Project title:	Biology of the cabbage whitefly, *Aleyrodes proletella.*
Project number:	CP 091
Project leader:	Dr Rosemary Collier
Report:	Annual report, October 2013.
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Industry Representative:	Andy Blair, Emmetts, UK.
Date project commenced:	1st October 2012
Date project completed (or expected completion date):	31st October 2015

[The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.]

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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CONTENTS

GROWER SUMMARY

Headline

Monitoring techniques for cabbage whitefly have been developed and initial information has been obtained on the establishment and development of whitefly infestations on kale and Brussels sprout crops.

Background

The cabbage whitefly (*Aleyrodes proletella*) has become an increasing problem for the Brassica industry in recent years, especially on Brussels sprout and kale. The reason for this is unknown, but it is believed to be due to a combination of climate change, removal of certain active ingredients from use and later harvest times of crops. Little research has focused on this species as, historically, it has been regarded as a minor pest. Knowledge about the biology of the cabbage whitefly is limited and most of what is currently understood about its ecology has been inferred from minimal anecdotal evidence.

The overall aim of this project is to understand population trends of cabbage whitefly in the most vulnerable crops, Brussels sprout and kale. This includes understanding the key times of population/generation increase and colonisation of a new crop. This information can then be used to inform the development of an integrated control strategy using insecticides and other tools, which might include biological control agents and methods of cultural or physical control.

Summary

Experiment 1.1. Developing an effective method for trapping active adult cabbage whitefly in the field

Blue and yellow sticky traps were tested for effectiveness at catching adult whitefly at ground level and a height of 1m. Yellow traps at ground level caught significantly more adults than the other test treatments. The preference for yellow traps was much less pronounced at 1m, with blue traps catching similar numbers. These results suggest that yellow traps at ground level should be used to monitor adult whitefly. However, blue traps might be used to monitor migration. Further research will be aimed at improving the trapping method and confirming whether blue traps can be used to monitor migration.

Experiment 1.2 Survey of wild host plants for the presence of whitefly in an uncultivated field

A field that had been removed from cultivation since 2008 was surveyed for wild hosts of cabbage whitefly. The survey focused on wild hosts described in Mound & Hasley (1978). Forty random quadrats of 0.5m^2 were surveyed within the field (~1ha) for the wild hosts and presence of cabbage whitefly. The only wild hosts found were *Sonchus (*Sow-thistle)*,* *Taraxacum* (Dandelion) and *Euphorbia spp.* (Spurge). *Sonchus* was most abundant at a mean density of 1.84 m^{-2} (average of 0.46 found within an experimental quadrat of 0.5m^2). No whitefly were found in this survey. However, spot checks of sow-thistle on the Wellesbourne campus in February 2013 showed that whitefly were present on their wild hosts in the locality. Further studies will focus on other habitats that have high densities of wild hosts, such as disturbed land, investigating their potential for harbouring populations of cabbage whitefly.

Experiment 1.3 Survey of a commercial oil seed rape crop for the presence of whitefly

A commercial oil seed rape (OSR) field (~10ha) was surveyed on three occasions (April, June, July 2013) for the presence of whitefly. A total of forty 0.5m^2 quadrat surveys were taken in a 40m x 40m grid pattern throughout the field. All leaves of all OSR plants were searched for whitefly. No whitefly were found in April or June. In July, a total of 4 adult whitefly were found from all quadrats, all of which were within 40m of the field margins. Extrapolation indicated that the whole crop might be supporting 40,000 whitefly. However, this may be an overestimate if whiteflies are more abundant on plants close to field margins. As no whitefly were found in April it seems unlikely that this field acted as an overwintering site for whitefly (although a very low population, not detected by the sampling approach, may have been present). This may have been due to a high level of damage to the plants by pigeons, causing considerable disturbance and defoliation. Although juvenile stages of whitefly were found in July, nymphs found at this time are likely to be of little importance for kale crops as the OSR was harvested shortly after the sampling date and this would have killed all juvenile stages.

Experiment 1.4. Egg laying rate and duration of egg laying on three different Brassica oleracea crops: Brussels sprout, kale and cauliflower

Newly emerged adult females were confined to the foliage of one of three *Brassica* crops, Brussels sprout (cv. Revenge) kale (cv. Reflex) or cauliflower (cv. Skywalker) and the numbers of eggs laid were recorded until death. The experiment was conducted in controlled conditions at 20°C, with 16hrs light and 8hrs dark. Eggs were counted and destroyed every 2 days, taking care not to disturb the females. On average the duration of egg laying was 33 days, 89 eggs being laid in total. There was no significant difference in the mean number of eggs laid in a 2-day period for the three crops/cultivars tested. Results show the potential for overlapping of generations of cabbage whitefly as the duration of the egg-laying period at 20°C exceeded the duration of the period of development from egg to adult. The first eggs laid by a female are likely to have emerged as adults before she has finished laying her final batches of eggs. Variation in the pattern of egg laying by females kept on Brussels sprout plants was high, showing that more replication is needed.

Experiment 1.5 Monitoring of whitefly on overwintering Brussels sprout plants

A small plot of overwintering Brussels sprout plants was sampled for whitefly over the winter 2012-13. Initial studies showed a distinct vertical pattern in the distribution of the different life stages within a plant, indicating that sampling approaches need to incorporate this vertical distribution. The plot was attacked by wild herbivores in December, greatly reducing the number of overwintering whitefly. The plants were then covered with netting to prevent further damage. The remaining population was surveyed monthly until March when fortnightly samples were taken. The first eggs appeared on plants in February but egg numbers did not increase during the very cold period at the beginning of March, suggesting a cessation of egg laying due to low temperatures. Air temperatures may have fallen below the lower thermal threshold for egg laying. It is also not clear whether the eggs laid in early February were still viable and were responsible for the appearance of nymphs in May. Egg numbers continued to rise for three months. The number of adults decreased during May but it could not be determined whether this was due to death or dispersal from the plants. The reduction of pupae along with the reduction of adults suggests that new adults were not emerging from overwintered pupae. The first generation appeared on overwintering Brussels on 28th June. This date is very similar to the dates found by Al-Houty (1979). Previous research has shown that pupae can survive sub-zero temperatures (Butler, 1938b) but thermal thresholds for survival have not been determined. Future studies should investigate this further along with thermal thresholds for egg laying and egg development/survival.

Experiment 1.6 Monitoring of whitefly on a newly-planted vulnerable field crops (Brussels sprout and kale) throughout the growing season

Figure 1. Study plot of Brussels sprout and kale covered in netting to prevent damage by pigeons.

Plots of Brussels sprout and kale were planted to investigate natural colonisation and population increase of the cabbage whitefly over a whole season. Plots consisted of 24 plants (3 x 8, 50cm spacing) of both Kale (cv. Reflex) and Brussels sprout (cv. Revenge). Five replicated plots were planted in different locations on the Wellesbourne site. Plants were raised in glasshouse conditions for 7 weeks prior to planting out in the field. Plots were covered in netting to prevent damage by pigeons. To determine the date of first colonisation to within a week, all the leaves of all the plants of all plots were surveyed weekly for a month after planting. The first colