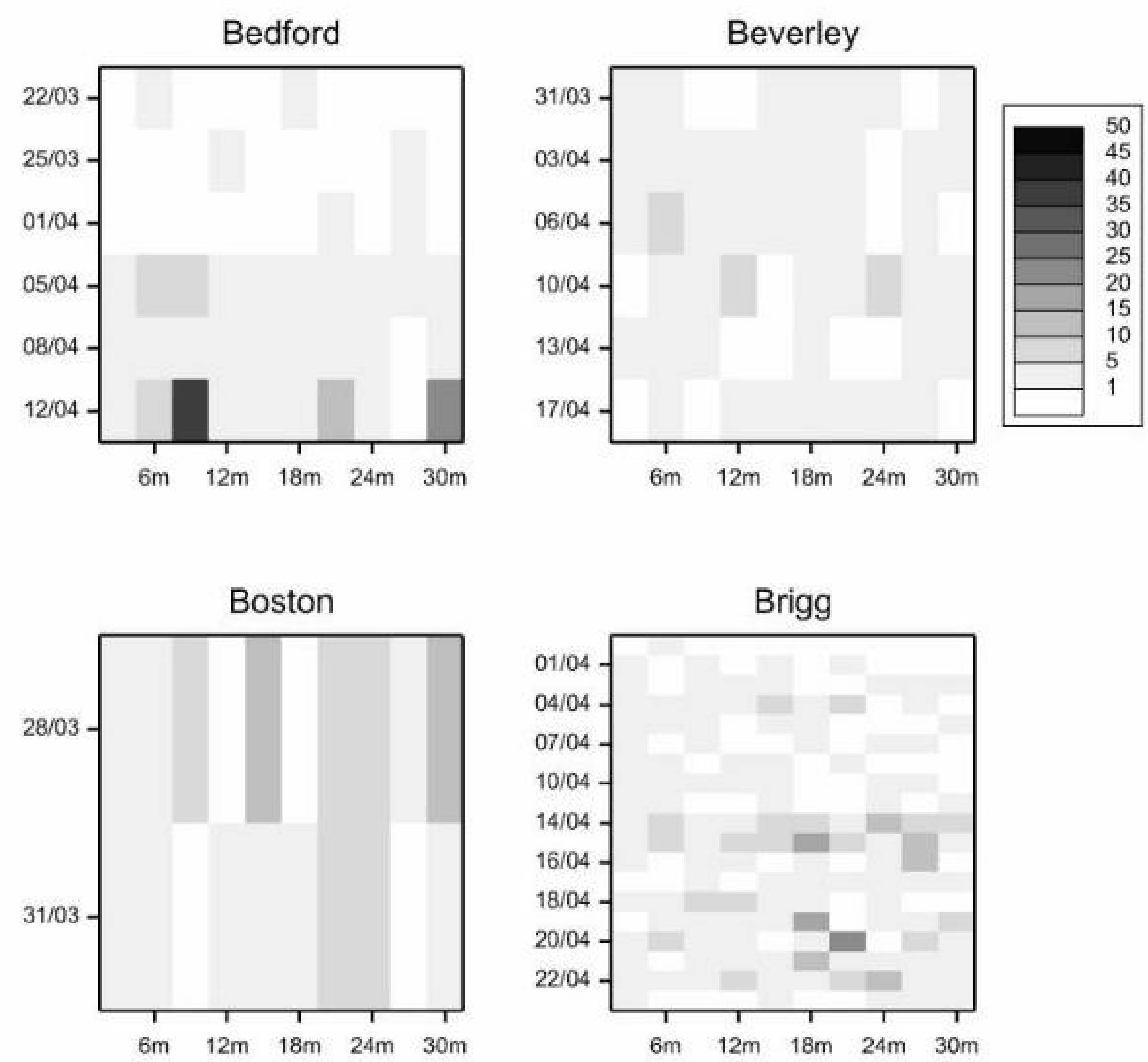
2016 Osier Field, Rothamsted Research



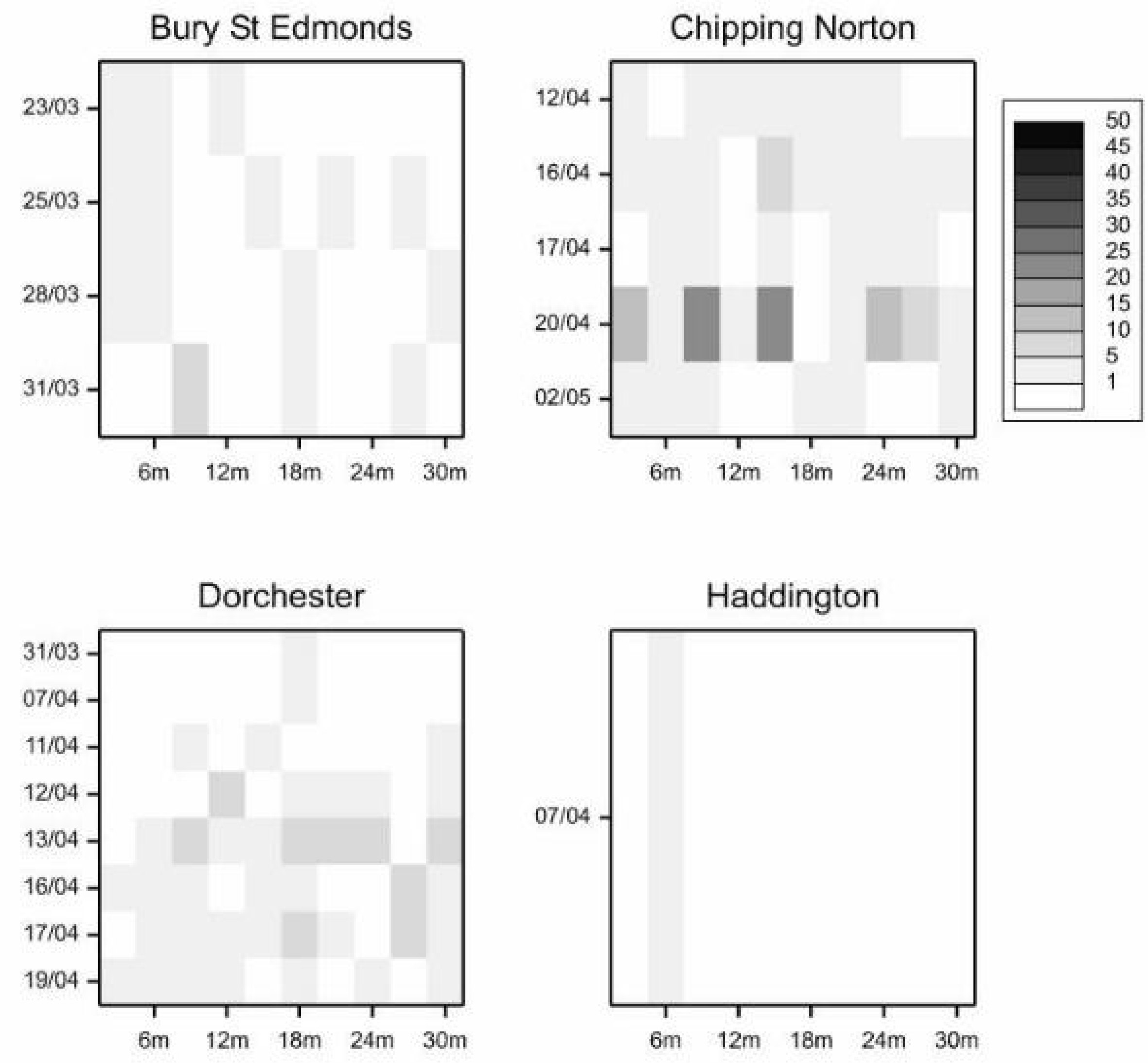
Appendix 1. 2016 Sawyers 2 Field, Rothamsted Research



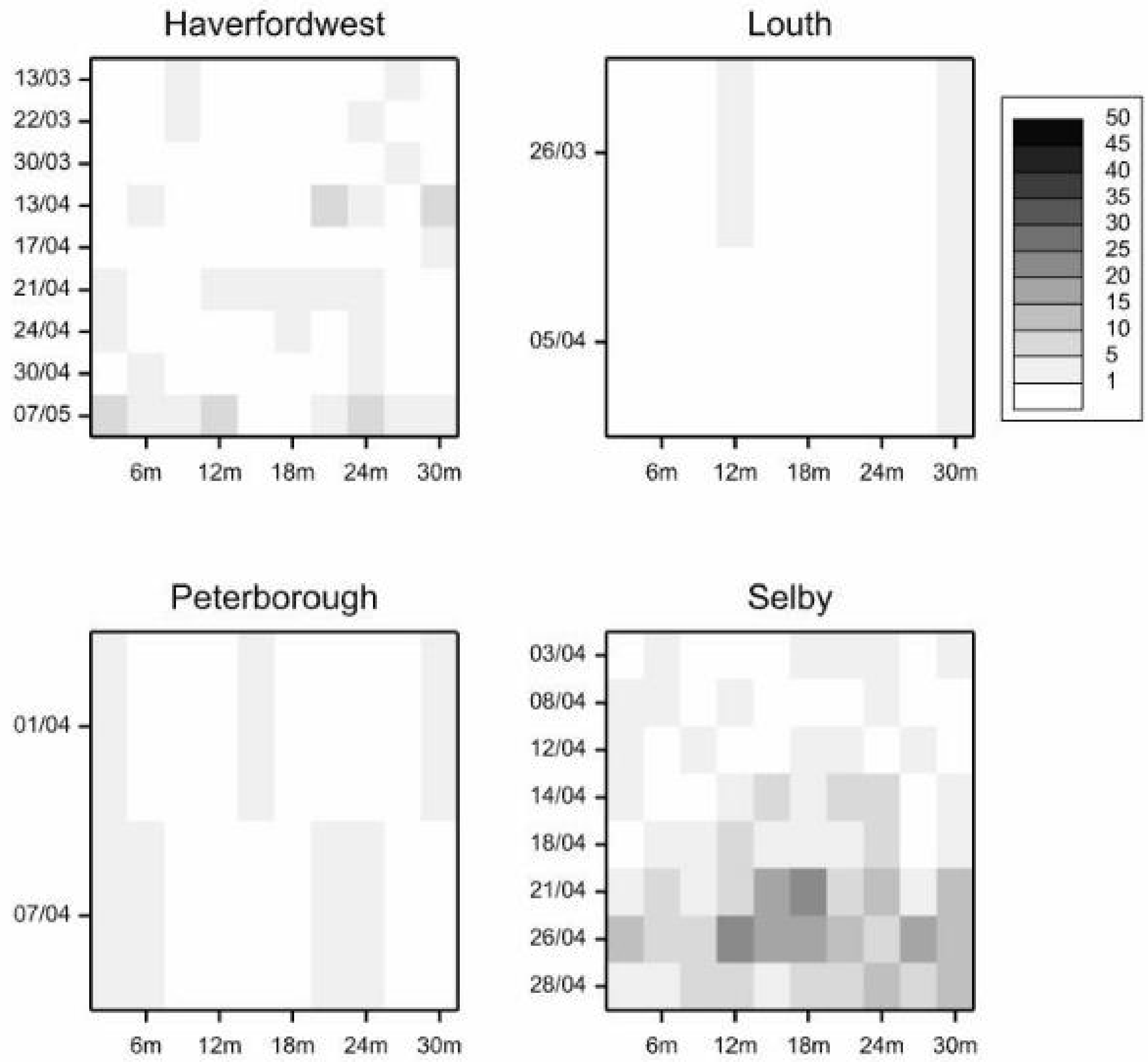
Appendix 1. 2016 Other sites



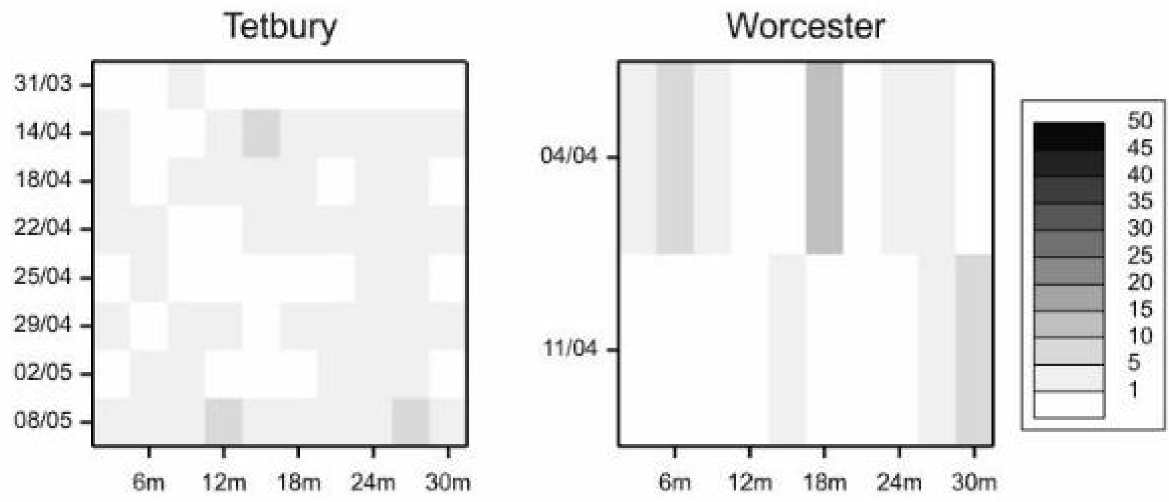
Appendix 1. 2016 Other sites



Appendix 1. 2016 Other sites



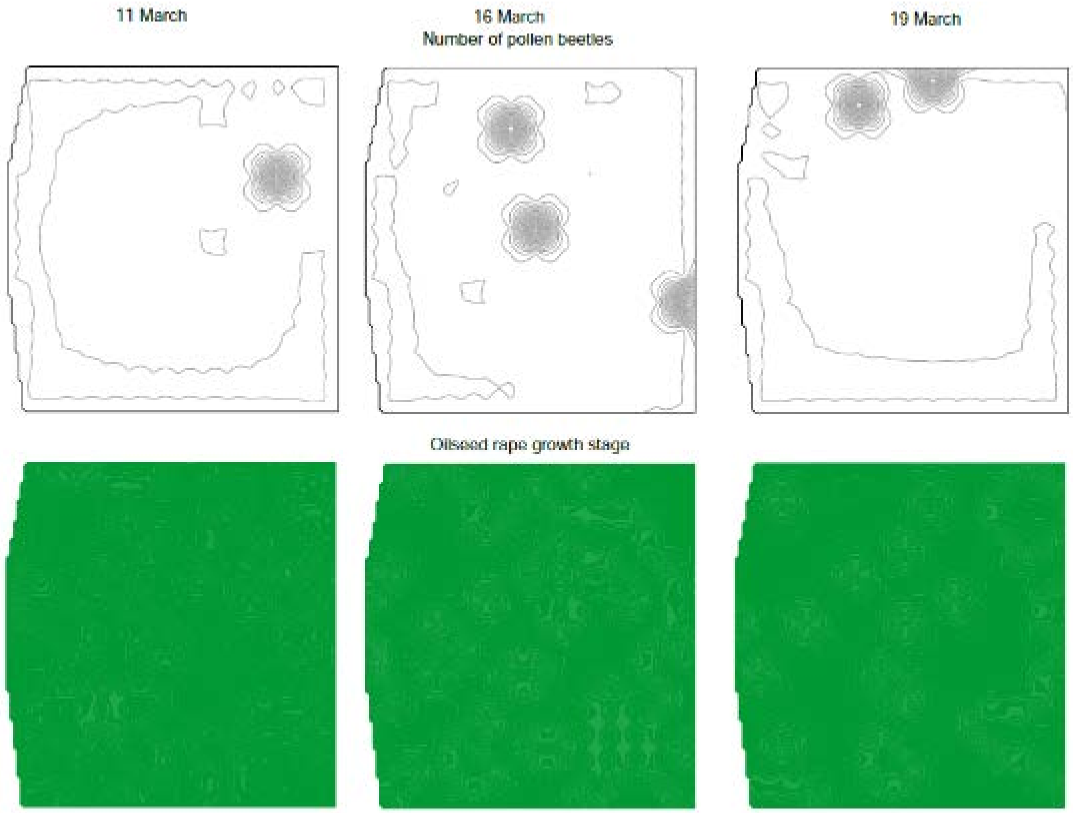
Appendix 1. 2016 Other sites



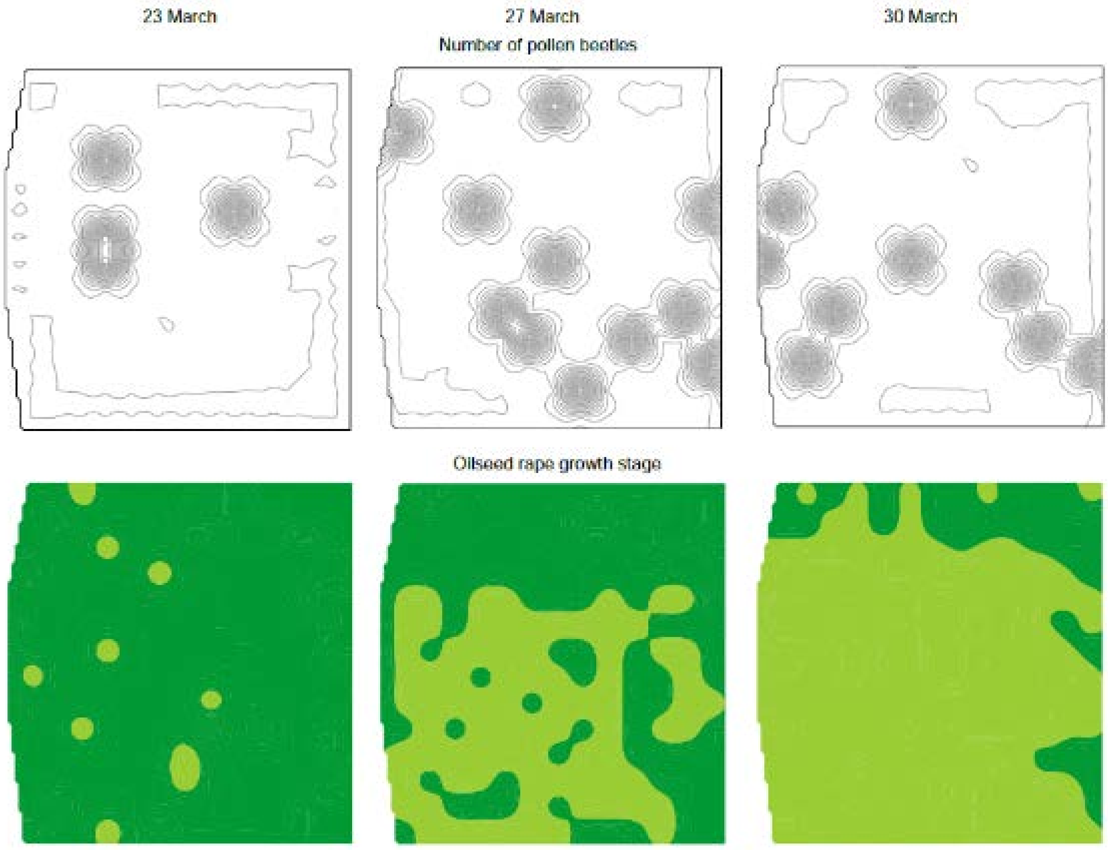
Appendix 2

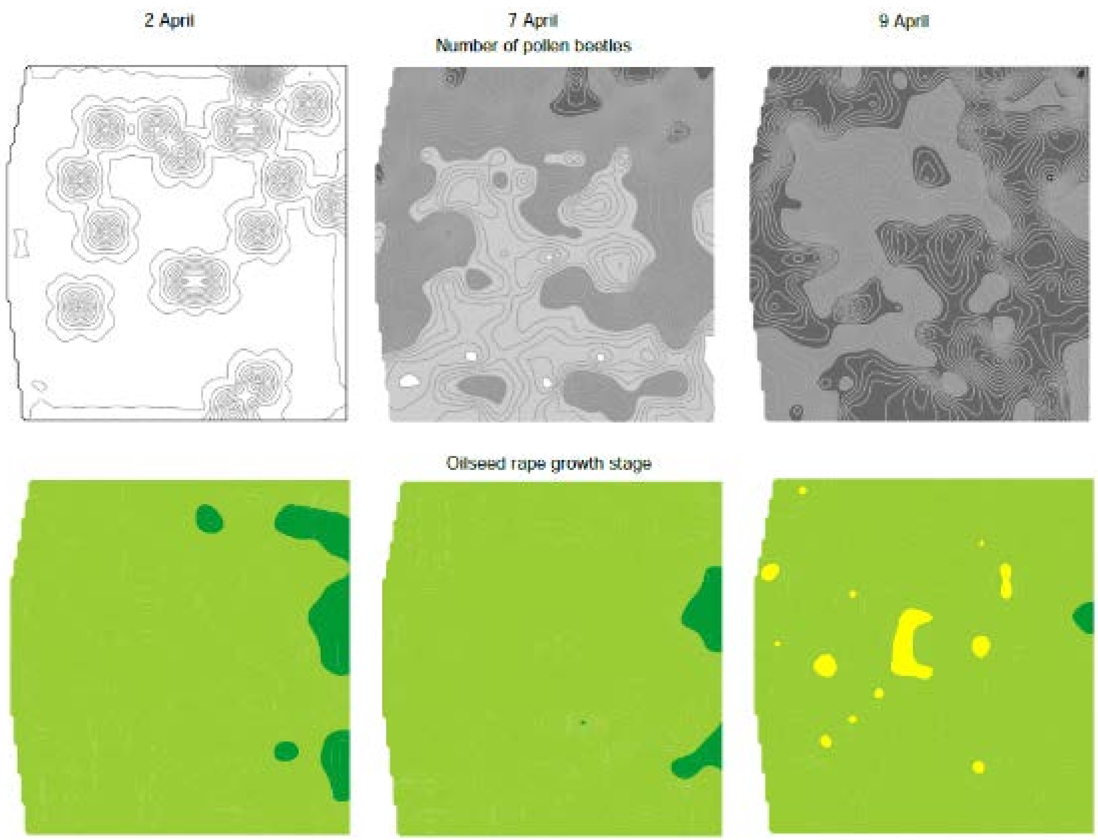
Spatio-temporal distribution of pollen beetle abundance and crop growth stage in three oilseed rape crops on Rothamsted Farm 2015. Greyscale maps show relative numbers of pollen beetles scaled across sites and time to allow comparisons; the darker the grey the more beetles/plant present). Coloured maps show growth stage of plants within the crop with dark green areas relating to buds present but not extended (BCCH 50-52), Light green relating to flower buds extended (BCCH 53-59) and yellow relating to flowering stages (BCCH 60+). The top end of each field is facing north/northeast.

Appendix 2a. Great Harpenden

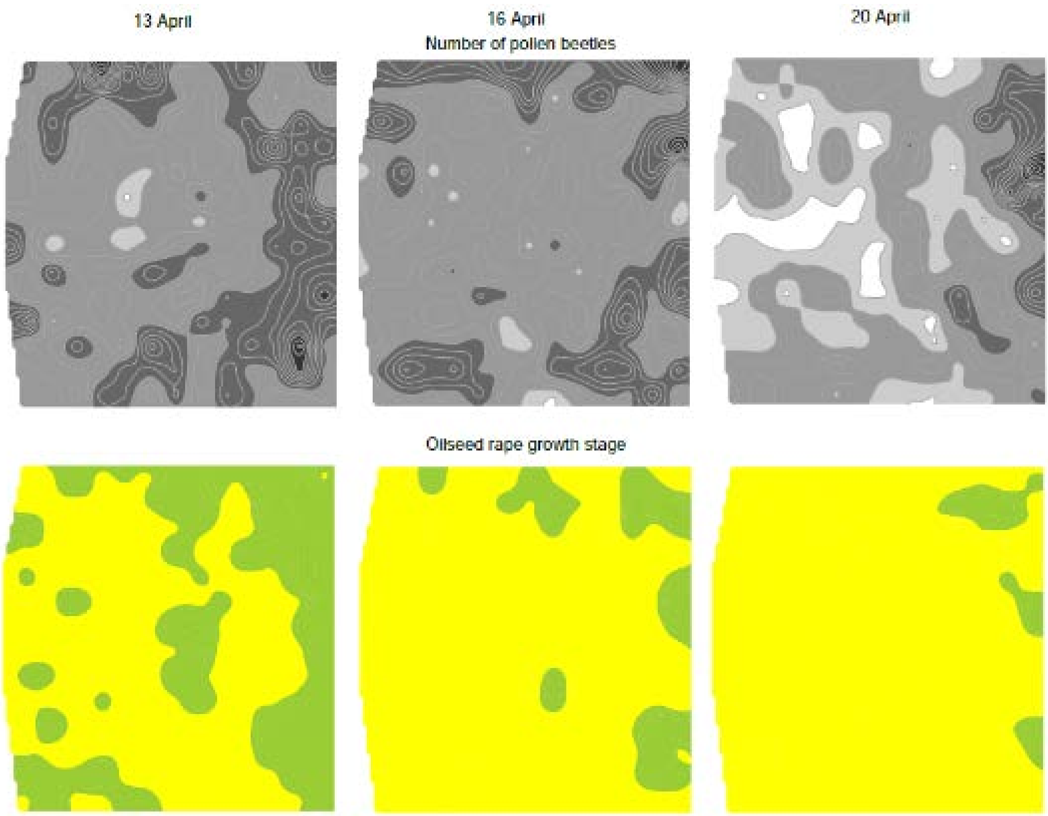


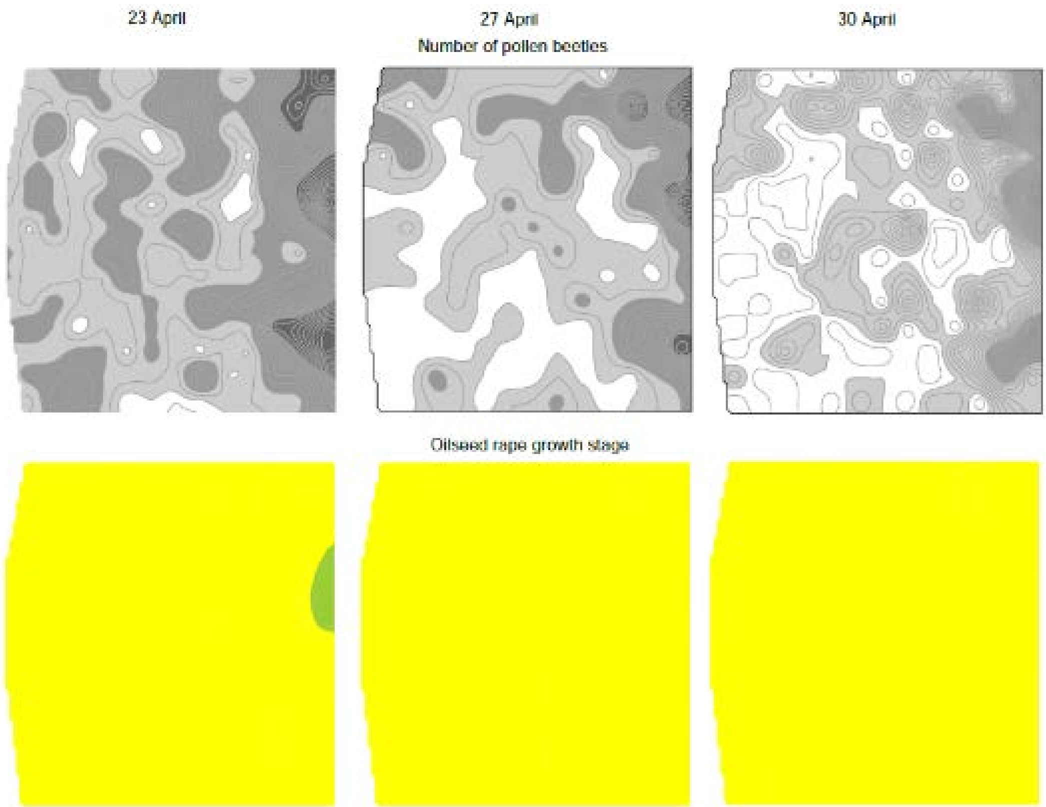
Appendix 2a Great Harpenden (continued)



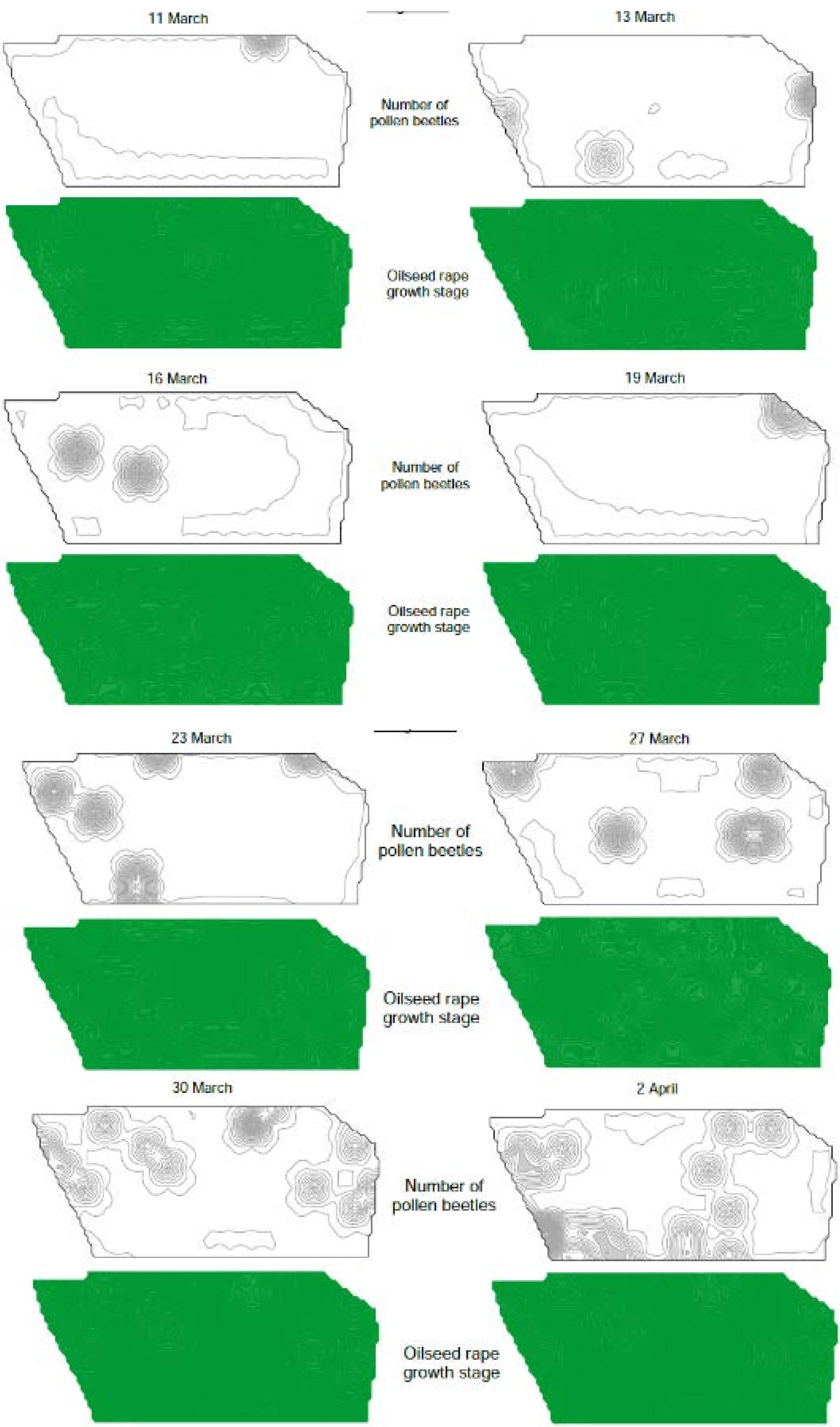


Appendix 2a Great Harpenden (continued)

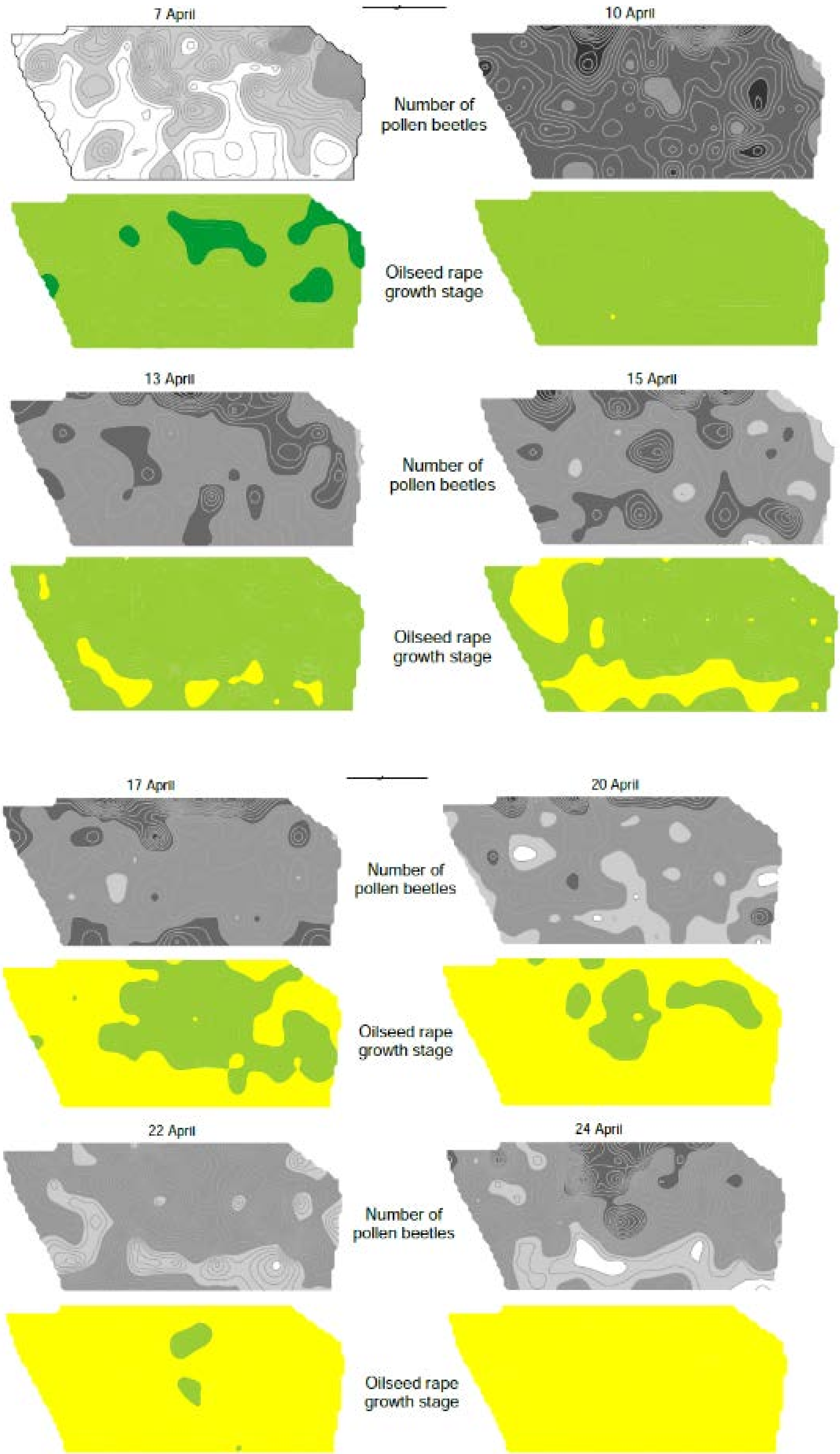




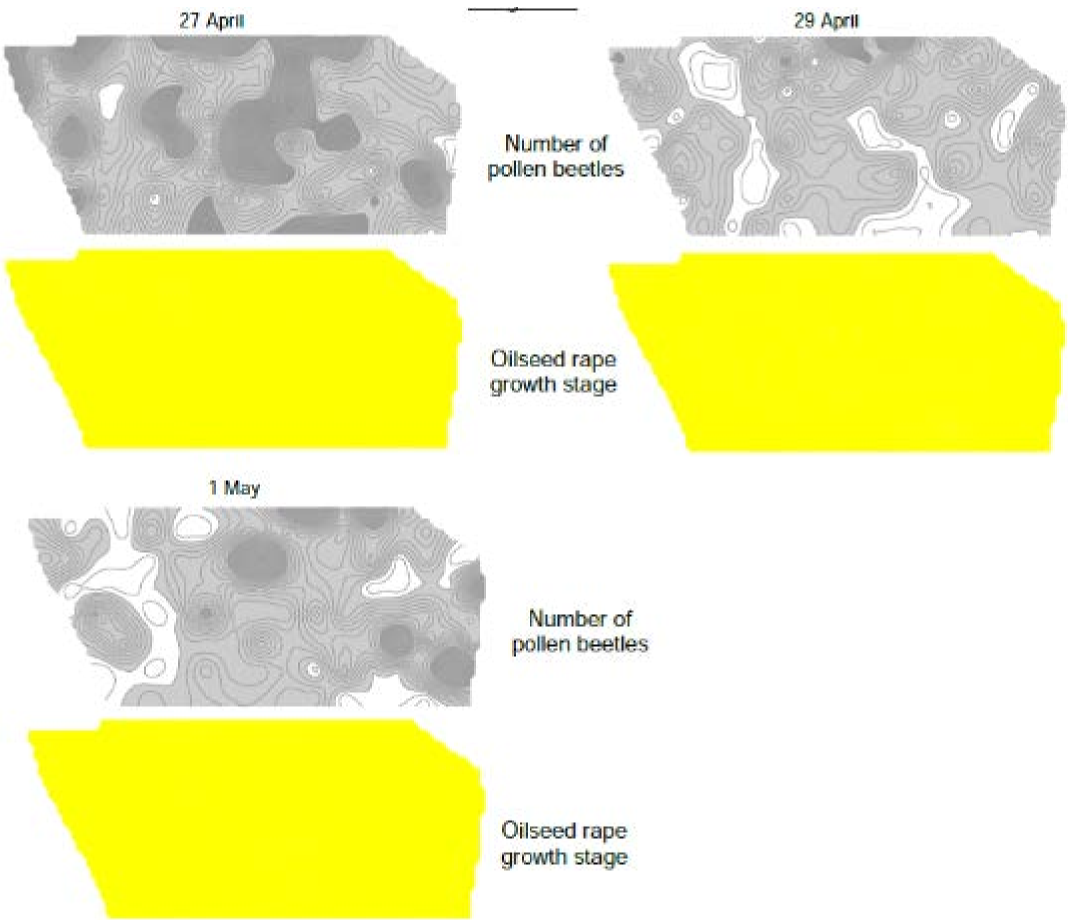
Appendix 2b Long Hoos



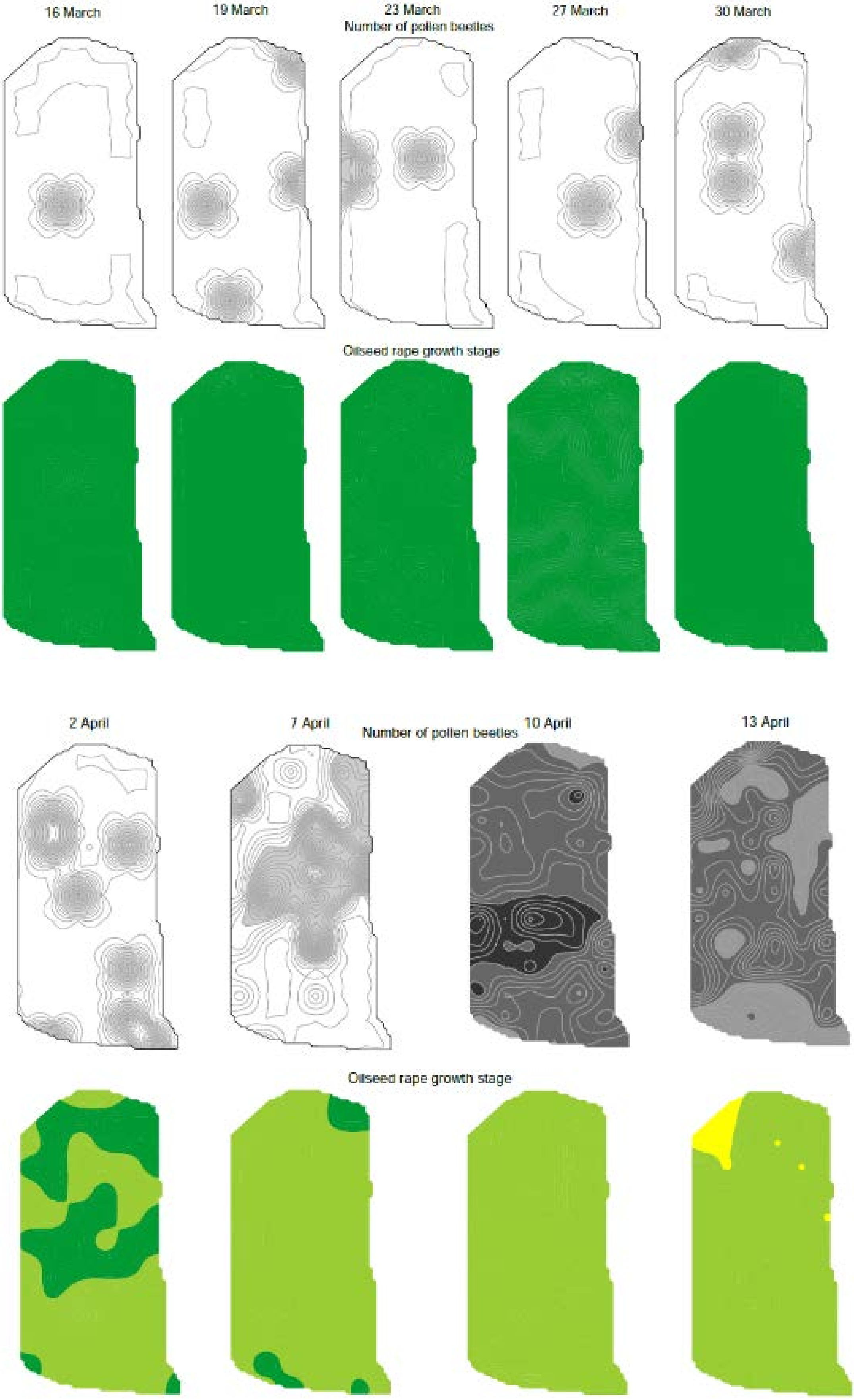
Appendix 2b Long Hoos (continued)



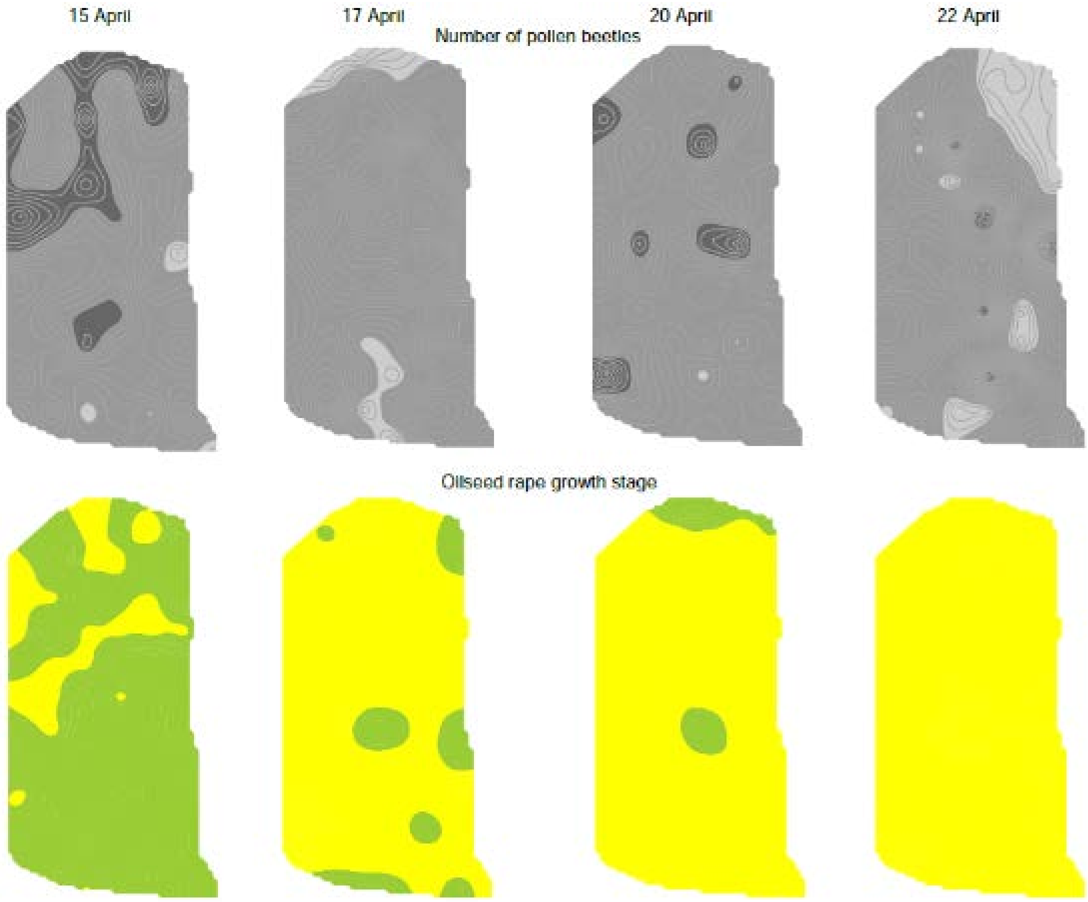
Appendix 2b Long Hoos (continued)

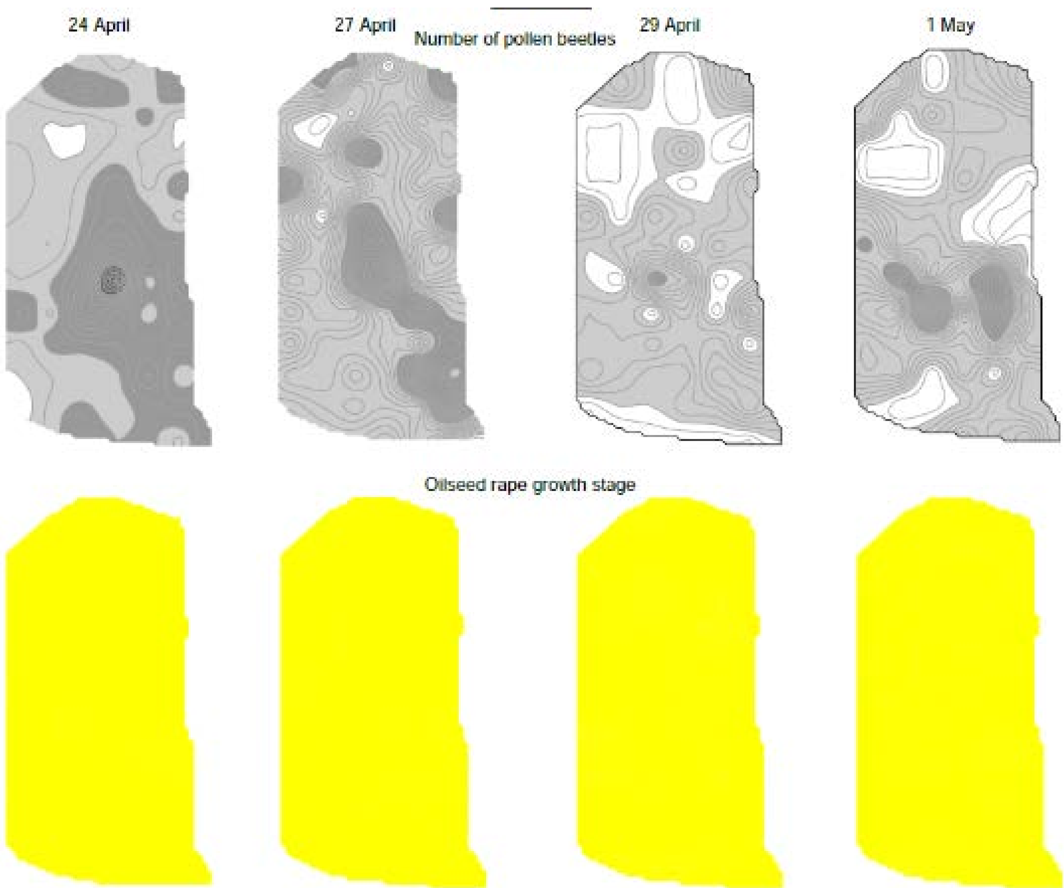


Appendix 2c Little Knott



Appendix 2c Little Knott (continued)





Appendix 3.

Performance of four control systems for pollen beetles in oilseed rape crops, Rothamsted Research, 2014-2016

Year/ Field	Assessment	**System**			
		Spray to threshold - Weekly monitoring	Spray to threshold - DSS-prompted monitoring	Prophylactic spray	No spray
2014 Drapers	No. monitoring events	4	4	0	0
	No. plots (from four) with thresholds exceeded	2	3	2	3
	Total no. times threshold reached	3	3	2	4
	No. times threshold exceeded and identified by system	0	3	NA	NA
	No. times threshold exceeded but missed	3	0	2	4
	Mean no. days delay between 1st experimental detection and system detection	Could not be determined; system monitoring did not detect when threshold exceeded in 2 plots	0 (n=3)	NA	NA
	No. missed treatments	3	0	0	4
	Total no. sprays	0	3	8	0
2014 Great Knott 3	No. monitoring events	5	4	0	0
	No. plots (from four) with thresholds exceeded	2	3	2	4
	Total no. times threshold reached	4	3	2	4
	No. times thresholds exceeded and identified by system	2	3	0	0
	No. times threshold exceeded but missed	2	0	2	4
	Mean no. days delay between 1st experimental detection and system detection	2 (n=2)	0 (n=3)	NA	NA
	No. missed treatments	0	0	0	4
	Total no. sprays	2	3	8	0

Appendix 3 Continued

Year/ Field	Assessment	System Spray to threshold - Weekly monitoring	Spray to threshold - DSS-prompted monitoring	Prophylactic spray	No spray
2015	No. monitoring events	5	7	0	0
Delafield	No. plots (from four) with thresholds exceeded	3	4	1	3
	Total no. times threshold reached	6	6	1	6
	No. times threshold exceeded and identified by system-	3	6	0	0
	No. times threshold exceeded but missed	3	0	1	6
	Mean no. days delay between 1st experimental detection and system detection	1.667 (n=3)	0 (n=4)	NA	NA
	No. missed treatments	0	0	0	3
	Total no. sprays	3	4	8	0
2016	No. monitoring events	7	1	0	0
Osier	No. plots (from four) with thresholds exceeded	4	1	4	4
	Total no. times threshold reached	6	1	4	4
	No. times threshold exceeded and identified by system	4	0	0	0
	No. times threshold exceeded but missed	2	1	4	4
	Mean no. days delay between 1st experimental detection and system detection	1 (n=4)	Could not be determined; system monitoring did not detect threshold breach	NA	NA
	No. missed treatments	0	1	4	4
	Total no. sprays	4	0	4	0

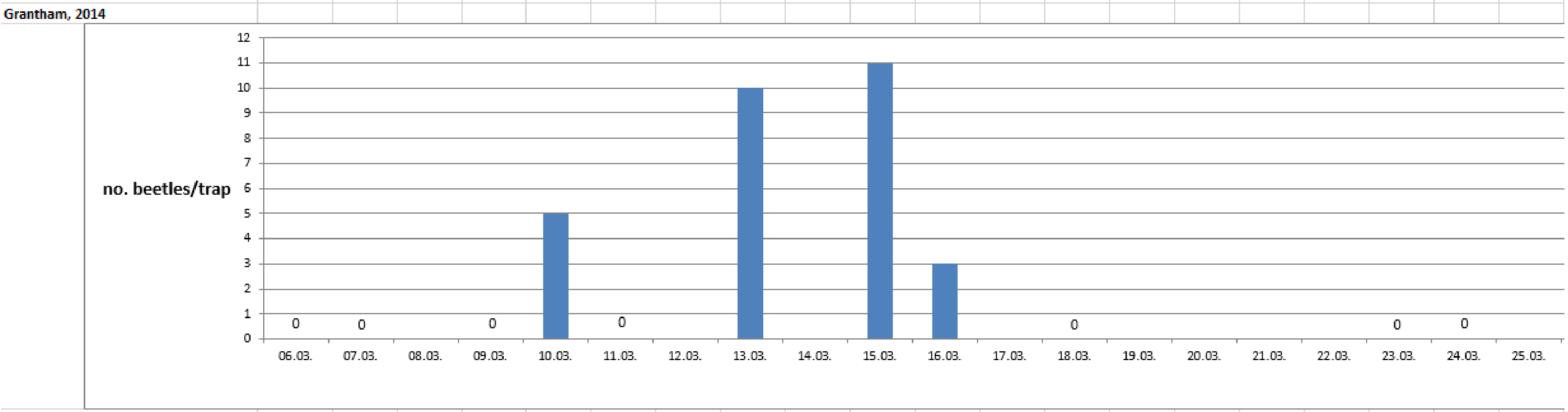
Appendix 3 Continued

Year/ Field	Assessment	System Spray to threshold - Weekly monitoring	Spray to threshold - DSS-prompted monitoring	Prophylactic spray	No spray
2016 Great Knott 1	No. monitoring events	7	2	0	0
	No. plots (from four) with thresholds	4	4	3	4
	Total no. times threshold reached	6	5	4	9
	No. times threshold exceeded and identified by system	4	3	0	0
	No. times threshold exceeded but missed	2	2	4	9
	Mean no. days delay between 1st experimental detection and system detection	3 (n=4)	0.667 (n=3) and 1 value could not be determined (system monitoring did not detect threshold breach)	NA	NA
	No. missed treatments	0	1	3	4
	Total no. sprays	3	3	4	0

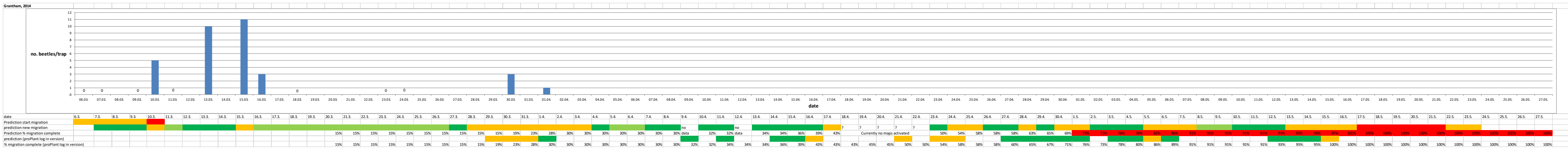
Appendix 4.

Assessment of the accuracy of predictions from the Bayer Pollen Beetle Prediction using data from local sites. A close-up of the data for start of migration is shown in the top panel for each site followed by the whole season in the lower panel.

Grantham, 2014

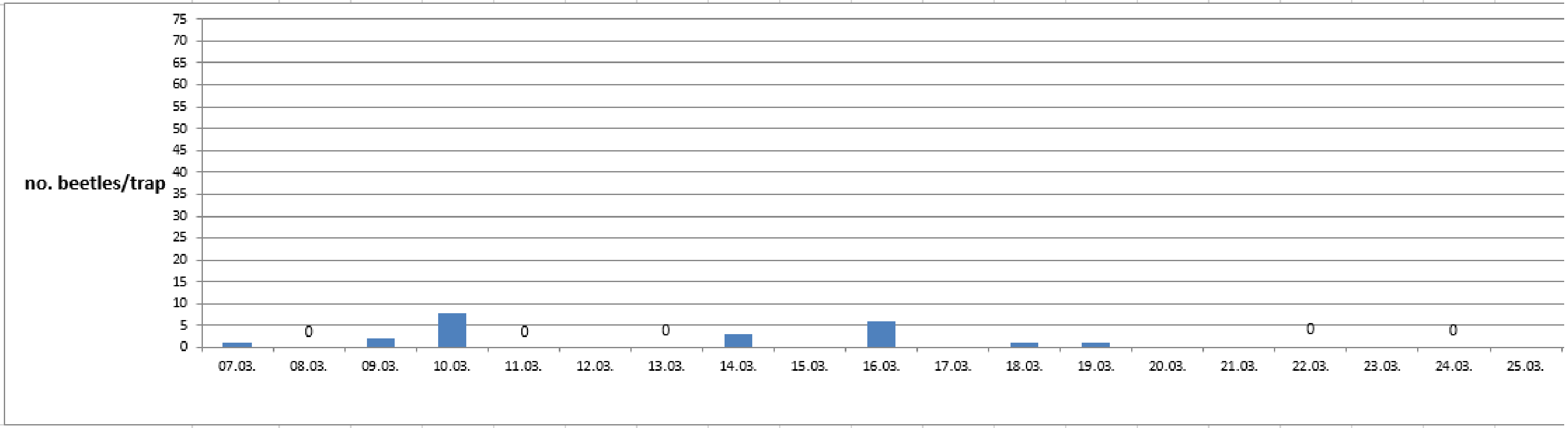


date	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.
Prediction start migration																				
prediction new migration																				
Prediction % migration complete															15%	15%	15%	15%	15%	15%
prediction (proPlant log in version)																				
% migration complete (proPlant log in version)															15%	15%	15%	15%	15%	15%

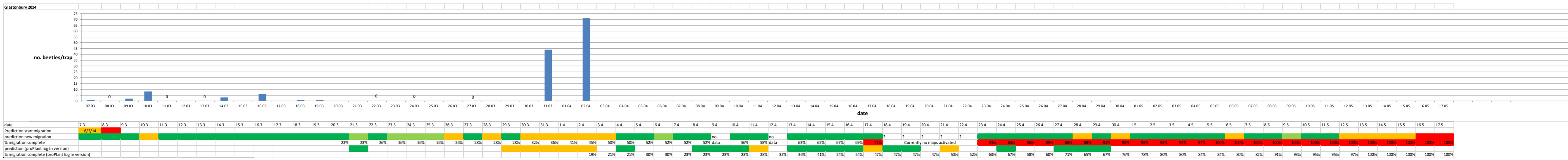


Appendix 4. Glastonbury, 2014

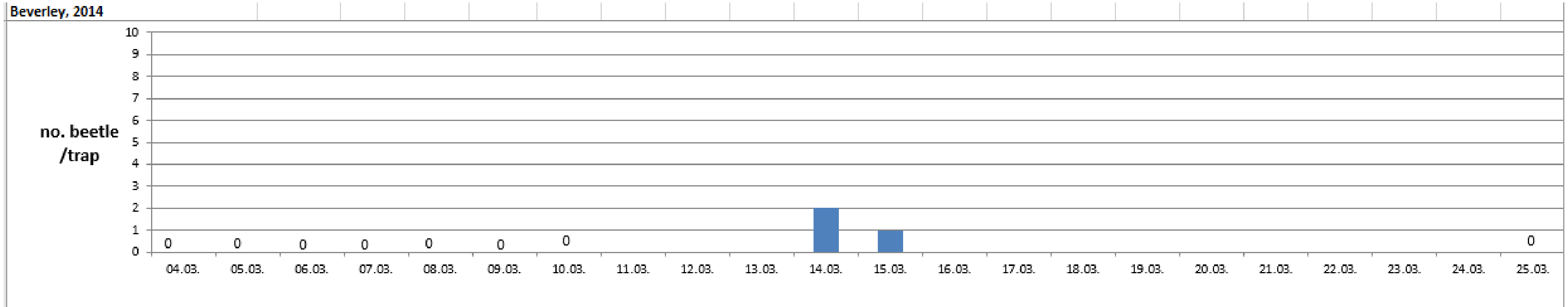
Glastonbury 2014



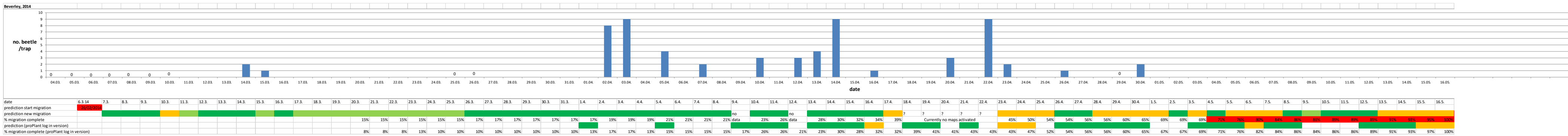
date	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.
Prediction start migration	6/3/14																		
prediction new migration																			
% migration complete														23%	23%	26%	26%	26%	26%
prediction (proPlant log in version)																			
% migration complete (proPlant log in version)																			



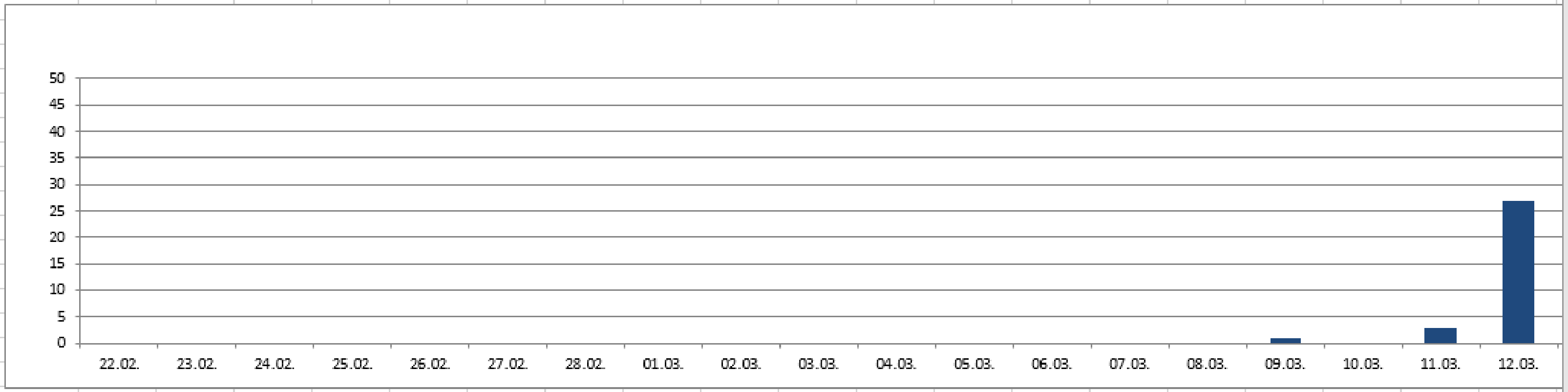
Appendix 4. Beverley, 2014



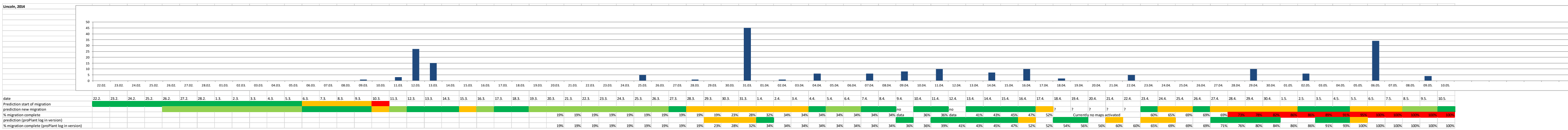
date	6.3.14	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.
prediction start migration	26/02/2014																			
prediction new migration																				
% migration complete															15%	15%	15%	15%	15%	15%
prediction (proPlant log in version)																				
% migration complete (proPlant log in version)															8%	8%	8%	13%	10%	10%



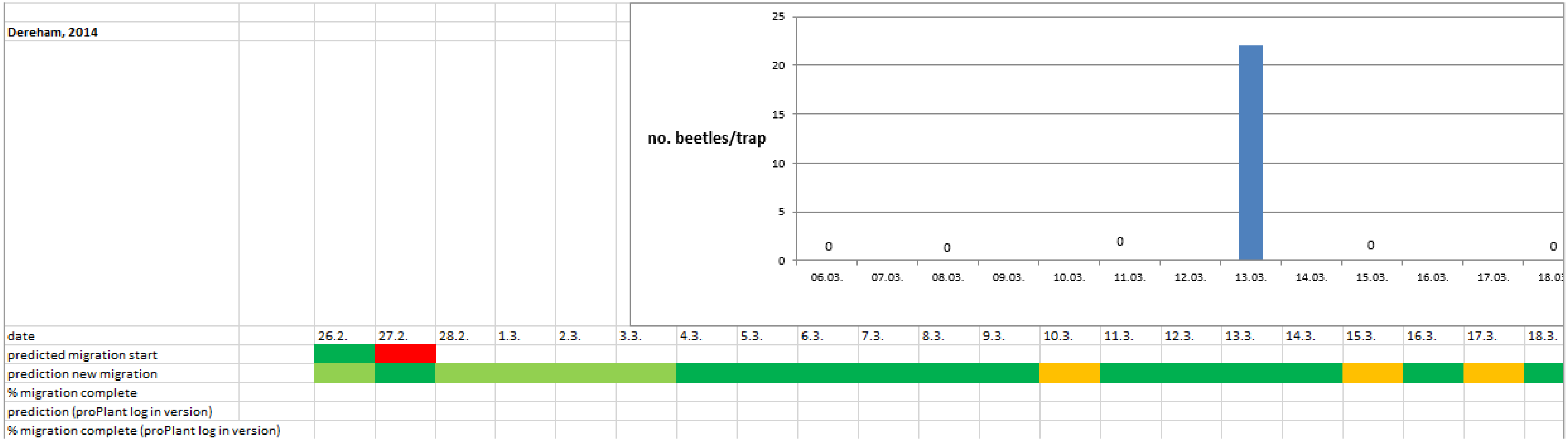
Appendix 4. Lincoln, 2014

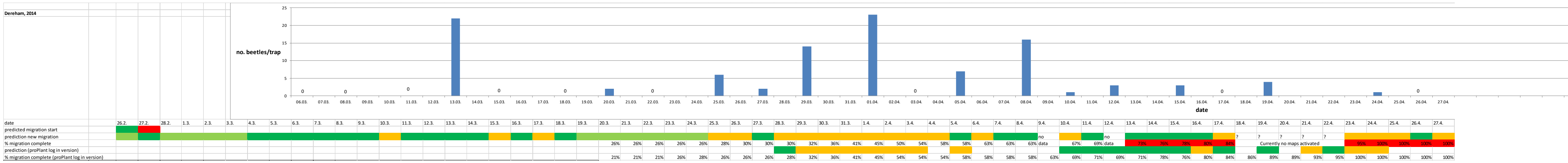


Lincoln, 2014																			
date	22.2.	23.2.	24.2.	25.2.	26.2.	27.2.	28.2.	1.3.	2.3.	3.3.	4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.
Prediction start of migration																			
prediction new migration																			
% migration complete																			
prediction (proPlant log in version)																			
% migration complete (proPlant log in version)																			



Appendix 4. Dereham, 2014

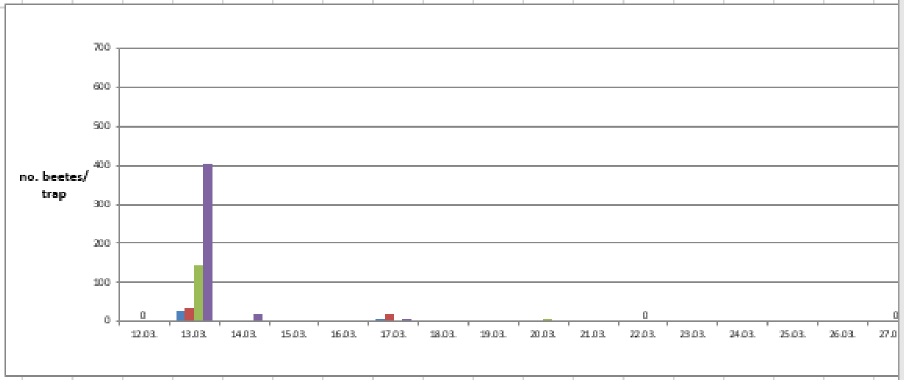




Appendix 4. Welwyn Garden City, 2014

Rothamsed, Delharding

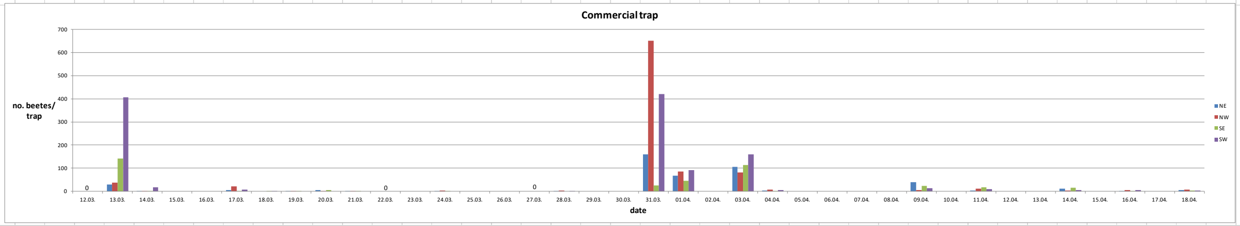
Welwyn Garden City – Rothamsted Delharding



date	22.2.	23.2.	24.2.	25.2.	26.2.	27.2.	28.2.	1.3.	2.3.	3.3.	4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.
migration start					22/2/14?												
prediction new migration																	
% migration complete																	
prediction (proPlant log in version)																	
% migration complete (proPlant log in version)																	

date	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3
migration start																	
prediction new migration																	
% migration complete										58%	58%	60%	63%	63%	65%	65%	
prediction (proPlant log in version)																	
% migration complete (proPlant log in version)										36%	39%	41%	63%	60%	43%	43%	

Welwyn Garden City - Rothamsted Delharding



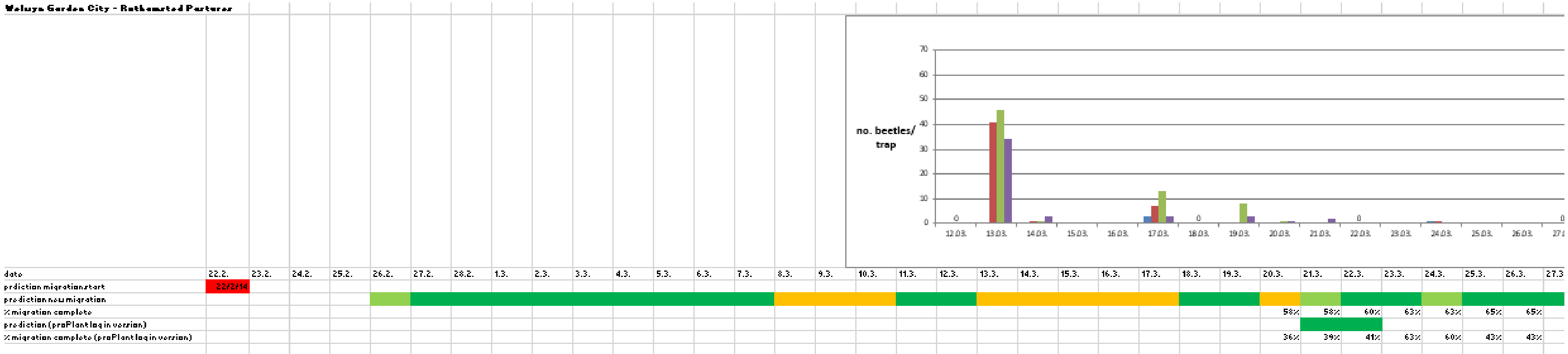
date	22.2.	23.2.	24.2.	25.2.	26.2.	27.2.	28.2.	1.3.	2.3.	3.3.	4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.
migration start					22/2/14?												
prediction new migration																	
% migration complete																	
prediction (proPlant log in version)																	
% migration complete (proPlant log in version)																	

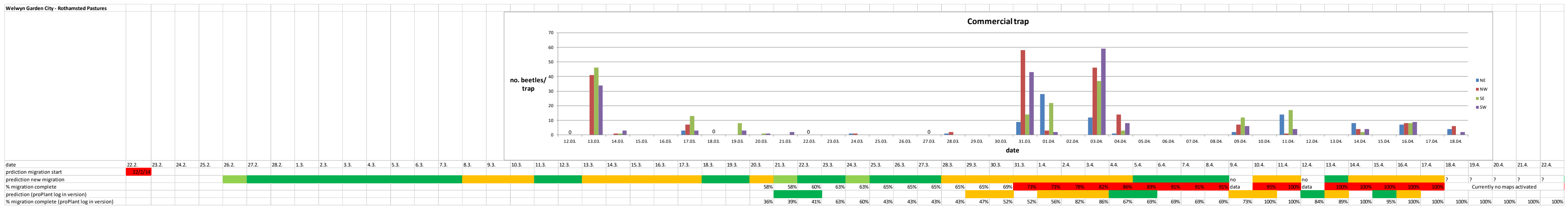
date	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.
migration start																					
prediction new migration																					
% migration complete										58%	58%	60%	63%	63%	65%	65%	65%	65%	65%	69%	73%
prediction (proPlant log in version)																					
% migration complete (proPlant log in version)										36%	39%	41%	63%	60%	43%	43%	43%	43%	47%	52%	52%

date	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.	7.4.	8.4.	9.4.	10.4.	11.4.	12.4.	13.4.	14.4.	15.4.	16.4.	17.4.	18.4.	19.4.	20.4.	21.4.	22.4.
migration start																						
prediction new migration									no			no						?	?	?	?	?
% migration complete	73%	78%	82%	86%	89%	91%	91%	91%	data	95%	100%	data	100%	100%	100%	100%	100%	Currently no maps activated				
prediction (proPlant log in version)																						
% migration complete (proPlant log in version)	56%	82%	86%	67%	69%	69%	69%	69%	73%	100%	100%	84%	89%	100%	95%	100%	100%	100%	100%	100%	100%	100%

Appendix 4. Welwyn Garden City, 2014

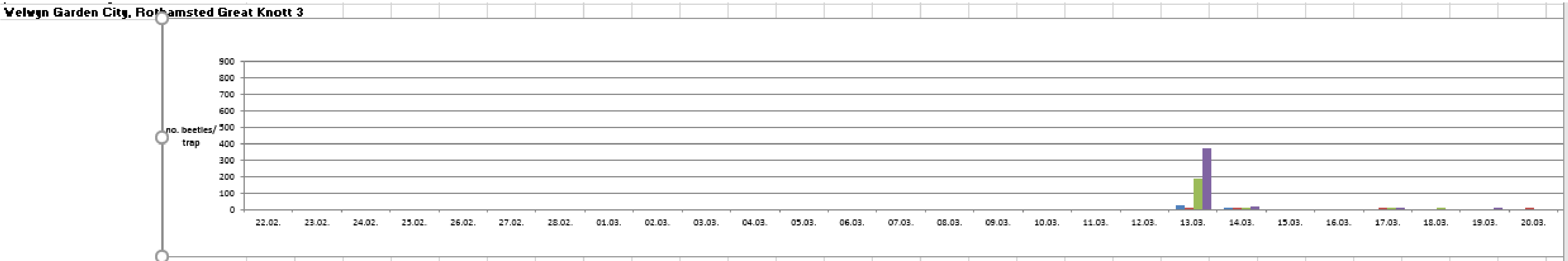
Rothamsed, Pastures



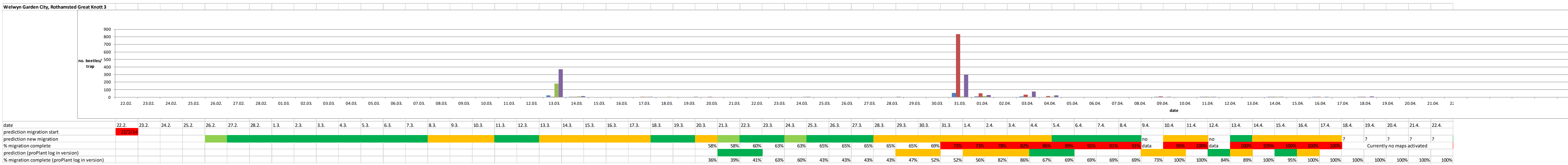


Appendix 4. Welwyn Garden City, 2014

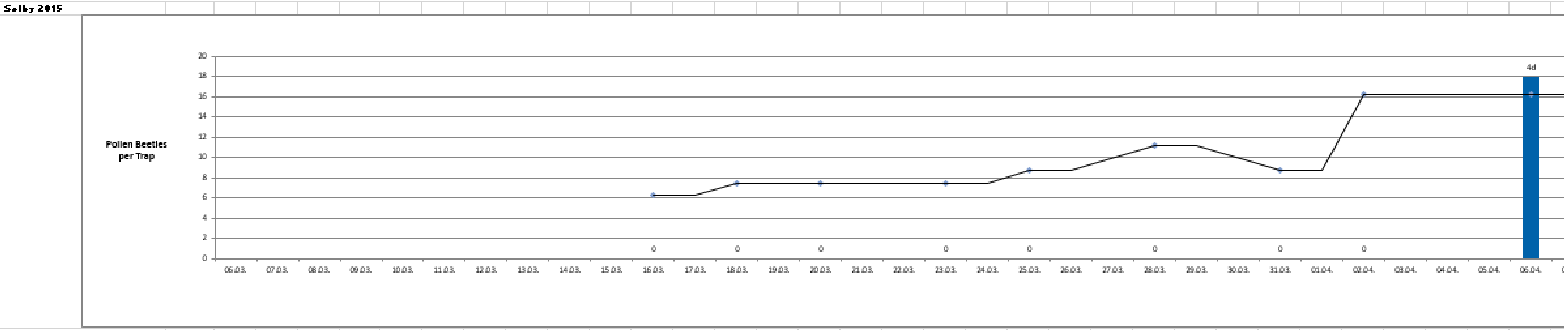
Rothamsed, Great Knott 3



date	22.2.	23.2.	24.2.	25.2.	26.2.	27.2.	28.2.	1.3.	2.3.	3.3.	4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.
prediction migration start	22/2/14																											
prediction new migration																												
% migration complete																											58%	
prediction (proPlant log in version)																												
% migration complete (proPlant log in version)																											36%	

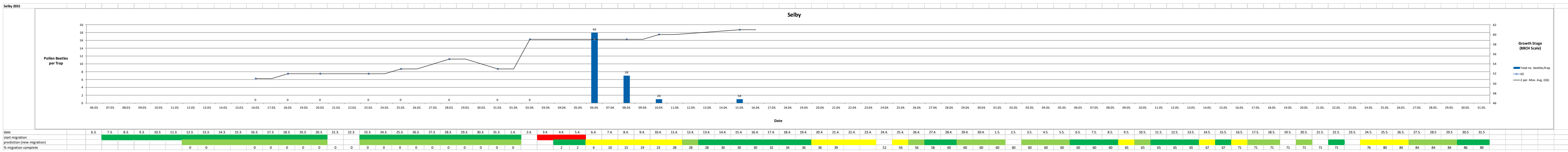


Appendix 4. Selby, 2015

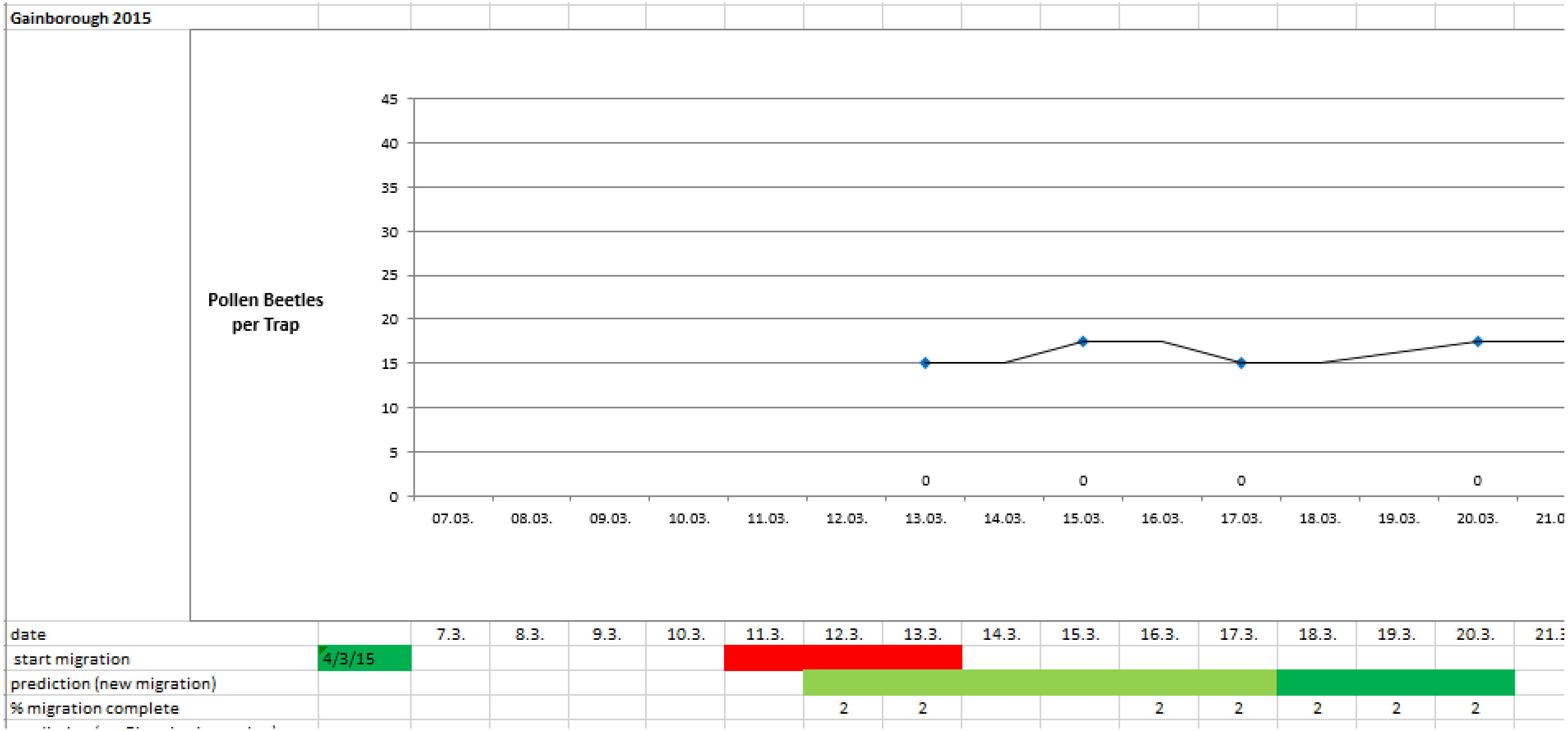


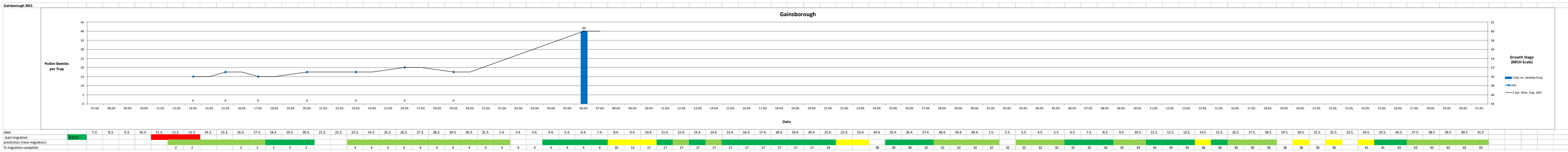
date	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.
start migration																																
prediction (new migration)																																
% migration complete							0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			2	2	6

date		6.3.	7.3.
start migration			
prediction (new migration)			
% migration complete			

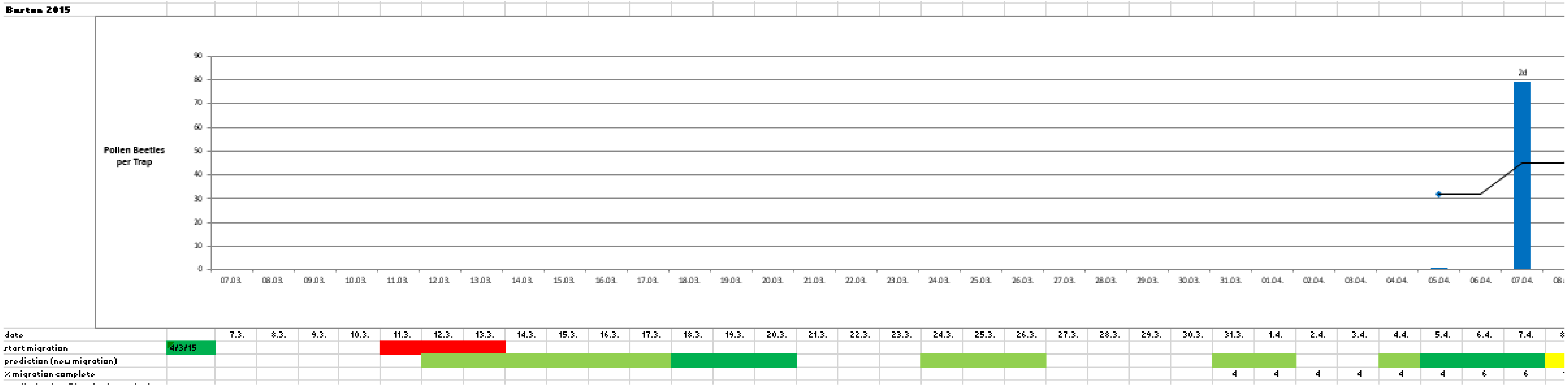


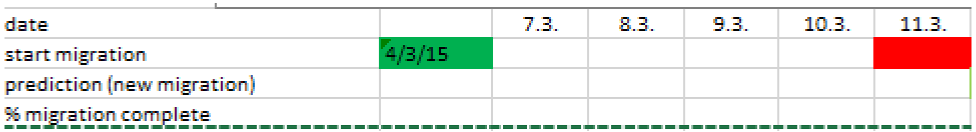
Appendix 4. Gainsborough, 2015



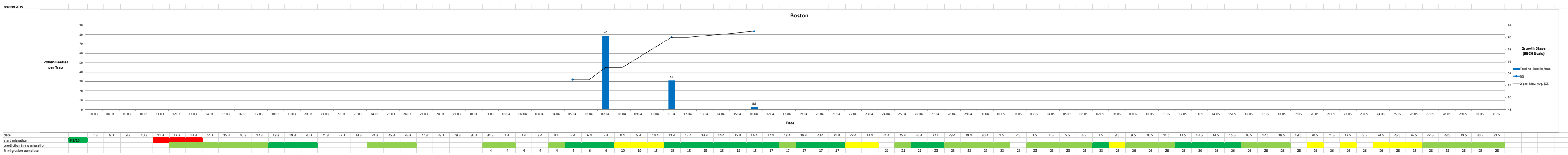


Appendix 4. Boston, 2015



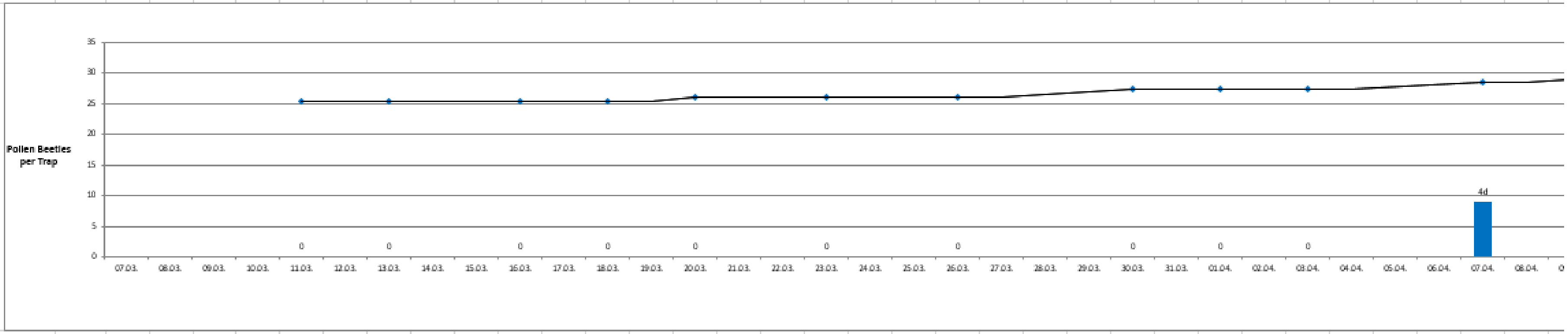


date		7.3.	8.3.	9.3.	10.3.	11.3.
start migration	4/3/15					
prediction (new migration)						
% migration complete						



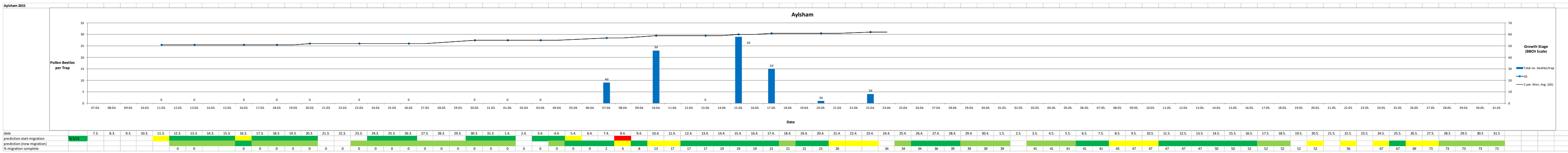
Appendix 4. Aylsham, 2015

Aylsham 2015



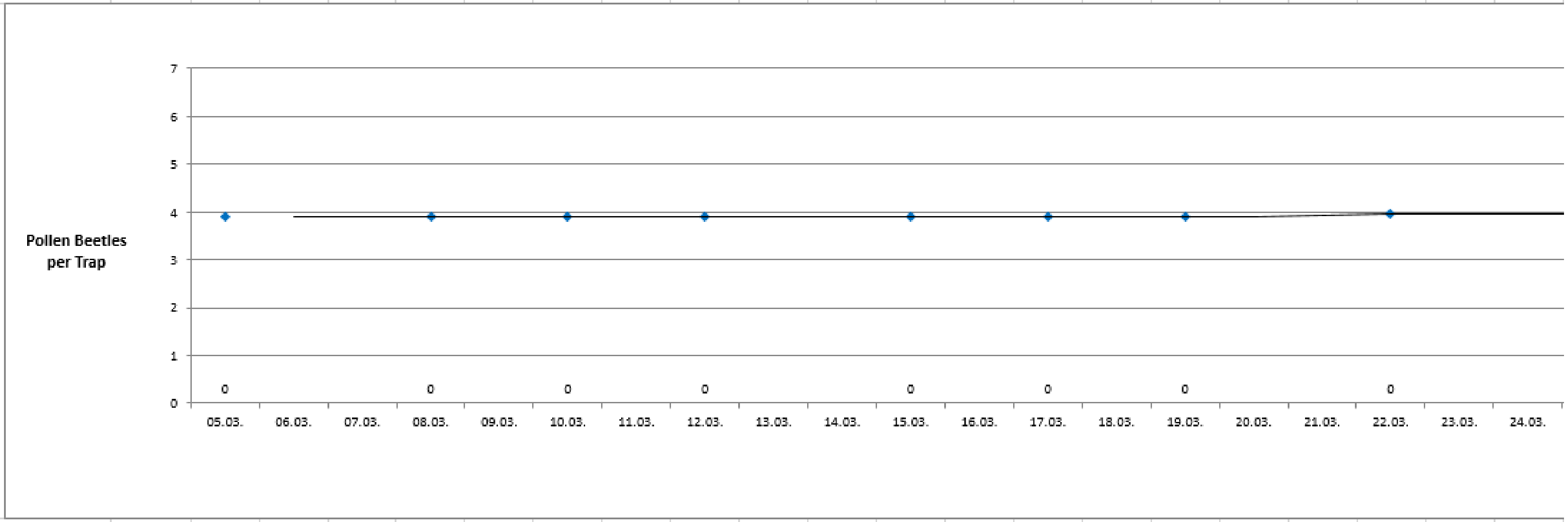
		7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.	7.4.	8.4.
date		7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.	7.4.	8.4.
prediction start migration	4/3/15																																	
prediction (new migration)																																		
% migration complete							0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6
prediction (proPlant login version)																																		

date		7.3.
prediction start migration	4/3/15	
prediction (new migration)		
% migration complete		

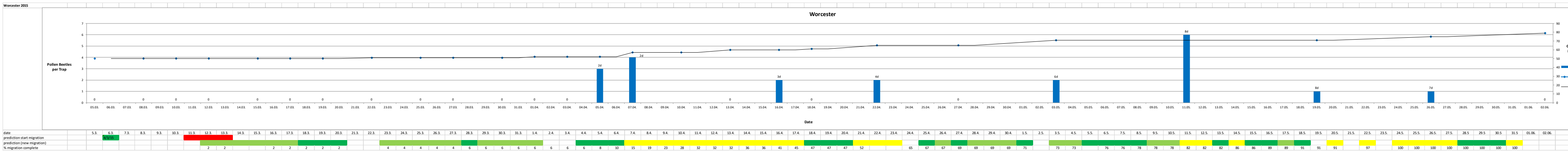


Appendix 4. Worcester, 2015

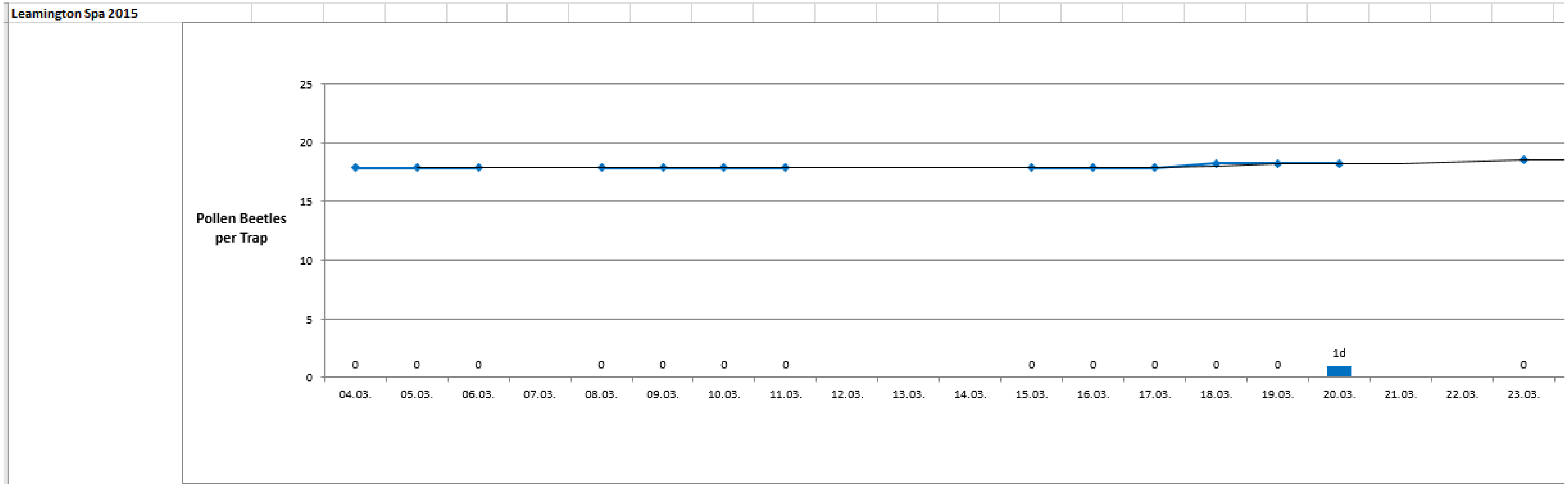
Worcester 2015



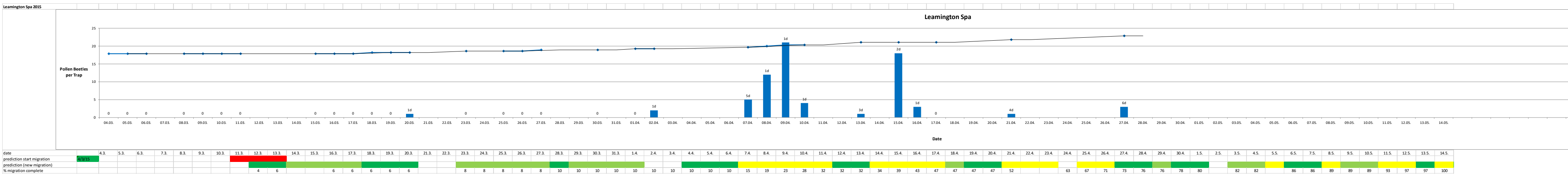
date		5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.
prediction start migration			4/3/15																		
prediction (new migration)																					
% migration complete									2	2			2	2	2	2	2			4	4



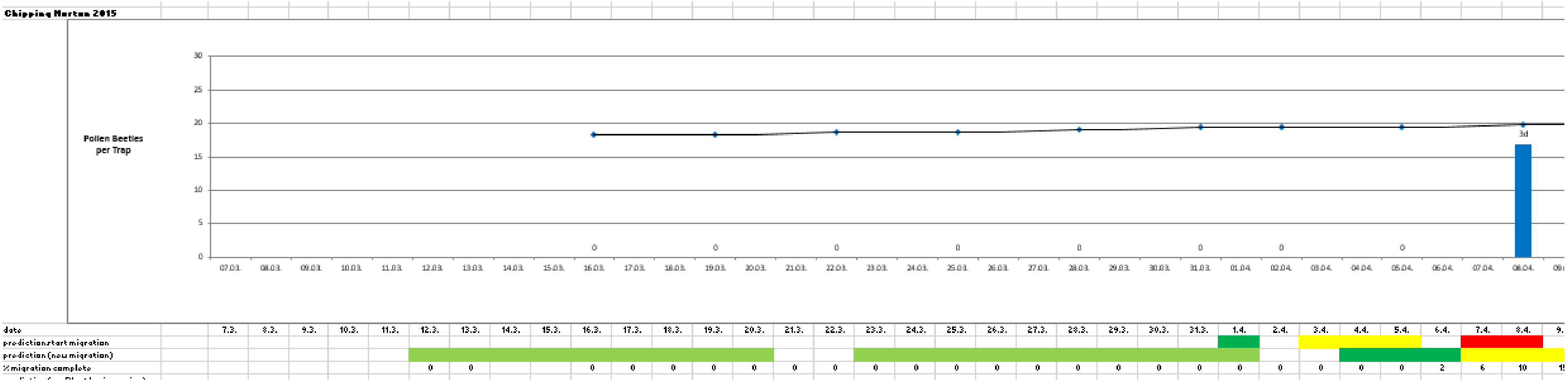
Appendix 4. Leamington Spa, 2015



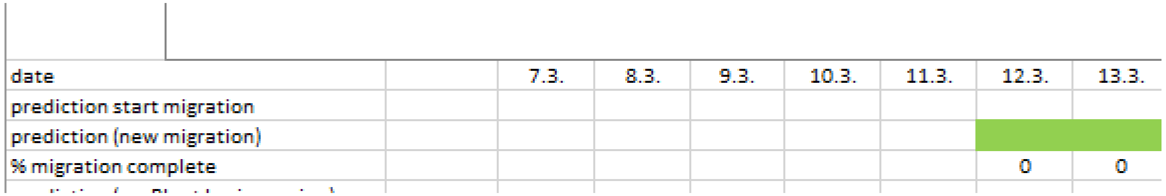
date		4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.
prediction start migration	4/3/15																				
prediction (new migration)																					
% migration complete										4	6			6	6	6	6	6			8



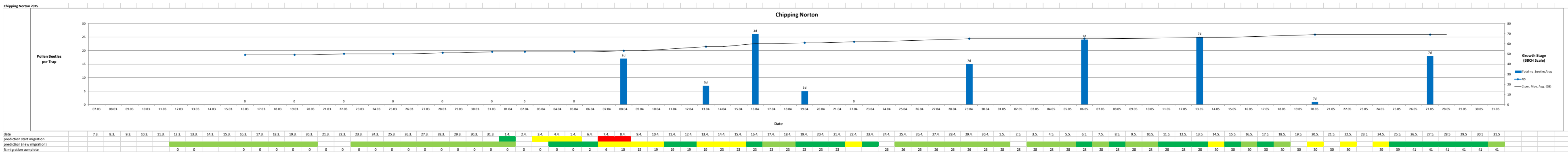
Appendix 4. Chipping Norton, 2015



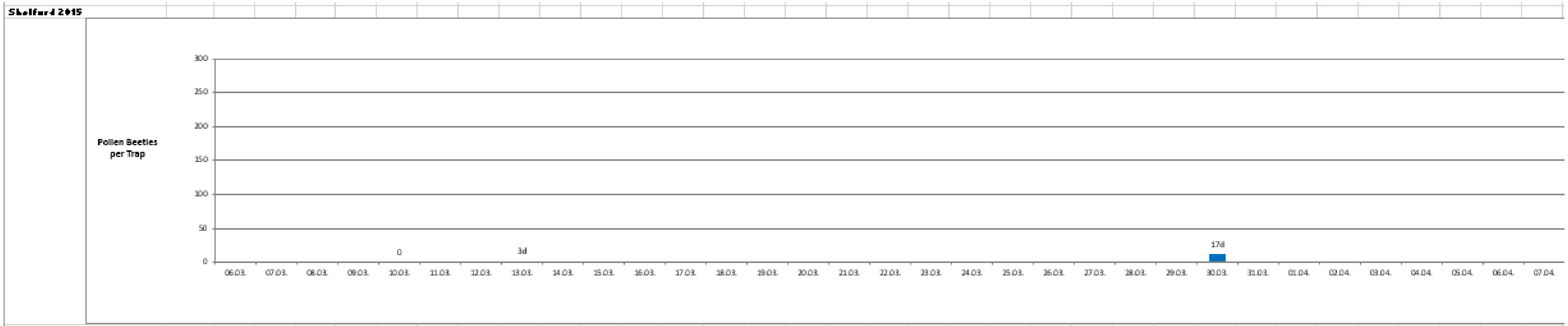
date	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.	7.4.	8.4.	9.
prediction start migration																																		
prediction (new migration)																																		
% migration complete						0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	10	1[illegible]



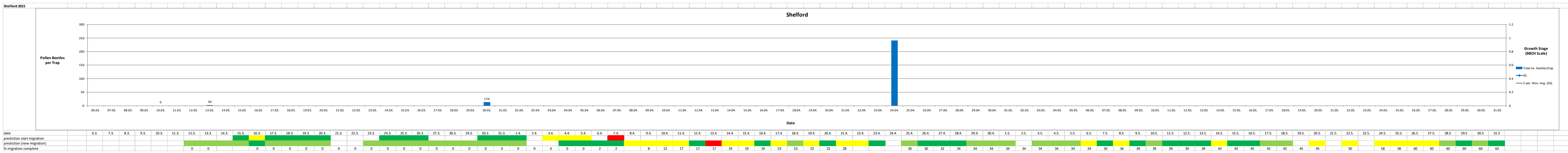
date	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.
prediction start migration							
prediction (new migration)							
% migration complete						0	0



Appendix 4. Shelford, 2015

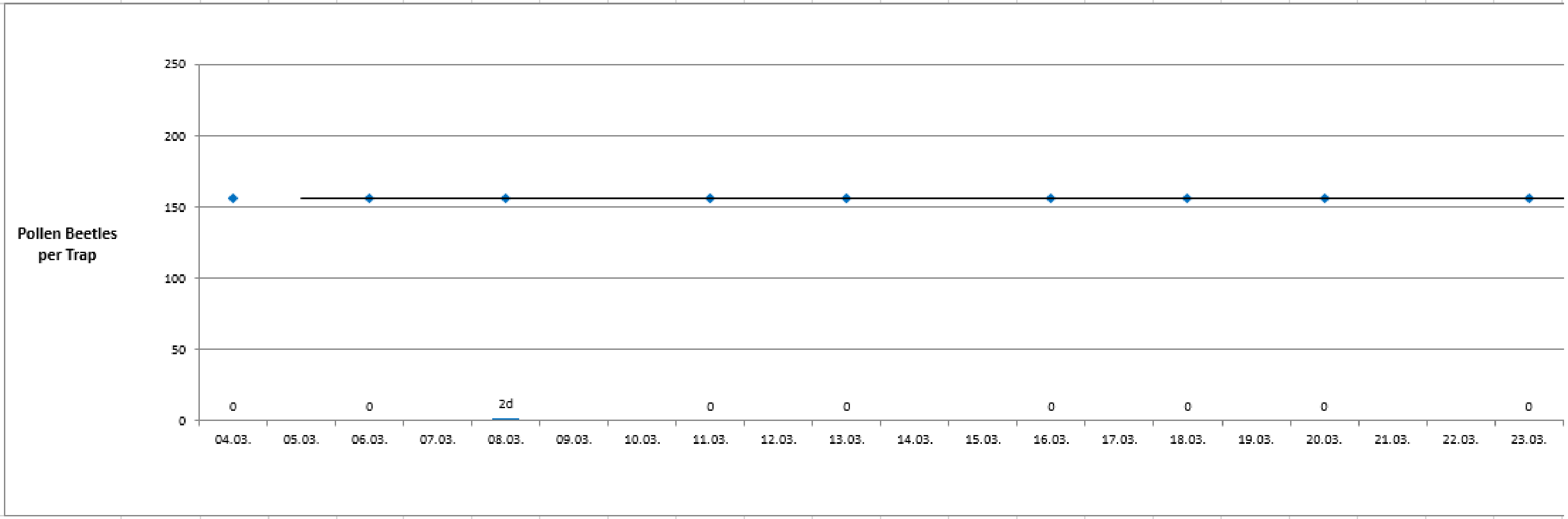


date		6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.	7.4.
prediction start migration																																		
prediction (new migration)																																		
% migration complete								0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2

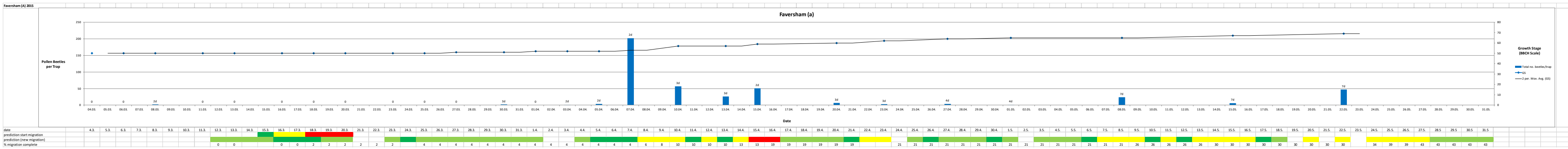


Appendix 4. Faversham, (Lenham) 2015

Faversham (A) 2015

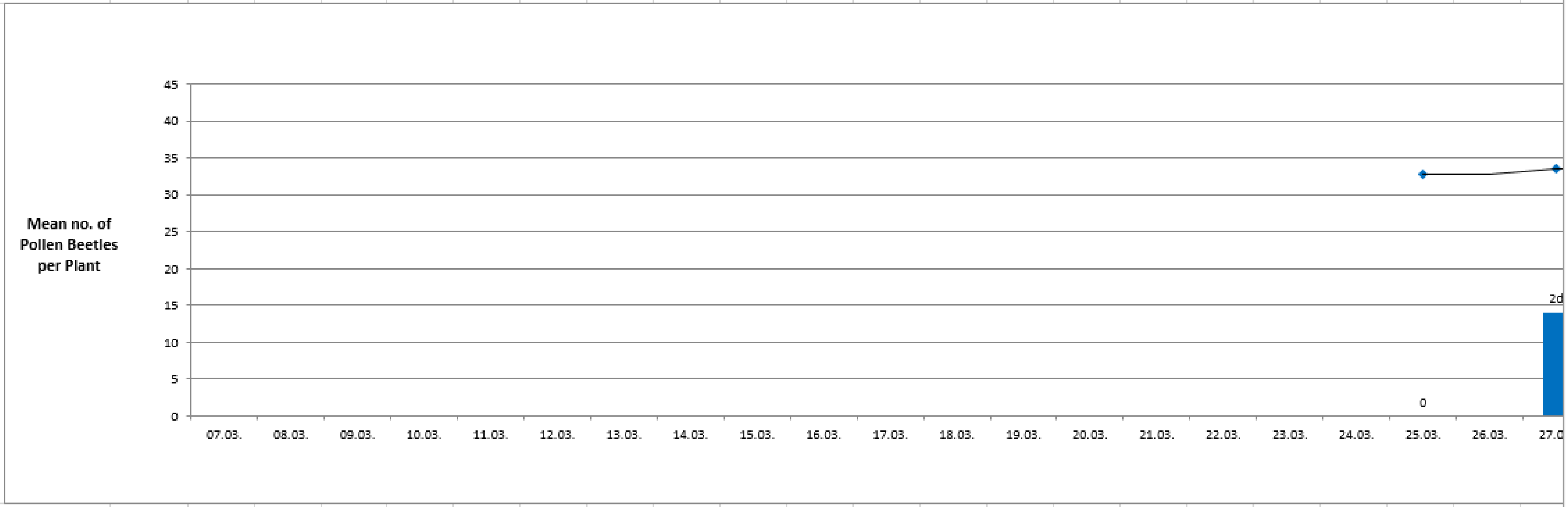


date		4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.
prediction start migration																					
prediction (new migration)																					
% migration complete										0	0			0	0	2	2	2	2	2	2

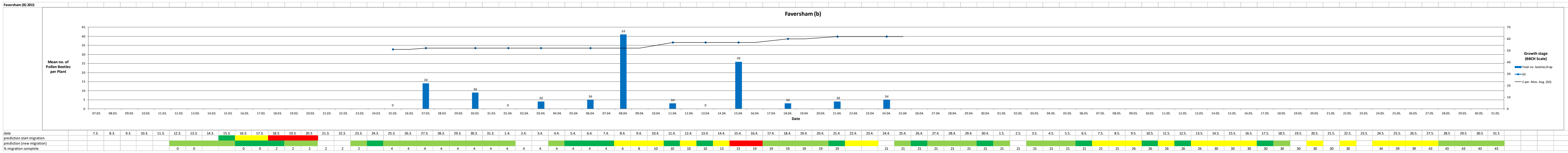


Appendix 4. Faversham (Tilmanstone) 2015

Faversham (B) 2015

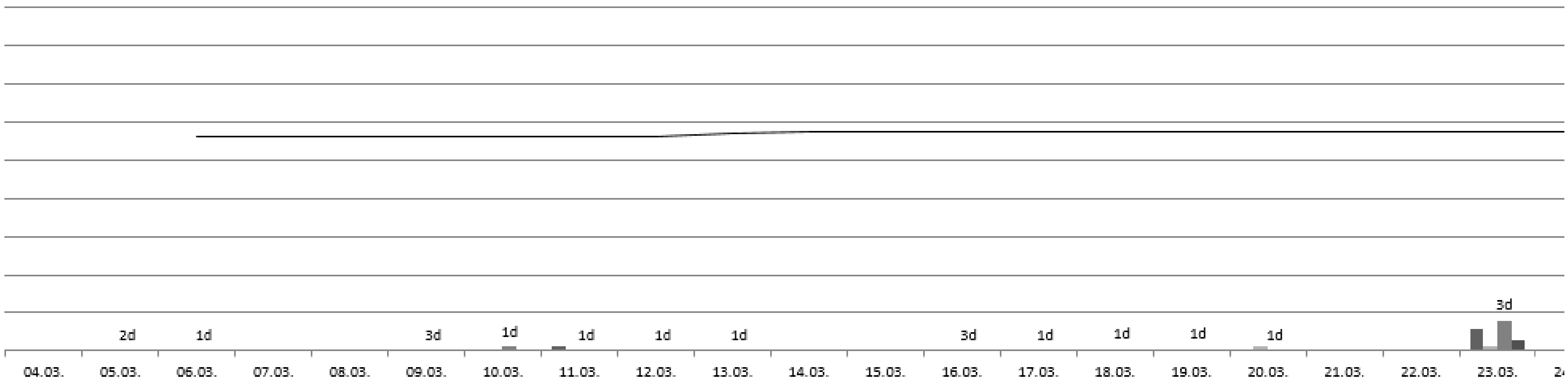


date		7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3
prediction start migration																						
prediction (new migration)																						
% migration complete							0	0			0	0	2	2	2	2	2	2		4	4	4

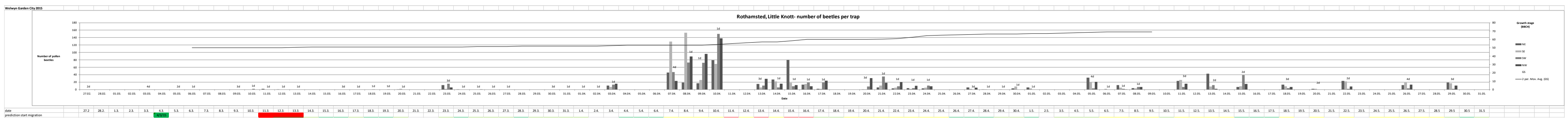


Appendix 4. Welwyn Garden City, 2015

Little Knott, Rothamsted

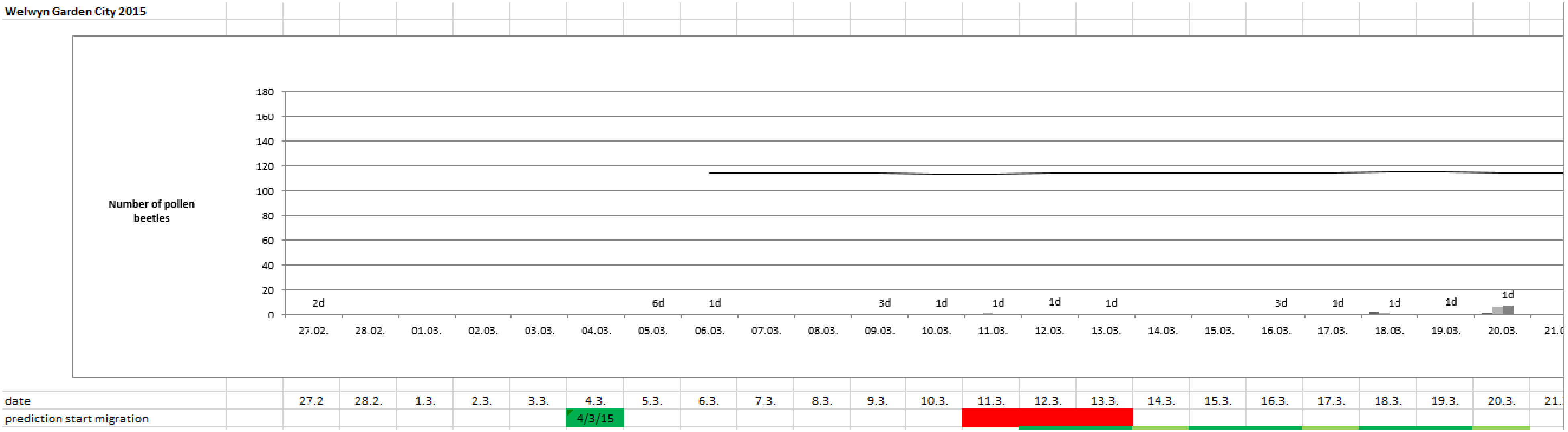


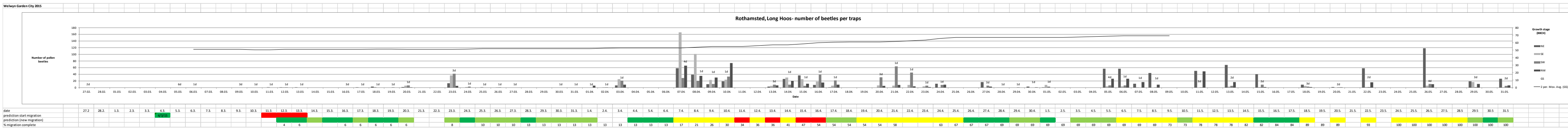
4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.
4/3/15																			



Appendix 4. Welwyn Garden City, 2015

Long Hoos, Rothamsted

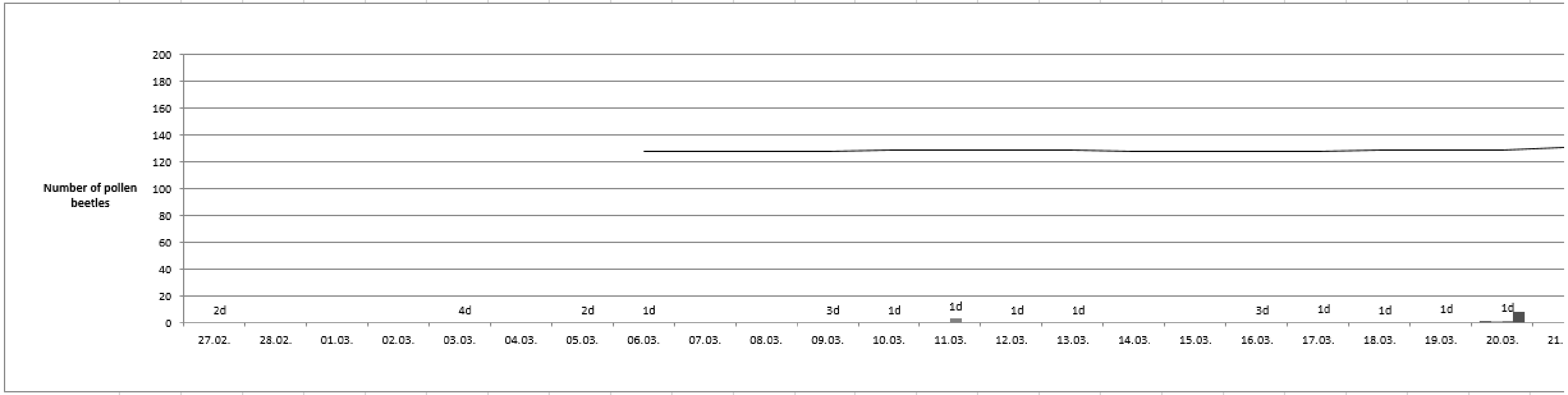




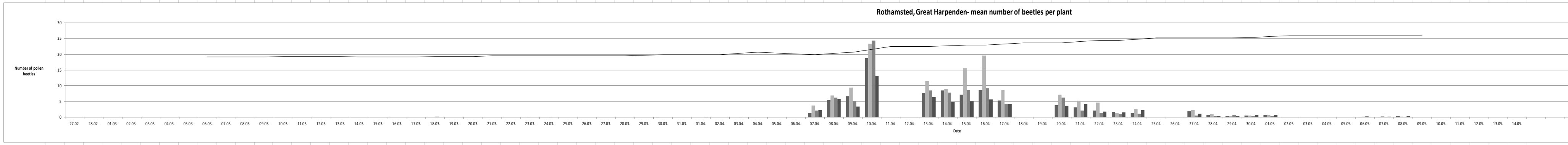
Appendix 4. Welwyn Garden City, 2015

Great Harpenden, Rothamsted

Welwyn Garden City 2015

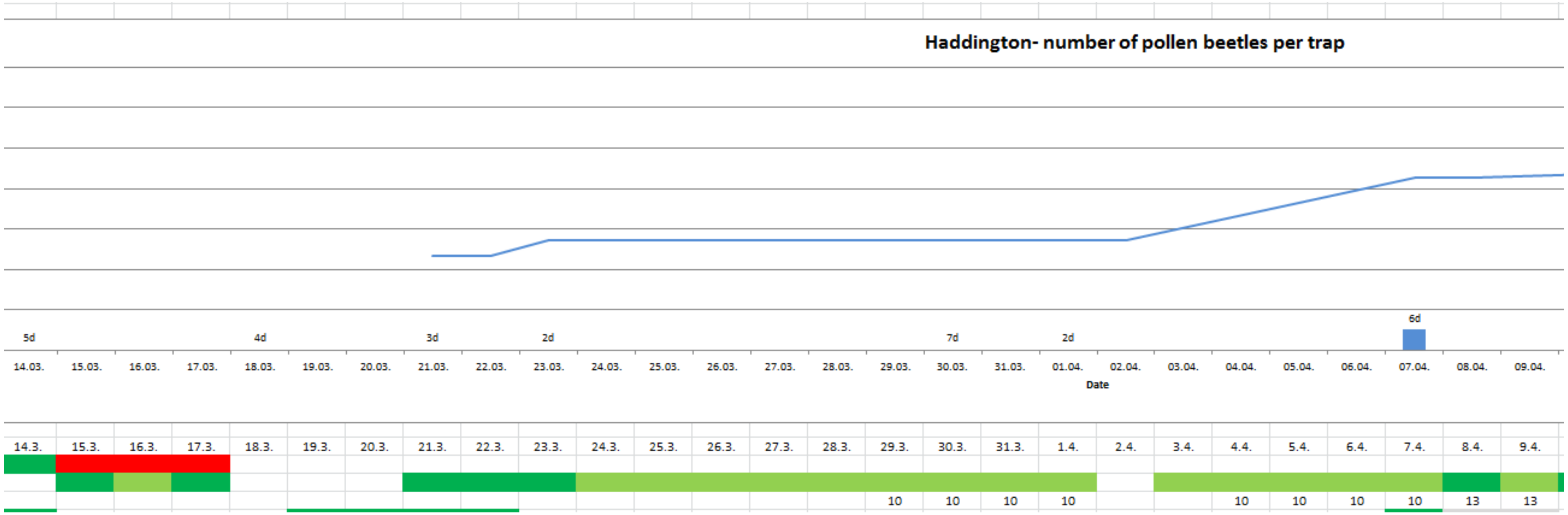


date	27.2	28.2.	1.3.	2.3.	3.3.	4.3.	5.3.	6.3.	7.3.	8.3.	9.3.	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.
prediction start migration						4/3/15																	

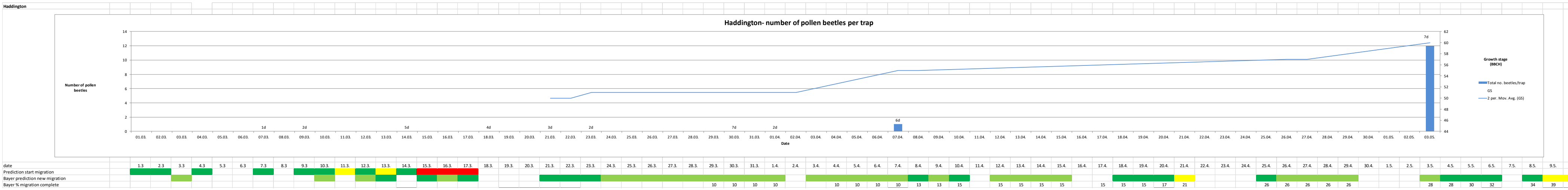


date	prediction start migration	prediction (new migration)	% migration complete	prediction (proPlant log in version)
27.2				
28.2.				
1.3.				
2.3.				
3.3.				
4.3.	4/3/15			
5.3.				
6.3.				
7.3.				
8.3.				
9.3.				
10.3.				
11.3.				
12.3.			4	
13.3.			6	
14.3.				
15.3.				
16.3.			6	
17.3.			6	
18.3.			6	
19.3.			6	
20.3.			6	
21.3.				
22.3.				
23.3.			8	
24.3.				
25.3.			10	
26.3.			10	
27.3.			10	
28.3.			13	
29.3.			13	
30.3.			13	
31.3.			13	
1.4.			13	
2.4.			13	
3.4.			13	
4.4.			13	
5.4.			13	
6.4.			13	
7.4.			17	
8.4.			21	
9.4.			26	
10.4.			30	
11.4.			34	
12.4.			36	
13.4.			36	
14.4.			41	
15.4.			47	
16.4.			54	
17.4.			54	
18.4.			54	
19.4.			54	
20.4.			54	
21.4.			58	
22.4.				
23.4.				
24.4.			63	
25.4.			67	
26.4.			67	
27.4.			67	
28.4.			69	
29.4.			69	
30.4.			69	
1.5.			69	
2.5.			69	
3.5.			69	
4.5.			69	
5.5.			69	
6.5.			69	
7.5.			69	
8.5.			69	
9.5.			73	
10.5.			73	
11.5.			78	
12.5.			78	
13.5.			78	
14.5.			82	

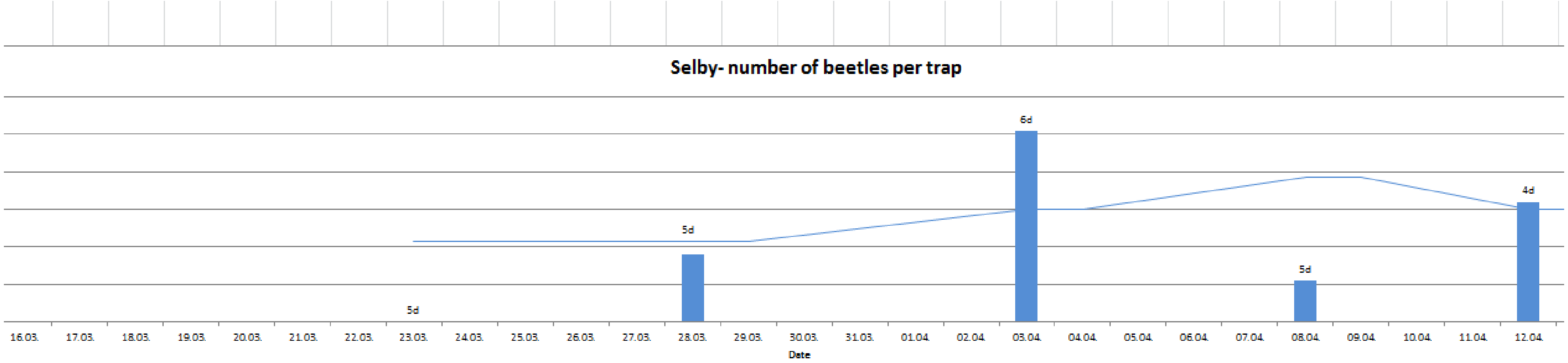
Appendix 4. Haddington, 2016



date		1.3	2.3	3.3
Prediction start migration				
Bayer prediction new migration				
Bayer % migration complete				

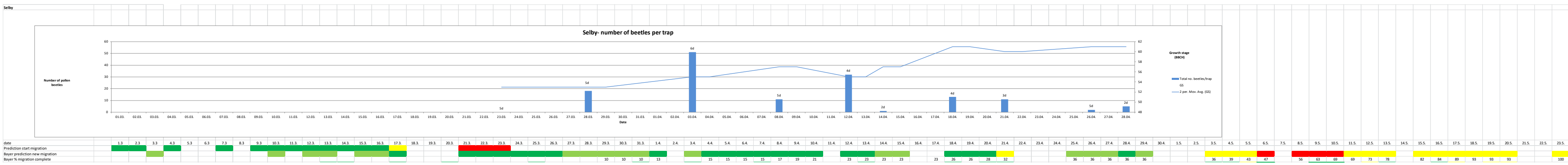


Appendix 4. Selby, 2016

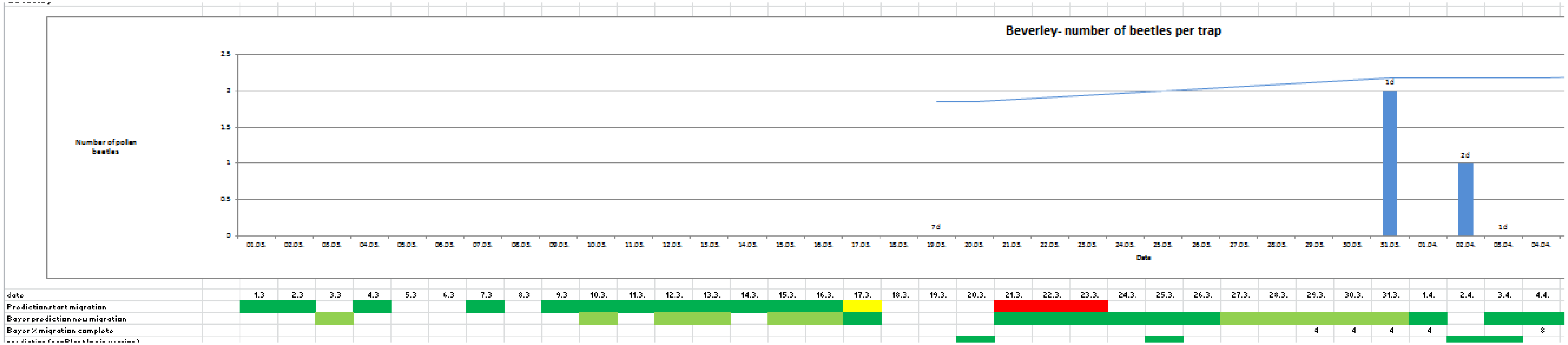


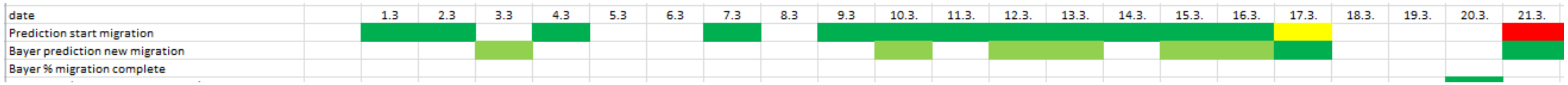
16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.	29.3.	30.3.	31.3.	1.4.	2.4.	3.4.	4.4.	5.4.	6.4.	7.4.	8.4.	9.4.	10.4.	11.4.	12.4.
													10	10	10	13			15	15	15	15	17	19	21		23

date		1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.
Prediction start migration																		
Bayer prediction new migration																		
Bayer % migration complete																		

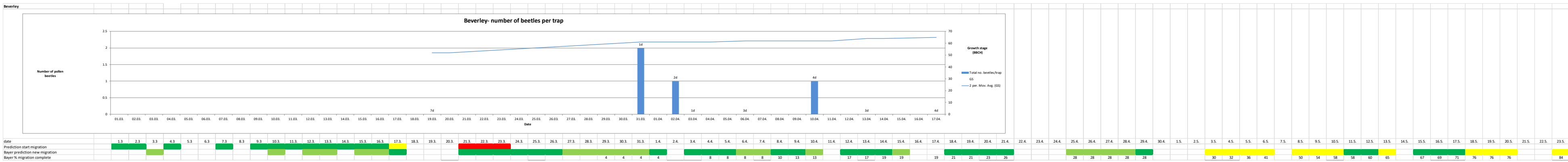


Appendix 4. Beverley, 2016

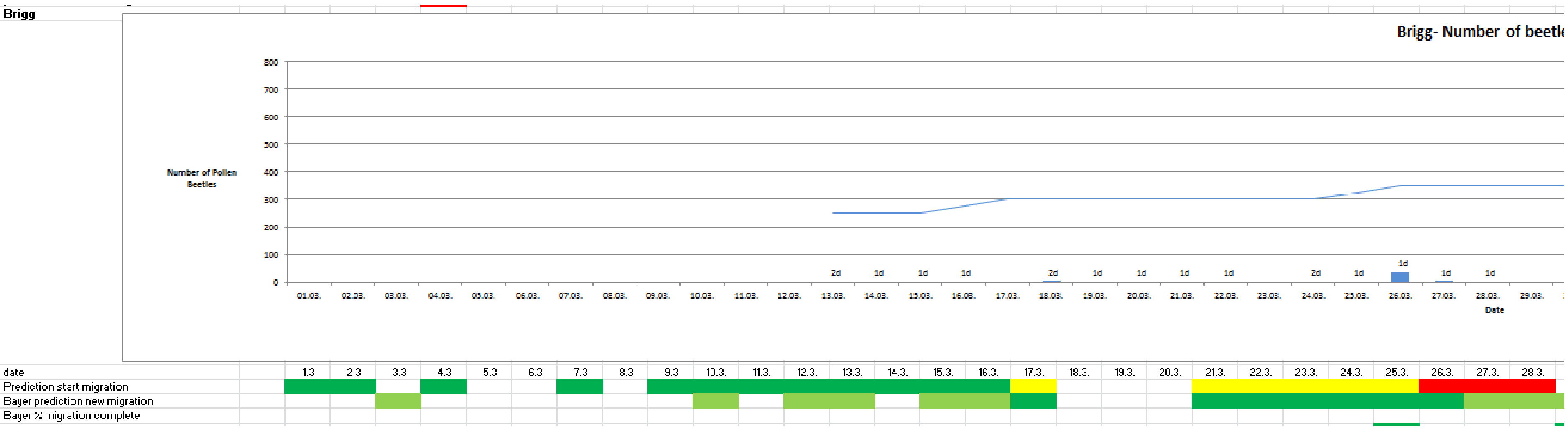


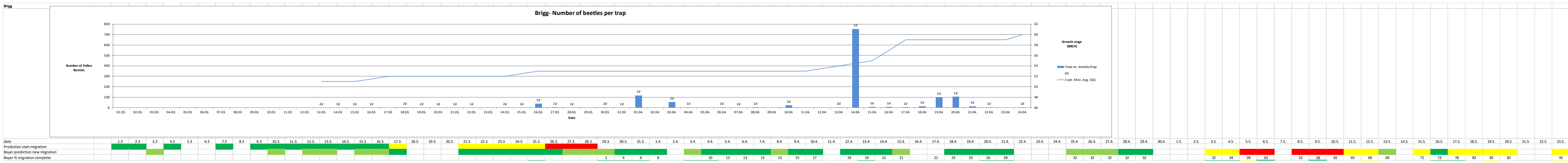


date		1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.
Prediction start migration																						
Bayer prediction new migration																						
Bayer % migration complete																						



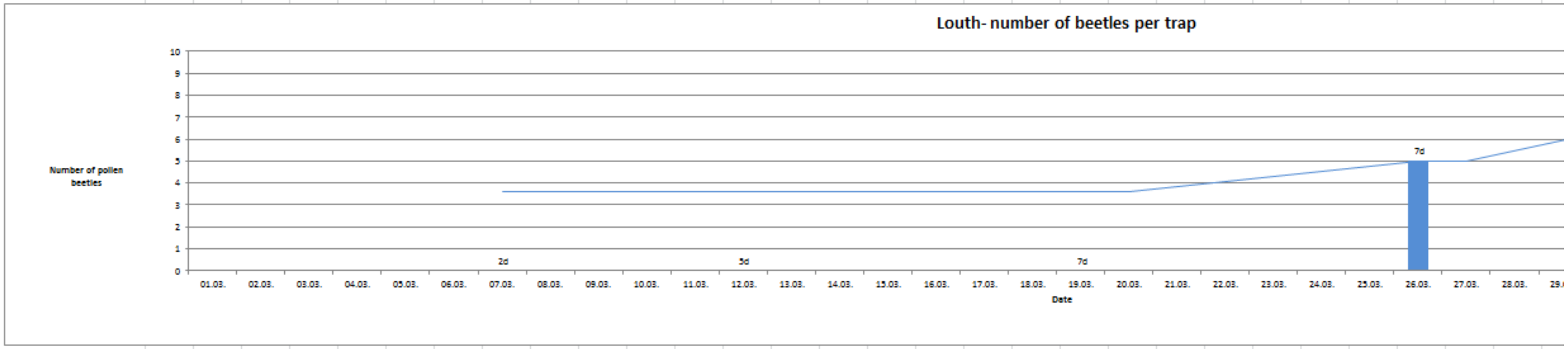
Appendix 4. Brigg, 2016





Appendix 4. Louth, 2016

Louth



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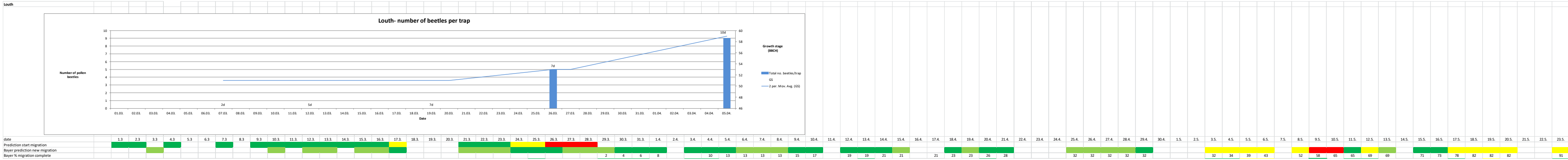
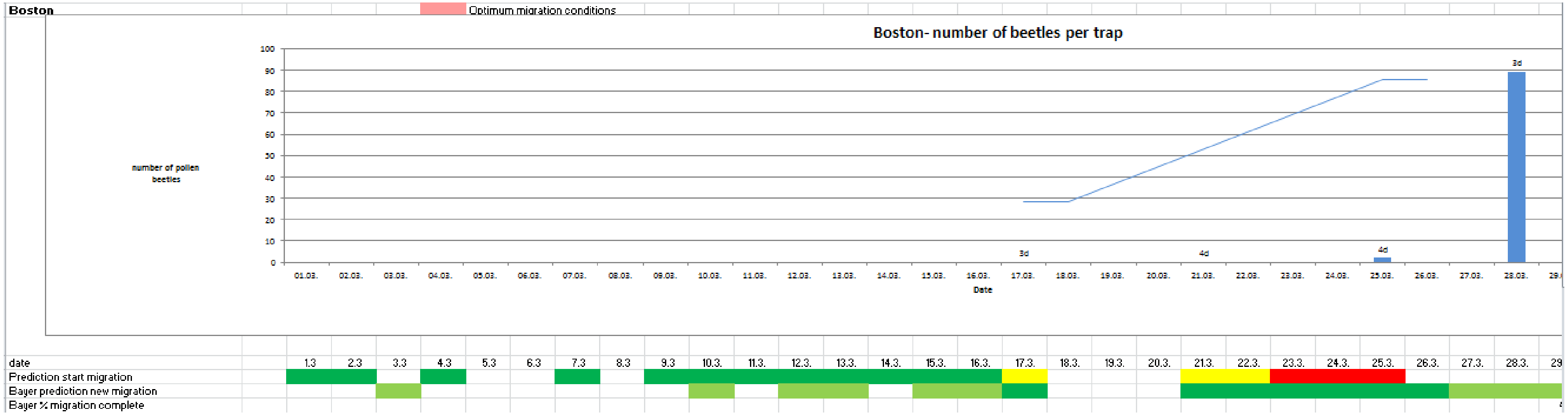
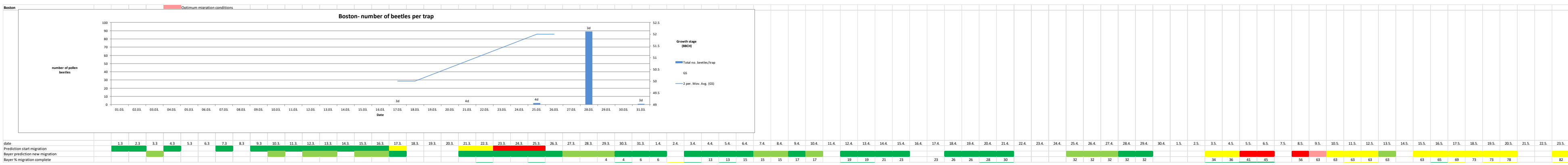
Prediction start migration																													
Bayer prediction new migration																													
Bayer % migration complete																													

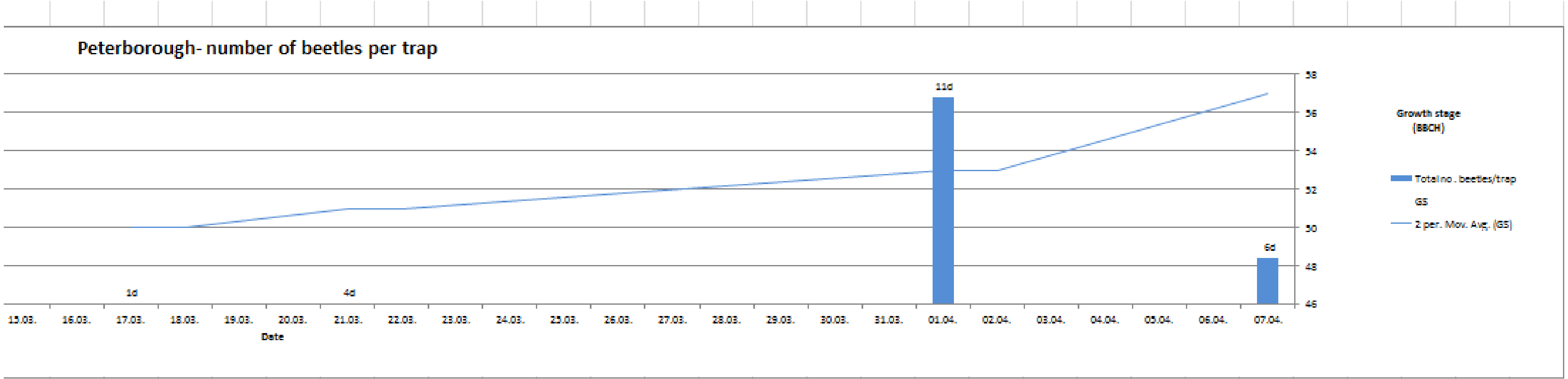


Appendix 4. Boston, 2016





Appendix 4. Peterborough, 2016



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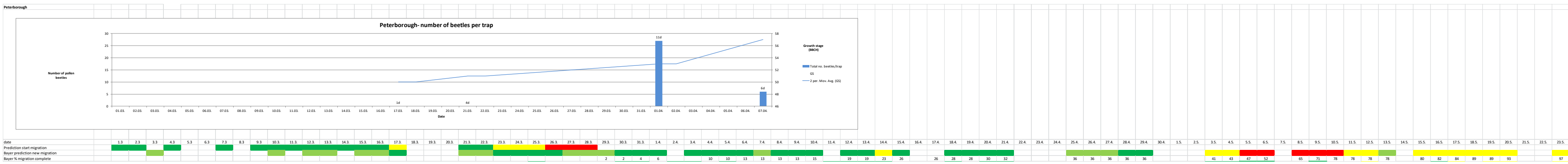
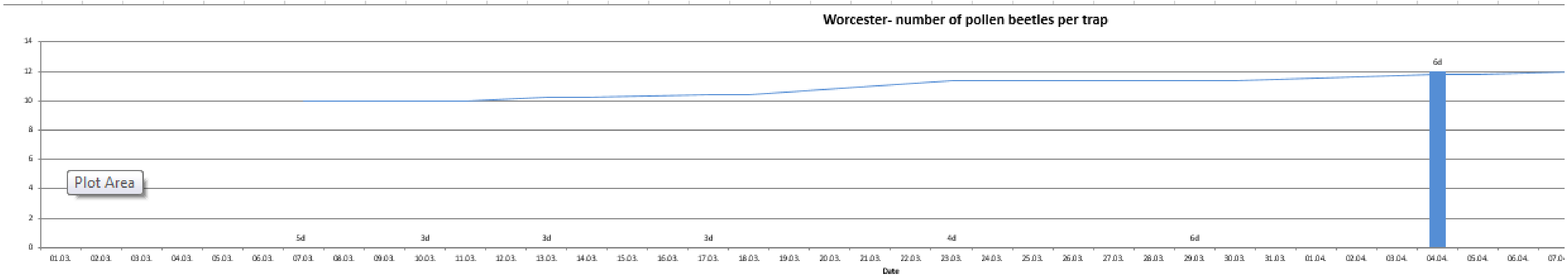
														2	2	4	6			10	10	13	13	13	13	15		19	19



Appendix 4. Worcester, 2016



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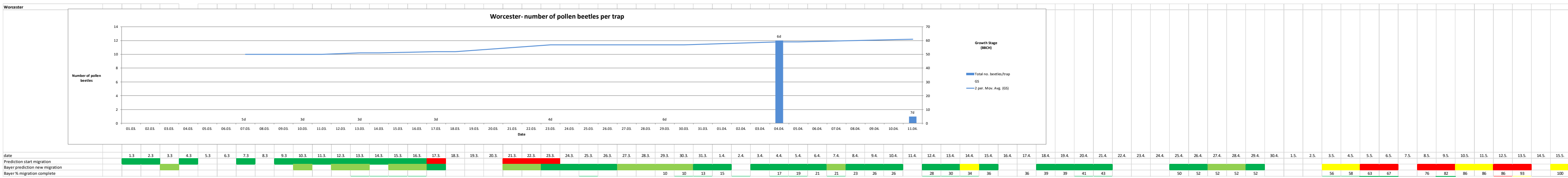
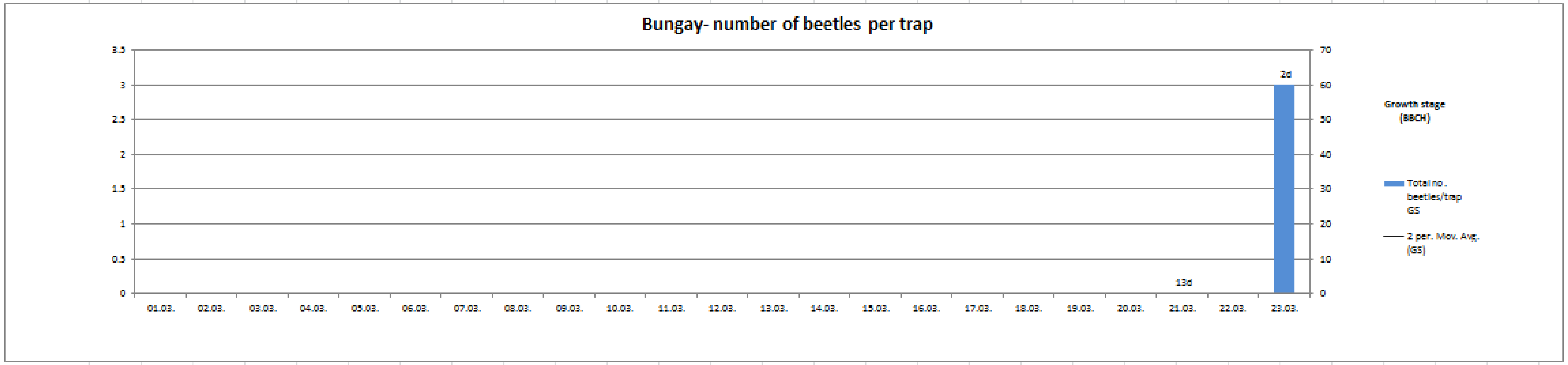
																												10	10	13	15			17	19	21	21

date		1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.
Prediction start migration																		
Bayer prediction new migration																		
Bayer % migration complete																		



Appendix 4. Bungay, 2016

Bungay



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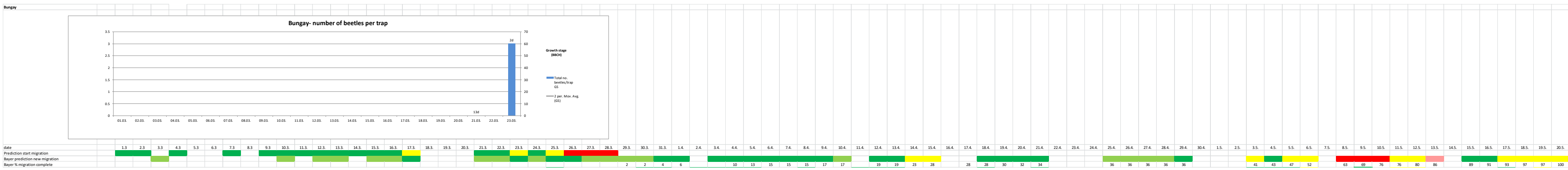
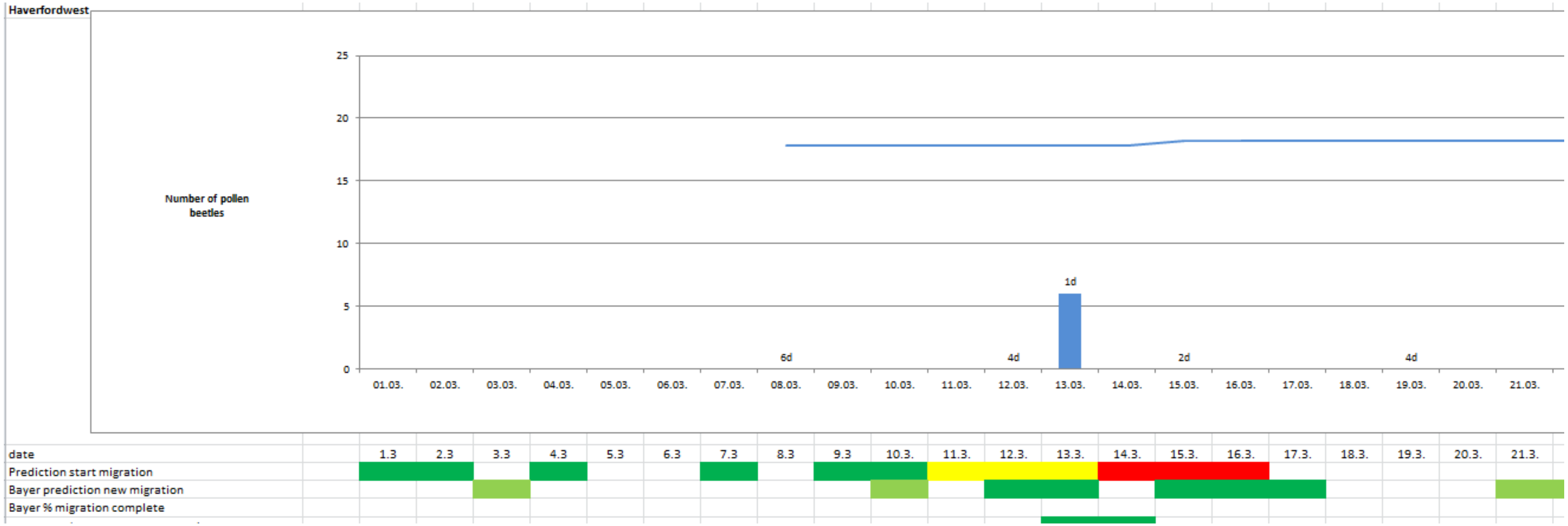
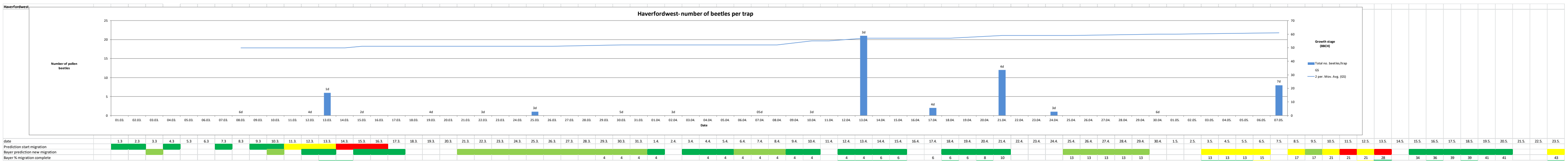
Prediction start migration																												
Bayer prediction new migration																												
Bayer % migration complete																												

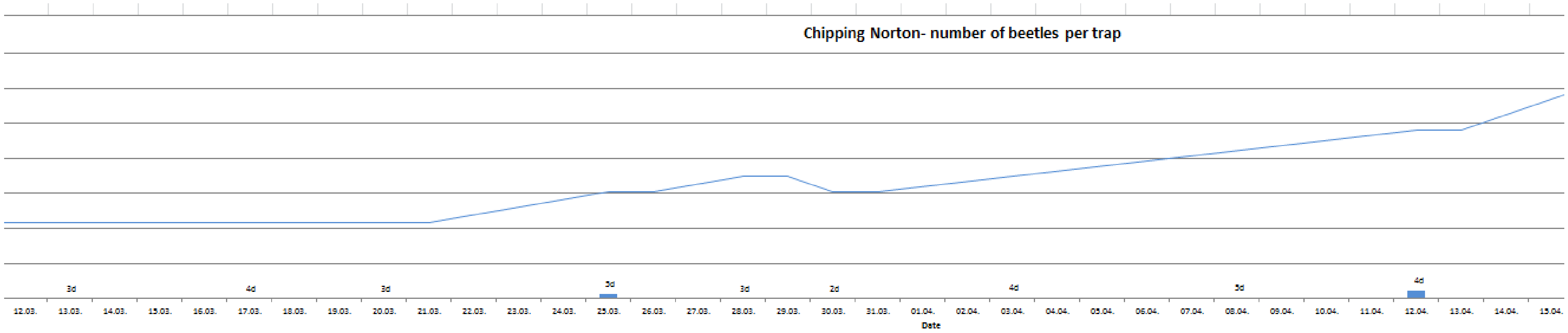


Appendix 4. Haverfordwest, 2016





Appendix 4. Chipping Norton, 2016



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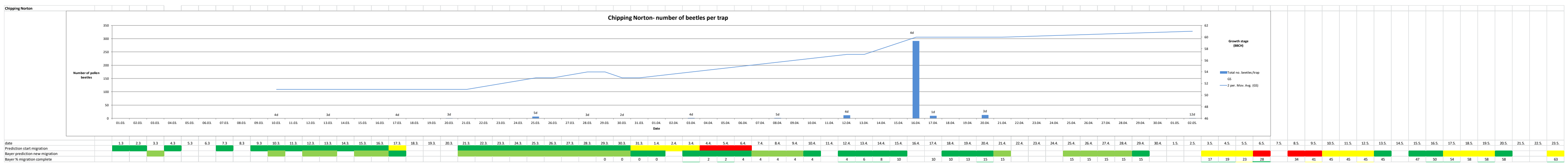
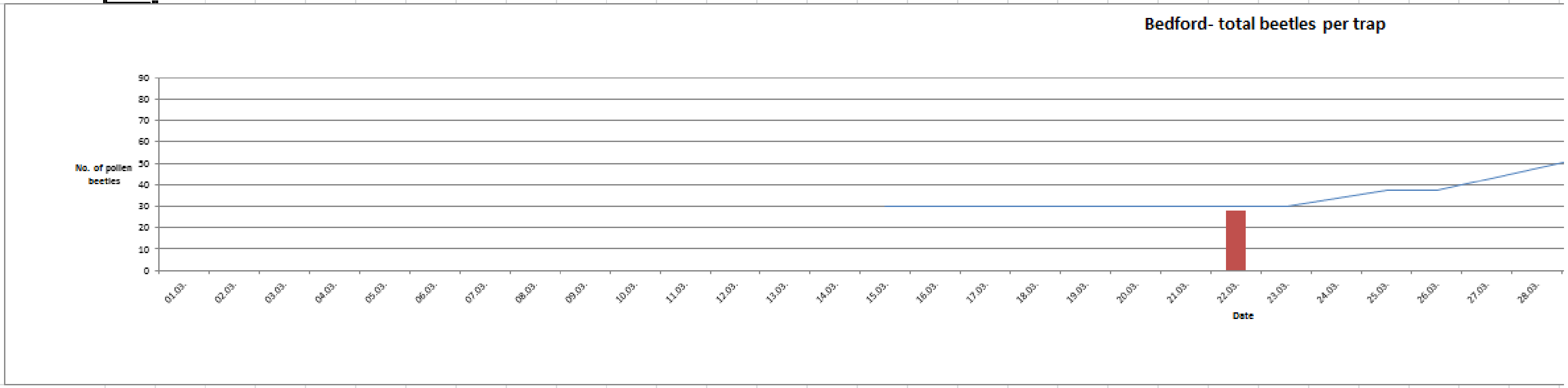
																	0	0	0	0			2	2	4	4	4	4	4		4	6	8	10

date		1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.
Prediction start migration																					
Bayer prediction new migration																					
Bayer % migration complete																					

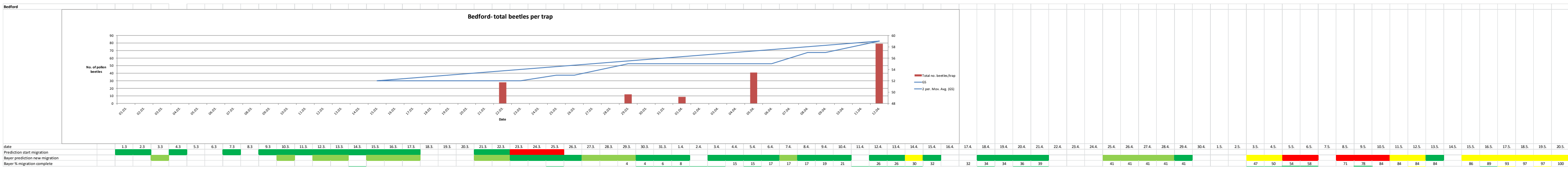


Appendix 4. Bedford, 2016

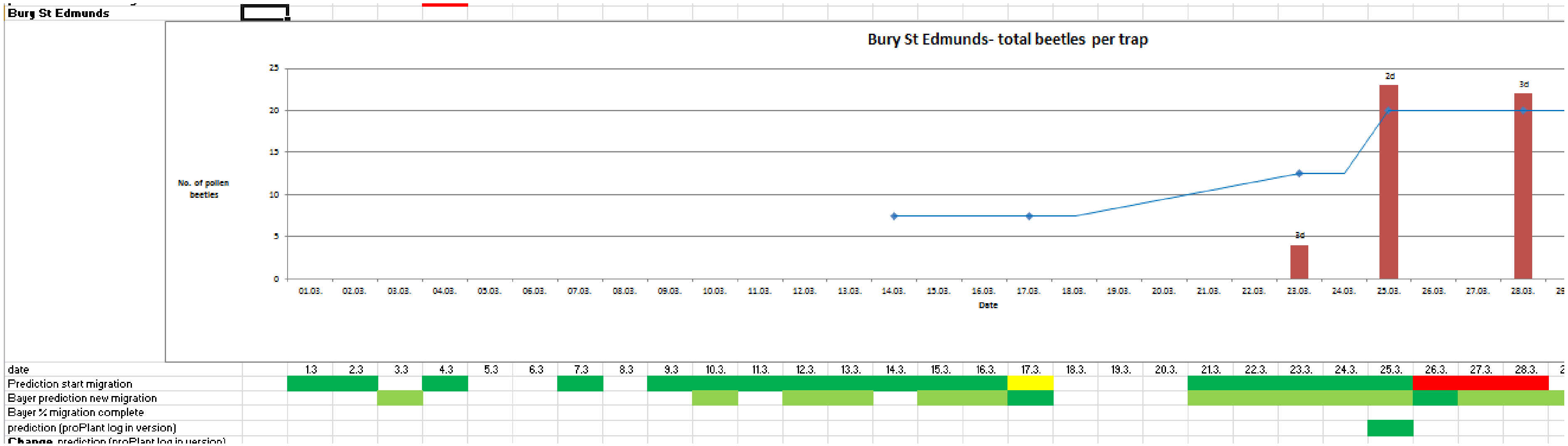
Bedford

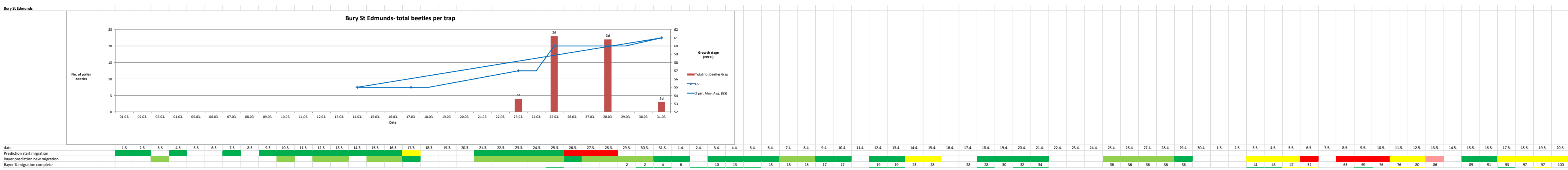


date		1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3.	21.3.	22.3.	23.3.	24.3.	25.3.	26.3.	27.3.	28.3.
Prediction start migration																													
Bayer prediction new migration																													
Bayer % migration complete																													

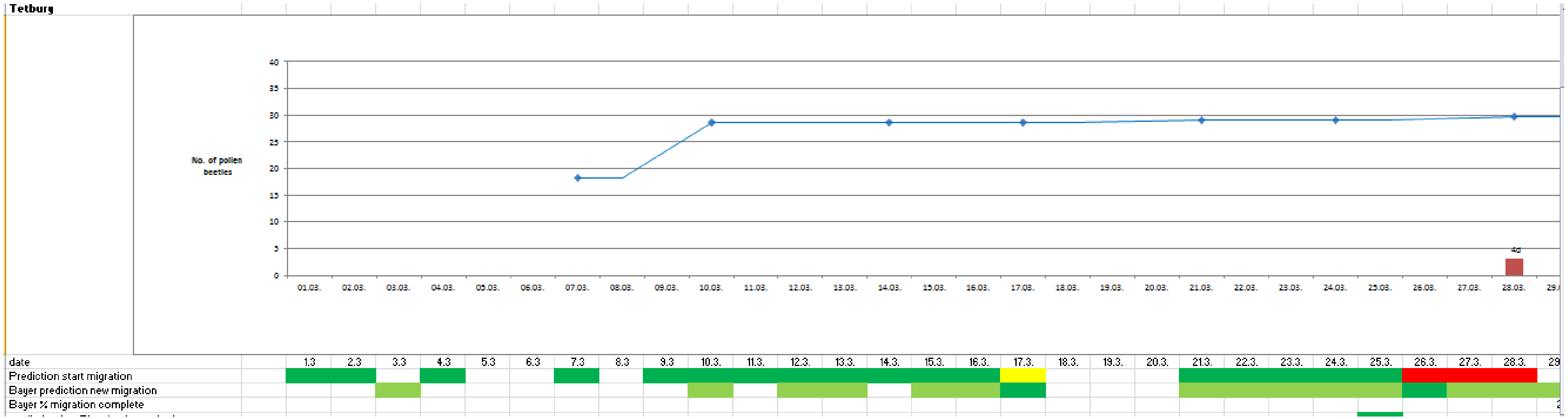


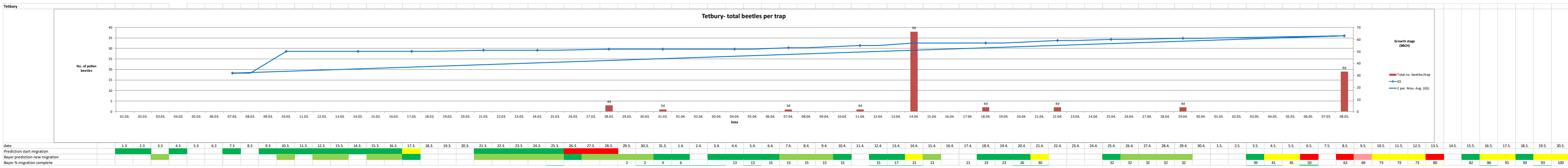
Appendix 4. Bury St Edmunds, 2016





Appendix 4. Tetbury, 2016

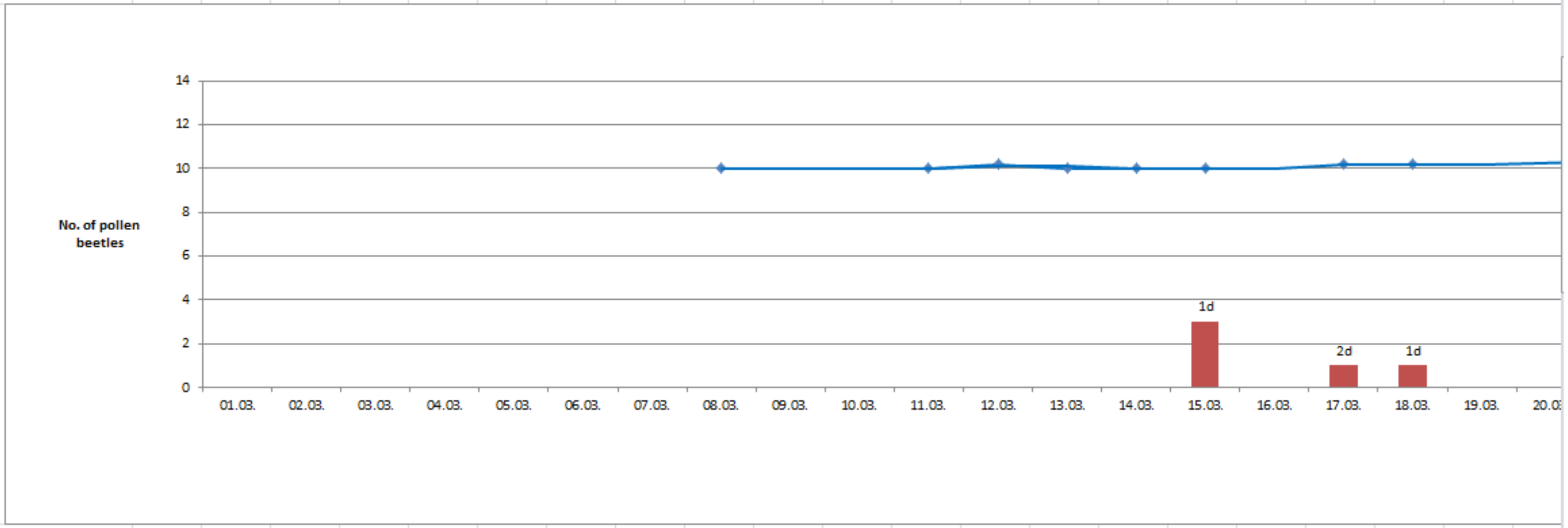




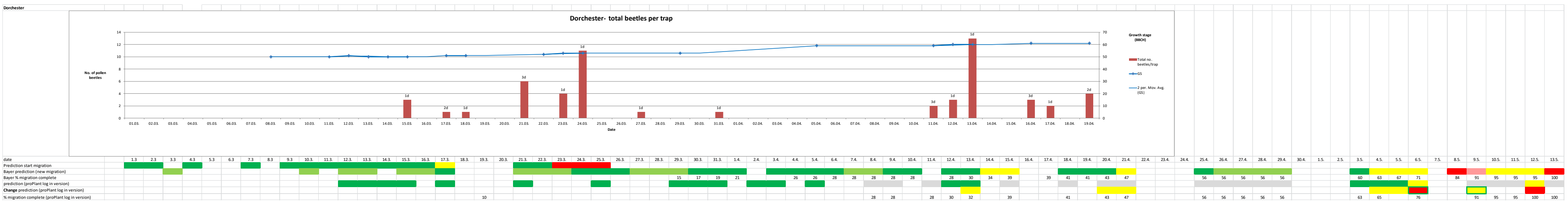
Appendix 4. Plymouth, 2016

Appendix 4. Dorchester, 2016

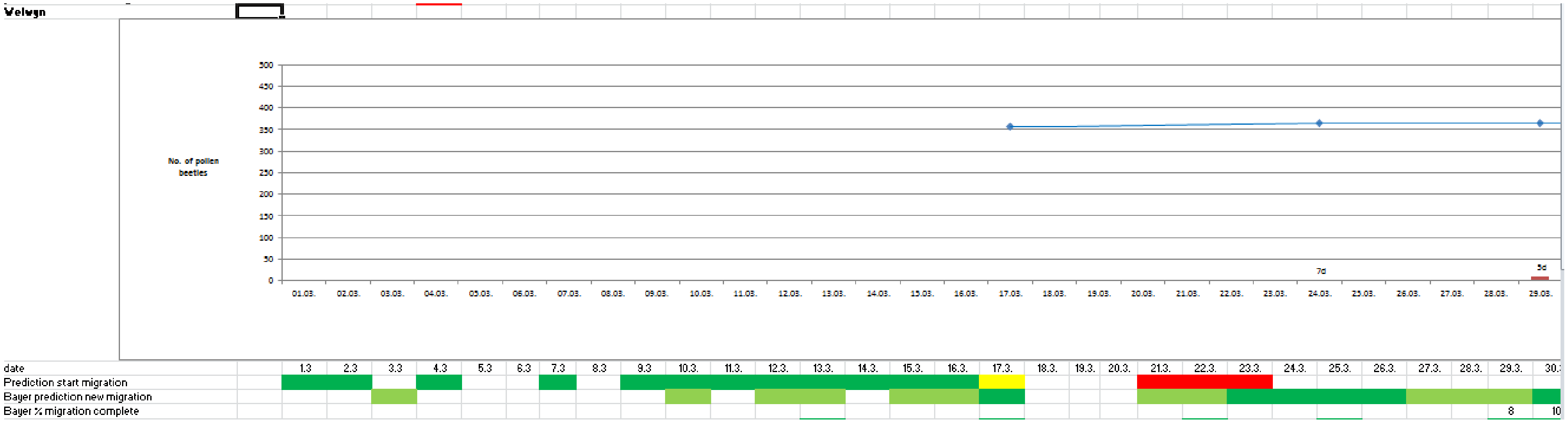
Dorchester

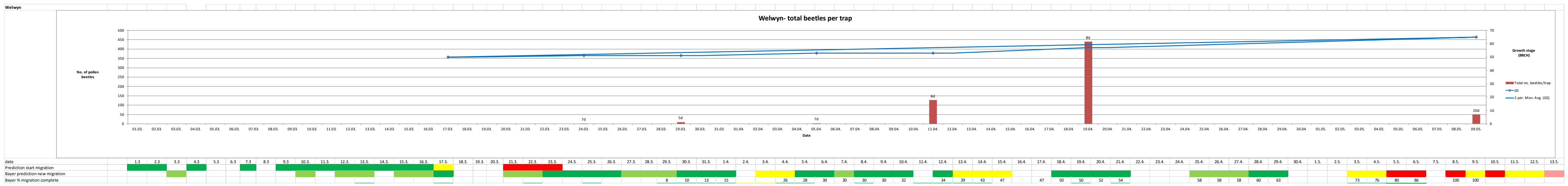


date	1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3.	11.3.	12.3.	13.3.	14.3.	15.3.	16.3.	17.3.	18.3.	19.3.	20.3
Prediction start migration																				
Bayer prediction (new migration)																				
Bayer % migration complete																				
prediction (proPlant log in version)																				
Change prediction (proPlant log in version)																				



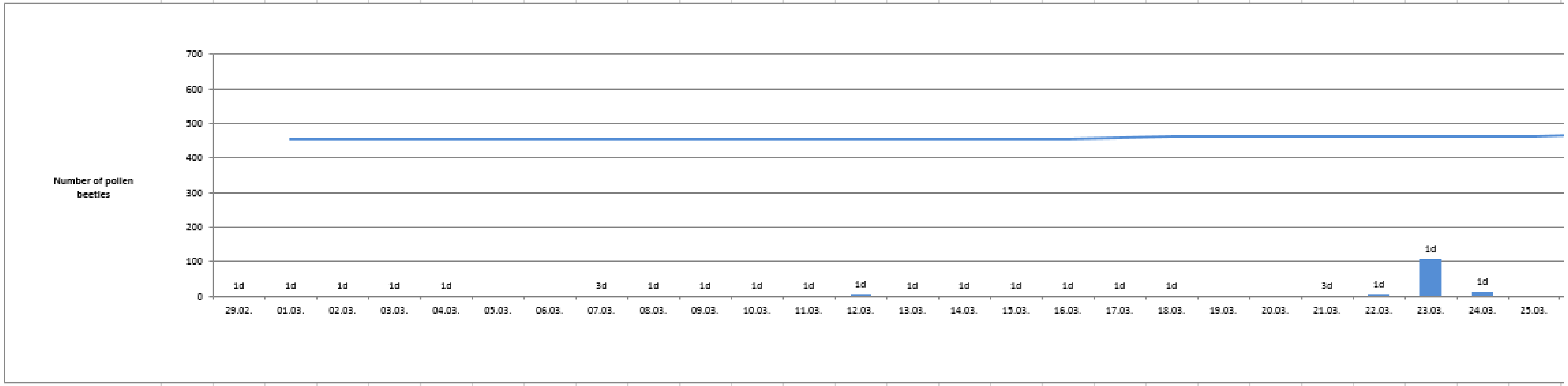
Appendix 4. Welwyn Garden City (Knebworth), 2016





Appendix 4. Welwyn Garden City (Rothamsted, Great Knott), 2016

Welwyn



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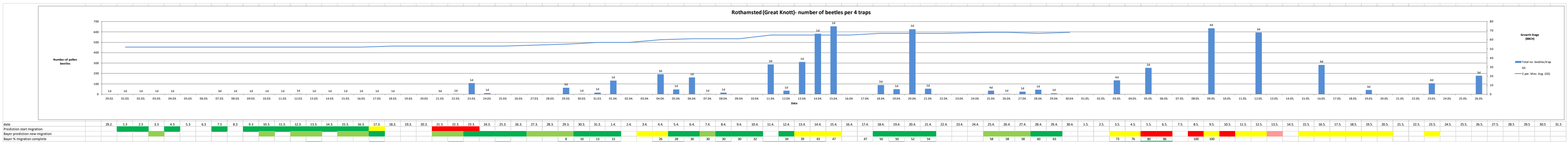
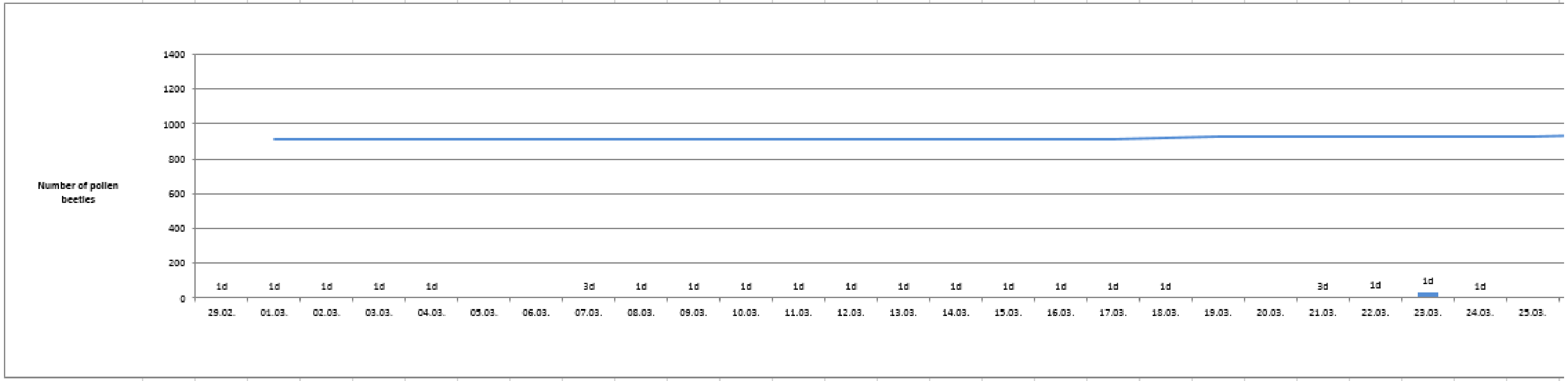
Prediction start migration																											
Bayer prediction new migration																											
Bayer % migration complete																											



Appendix 4. Welwyn Garden City (Rothamsted, Osier), 2016

Welwyn



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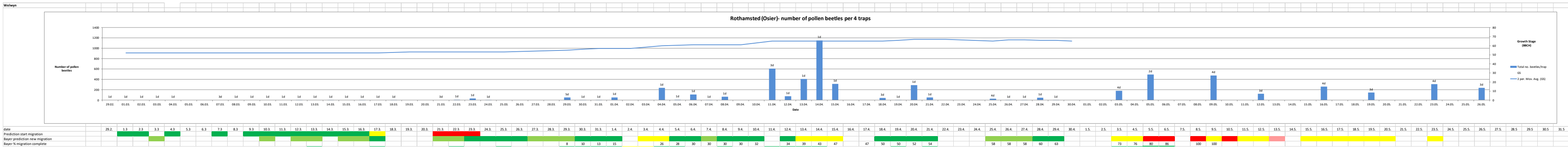
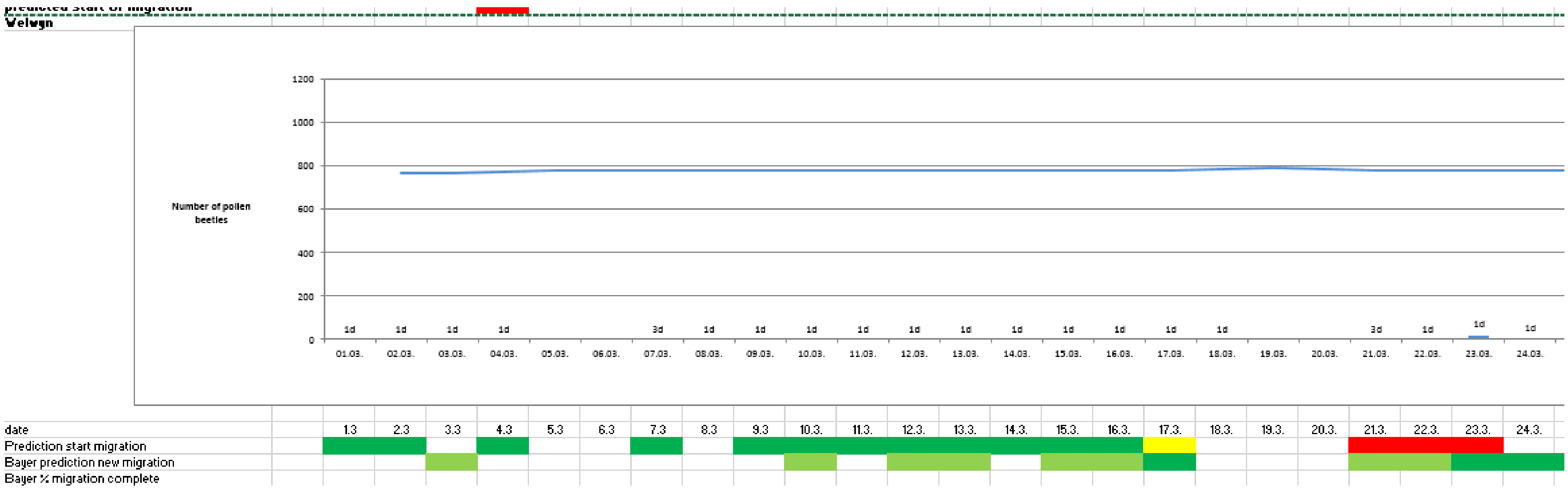
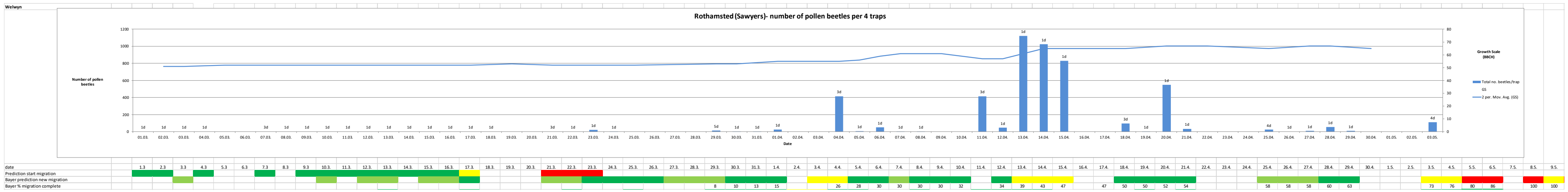
Prediction start migration																											
Bayer prediction new migration																											
Bayer % migration complete																											



Appendix 4. Welwyn Garden City (Rothamsted, Sawyers), 2016





Appendix 5.

Site details of participants in pollen beetle assessments 2014-2016 and accuracy measurements of Bayer Pollen Beetle Precictor using site data

Site	Met station (approx. distance in Km)	Crop cv. (sowing date)	Plants/m^2 (PB threshold)	Threshold exceeded?	Prediction migration will start in 'next few days' (1st yellow dot)	Predicted start migration (1st red dot)	Date traps out	Date 1st trap catch	No. days between prediction migration will start (1st yellow dot) and 1st trap catch	Migration will start in next few days - Prediction accurate to within 3 days?	Migration will start next few days - prediction accurate to within 7 days?	No. days between prediction start (1st red dot) and 1st trap catch	Start immigration predicted well (within 3 days)?	migration predicted 100% complete	Date last trap catch	Migration complete predicted well?
2014																
Grantham	Grantham (13)	nr	nr (nd)	nd	6/3/14	10/3/14	1/3/14	10/3/14	4	No Early	yes	0	yes	16/5/14	1/4/14	nd
Frome	Glastonbury (24)	Trinity, 4/9/13	64 (11)	no	6/3/14	8/3/14	3/3/14	7/3/14	1	Yes (but trap out too late to get preceeding zero)	Yes (but trap out too late to get preceeding zero)	-1	Yes	5/5/14	2/4/14	nd
Malton	Beverley (22)	nr	Nr (nd)	nd	26/2/14	6/3/14	3/3/14	14/3/14	nd (traps not our before prediction)	nd	nd	8	No, early	16/5/14	30/4/14	nd
Lincoln	Lincoln (20)	nr	48 (18)	no	6/3/14	10/3/14	3/3/14	9/3/14	3	yes	yes	-1	Yes	6/5/14	9/5/14	OK - BUT beetles still being caught at low level
Eastern	Dereham (11)	DK Cabernet, 30/8/13	35 (25)	no	no yellow dot given	27/2/14	4/3/14	13/3/14	nd (traps not our before prediction)	nd	nd	nd	nd	24/4/14	26/4/14	Yes. Good conditions predicted on 24/25th did not return positive catch on 26/4

Site	Met station (approx. distance in Km)	Crop cv. (sowing date)	Plants/m^2 (PB threshold)	Threshold exceeded?	Prediction migration will start in 'next few days' (1st yellow dot)	Predicted start migration (1st red dot)	Date traps out	Date 1st trap catch	No. days between prediction migration will start (1st yellow dot) and 1st trap catch	Migration will start in next few days - Prediction accurate to within 3 days?	Migration will start next few days - prediction accurate to within 7 days?	No. days between prediction start (1st red dot) and 1st trap catch	Start immigration predicted well (within 3 days)?	migration predicted 100% complete	Date last trap catch	Migration complete predicted well?
Delharding, Rothamsted	Welwyn Garden City (9)	Quartz, 28/8/13	49 (18)	no	no yellow dot given	26/2/14	11/3/14	7/3/14 8/3/14	nd (traps not our before prediction)	nd	nd	nd	nd	11/4/14	18/4/14	Yes - BUT but beetles still being caught at very low level
Pastures, Rothamsted	Welwyn Garden City (9)	Quartz, 5/9/13	72 (7)	no	no yellow dot given	26/2/14	11/3/14	7/3/14 13/3/14	nd (traps not our before prediction)	nd	nd	nd	nd	11/4/14	18/4/14	OK - BUT beetles still being caught at low level
Great Knott 3, Rothamsted	Welwyn Garden City (9)	Compass, 23/8/13	59 (11)	no	no yellow dot given	26/2/14	11/3/14	13/3/14	nd (traps not out before prediction)	nd	nd	nd	nd	11/4/14	18/4/14	Yes - BUT but beetles still being caught at very low level
2015																
Askham Bryan College, Headly Hall	Selby (17)	Palmedor (HEAR), 21/8/14	12 (25)	no	no yellow dot given	3/4/15	13/3/15	6/4/15	nd (traps not out before prediction)	nd	nd	nd	yes	89% on 31/5/15	15/4/15	nd (trapping ceased too soon)
Harpswell	Gainsborough (9)	Excalibur nr	Nr (nd)	nd	no yellow dot given	11/3/15	11/3/15	6/4/15	nd (traps not out before prediction)	nd	nd	25	No, early	43% on 31/5/15	6/4/15	nd (trapping ceased too soon)
Thorpe St Peter, Skegness	Boston (25)	Charger, 26/8/14	25-30 (25)	no	no yellow dot given	11/3/15	?/04/2015	5/4/15	nd (traps not out before prediction)	nd	nd	nd	nd	28% on 31/5/15		nd (trapping ceased too soon)

Site	Met station (approx. distance in Km)	Crop cv. (sowing date)	Plants/m² (PB threshold)	Threshold exceeded?	Prediction migration will start in 'next few days' (1st yellow dot)	Predicted start migration (1st red dot)	Date traps out	Date 1st trap catch	No. days between prediction migration will start (1st yellow dot) and 1st trap catch	Migration will start in next few days - Prediction accurate to within 3 days?	Migration will start next few days - prediction accurate to within 7 days?	No. days between prediction start (1st red dot) and 1st trap catch	Start immigration predicted well (within 3 days)?	migration predicted 100% complete	Date last trap catch	Migration complete predicted well?
Dilham	Aylsham (13)	Charger, 20/8/14	33 (18)	no BUT 14.7 recorded on 10/4/15	11/3/15	8/4/15	9/3/15	7/4/15	26	No, early	No, early	-1	yes	73% on 31/5/15	23/4/15	nd (trapping ceased too soon)
Stanford Bridge	Worcester (18)	PT211, 24/8/14	27 (25)	no	no yellow dot given	11/3/15	3/3/15	5/4/15	nd	nd	nd	24	No, early	24/5/15	2/6/15	yes? No beetles caught on last trap
Upton House Estate, Banbury	Leamington Spa (19)	nr	44 (18)	no	no yellow dot given	11/3/15	3/3/15	20/3/15	nd	nd	nd	9	No, early	15/5/15	27/4/17	nd (trapping ceased too soon)
Chipping Norton	Chipping Norton (2)	Incentive, 5/9/14	35 (25)	no	3/4/15	7/4/15	12/3/15	8/4/15	5	No, early	yes	-1	yes	41% on 31/5/15	27/5/15	nd (trapping ceased too soon)
Royston	Shelford (15)	PH106, 12/8/14	19 (25)	nd (no crop monitoring done	16/3/15	7/4/15	3/3/15	30/3/15	nd (no traps within 7d)	nd	nd	nd (no trap within 3d)	nd	63% on 31/5	24/4/15	nd (trapping ceased too soon)
Maidstone	Faversham (13)	Picto, 2/9/14	45-55 (11)	no	16/3/15	18/3/15	2/3/15	6/3/15	-8	No, late	No, late	-10	No, late	43% on 31/5/15	22/5/15	nd (trapping ceased too soon)
Eastry	Faversham (30)	nr	nr (nd)	nd	16/3/15	18/3/15	23/3/15	27/3/15	nd (traps not out before prediction)	nd	nd	nd	nd		24/5/15	nd (trapping ceased too soon)
Rothamsted	Welwyn Garden City (9)	Charger, 24/8/14	28 (25)	no BUT 24.3 recoded on 10/4	no yellow dot given?	11/3/15	25/2/15	11/3/15	nd	nd	nd	0	yes	24/5/15	29/5/15	44/trap caught on last event

Site	Met station (approx. distance in Km)	Crop cv. (sowing date)	Plants/m^2 (PB threshold)	Threshold exceeded?	Prediction migration will start in 'next few days' (1st yellow dot)	Predicted start migration (1st red dot)	Date traps out	Date 1st trap catch	No. days between prediction migration will start (1st yellow dot) and 1st trap catch	Migration will start in next few days - Prediction accurate to within 3 days?	Migration will start next few days - prediction accurate to within 7 days?	No. days between prediction start (1st red dot) and 1st trap catch	Start immigration predicted well (within 3 days)?	migration predicted 100% complete	Date last trap catch	Migration complete predicted well?
Rothamsted	Welwyn Garden City (9)	Quartz, 22/8/14	31 (18)	no BUT 17.5 recoded on 10/4			25/2/15	11/3/15	nd	nd	nd	0	yes		29/5/15	27/trap caught last event
Rothamsted	Welwyn Garden City (9)	Quartz, 22/8/14	39(18)	no BUT >15 recorded on 10/4/15			25/2/15	10/3/15	nd	nd	nd	-1	yes		29/5/15	17/trap caught on last event
2016																
Kinghorn	Haddington (28)	Anastasia, 9/12/15	66 (11)	no	11/3/16	15/3/16	6/3/16	7/4/16	-26	No, early	No, early	-22d	No, early	Reached 89% before system shut down	3/5/16	nd
Askham Bryan College, Home Farm	Selby (17)	nr	nr (nd)	nd	17/3/16	21/3/16	18/3/16	28/3/16	-11	No, Early	No, early	-7	No, early	23/5/16	28/4/16	nd
Scunthorpe	Beverley (19)	DK Extrovert, 21/08/15	55 (11)	no	17/3/16	21/3/16	12/3/16	31/3/16	14	No, early	nd	10	nd	84% on 23/5/16	17/4/16	nd
Brigg	Brigg (4)	Exalte, 23/8/15	62 (11)	no	17/3/16	26/3/16	11/3/16	18/3/16	1	yes	yes	-8	No, Late	91% on 23/5/16	24/4/16	nd
Louth	Louth (5)	Compass, 23/8/15	32 (18)	no	17/3/16	26/3/16	5/3/16	26/3/16	9	No, early	nd	0	yes	91% on 23/5/16	5/4/16	nd
Thorpe St Peter, Skegness	Boston (25)	nr	nr (nd)	nd	17/3/16	23/3/16	14/3/16	25/3/16	8	nd	No, Early	2	yes	82% on 23/5/16	31/3/16	nd

Site	Met station (approx. distance in Km)	Crop cv. (sowing date)	Plants/m^2 (PB threshold)	Threshold exceeded?	Prediction migration will start in 'next few days' (1st yellow dot)	Predicted start migration (1st red dot)	Date traps out	Date 1st trap catch	No. days between prediction migration will start (1st yellow dot) and 1st trap catch	Migration will start in next few days - Prediction accurate to within 3 days?	Migration will start next few days - prediction accurate to within 7 days?	No. days between prediction start (1st red dot) and 1st trap catch	Start immigration predicted well (within 3 days)?	migration predicted 100% complete	Date last trap catch	Migration complete predicted well?
Hemington	Peterborough (14)	Camelot, 9/7/15	nr (nd)d	nd	17/3/16	26/3/16	16/3/16	4/1/16	19	nd	No, early	9	nd	97% on 23/5/16	4/7/16	nd
Stanford Bridge	Worcester (18)	PT211, 28/8/15	21 (25)	no	no yellow dot given	17/3/16	2/3/16	4/4/16	na	na	na	18	nd	15/5/16	11/4/16	nd
Redenhall	Bungay (9)	Extrovert, 14/8/15	30 (18)	nd	17/3/16	26/3/16	8/3/16	23/3/16	6	nd	yes	-3	yes	20/5/16	21/3/16	nd
Cardigan	Haverfordwest (42)	nr	nr (nd)	no	3/11/16	14/3/16	2/3/16	13/3/16	2	yes	yes	-1	yes	43% on 23/5/16	7/5/16	nd
Horley	Chipping Norton (22)	Harper, 25/8/15	10 (25)	no	17/3/16	4/4/16	6/3/16	25/3/16	3	No, early	no, early	-15	No, late	63% on 31/5/16	2/5/16	nd
Shefford	Bedford (13)	DK Cabernet, 23/8/15	31 (18)	no	not recorded	23/3/16	13/3/16	22/3/16	nd	nd	nd	-1	yes	20/5/16	12/4/16	nd
Great Saxham	Bury St Edmunds (5)	Extrovert, 14/8/15	60 (11)	no	17/3/16	26/3/16	12/3/16	23/3/16	6	nd	yes	-3	yes	20/5/16	31/3/16	nd
Kingscote	Tetbury (7)	Picto, 9/3/15	45 (18)	no	17/3/16	26/3/16	3/3/16	28/3/16	11	nd	nd	2	yes	20/5/16	8/5/16	nd
Knebworth		Incentive, 19/8/15	30 (18)	nd			14/3/16	24/3/16	7	nd	yes	3	yes		9/5/16	nd
Rothamsted, Great Knott I	Welwyn Garden City (9)	DK Exalte, 21/8/15	24 (25)	**YES**	17/3/16	21/3/16	29/2/16	12/3/16	5	No, early	yes	9	yes	9/5/16	26/5/16	? Still large catches
Rothamsted, Sawyers II		DK Exalte, 22/8/15	28 (25)	**YES**			29/2/16	21/3/16	12	No, early	yes	0	yes		3/5/16	nd
Rothamsted, Osier		DK Exalte, 22/8/15	21 (25)	**YES**			29/2/16	12/3/16	5	No, early	yes	9	yes		26/5/16	? Still large catches

Site	Met station (approx. distance in Km)	Crop cv. (sowing date)	Plants/m² (PB threshold)	Threshold exceeded?	Prediction migration will start in 'next few days' (1st yellow dot)	Predicted start migration (1st red dot)	Date traps out	Date 1st trap catch	No. days between prediction migration will start (1st yellow dot) and 1st trap catch	Migration will start in next few days - Prediction accurate to within 3 days?	Migration will start next few days - prediction accurate to within 7 days?	No. days between prediction start (1st red dot) and 1st trap catch	Start immigration predicted well (within 3 days)?	migration predicted 100% complete	Date last trap catch	Migration complete predicted well?
Saltash	Plymouth (16)	V316 OL, 25/8/15	nr (nd)	nd	no yellow dot?	14/3/16	14/3/16	19/3/16	na	na	na	5	nd	23/5/16	10/5/16	nd
Langton Herring	Dorchester (10)	DK Imperial, 3/9/15	45 (18)	no	17/3/16	23/3/16	7/3/16	15/3/16	-2	yes	yes	-8	No, late	13/5/16	19/4/16	nd

Appendix 6.

List of sites from Objectives 4-6 which exceeded threshold numbers of pollen beetles (regardless of plant density; note no sites exceeded threshold when plant density is accounted for).

Year of Study	No. sites in study (n)	Pollen beetle threshold 7	11	18	25
2014	9	Dereham			
		Grantham	Grantam	Grantham	
		Lincoln	Lincoln		
		Welwyn Garden City (RRes Delharding)			
2015	11	Aylsham	Aylsham		
		Chipping Norton			
		Faversham (Lenham)			
		Faversham (Tilmanstone)			
		Leamington Spa			
		Selby	Selby		
		Welwyn Garden City (RRes Great Harpenden)	Welwyn Garden City (RRes Great Harpenden)	Welwyn Garden City (RRes Great Harpenden)	
		Welwyn Garden City (RRes Little Knott)	Welwyn Garden City (RRes Little Knott)		
		Welwyn Garden City (RRes Long Hoos)	Welwyn Garden City (RRes Long Hoos)		
2016	17	Bedford			
		Chipping Norton			
		Selby			
		Welwyn Garden City	Welwyn Garden City	Welwyn Garden City	Welwyn Garden City

Year of Study	No. sites in study (n)	Pollen beetle threshold 7	11	18	25
		(RRes Great Knott)	(RRes Great Knott)	(RRes Great Knott)	(RRes Great Knott)
		Welwyn Garden City	Welwyn Garden City	Welwyn Garden City	Welwyn Garden City
		(RRes Sawyers 2)	(RRes Sawyers 2)	(RRes Sawyers 2)	(RRes Sawyers 2)
		Welwyn Garden City	Welwyn Garden City	Welwyn Garden City	Welwyn Garden City
		(RRes Osier)	(RRes Osier)	(RRes Osier)	(RRes Osier)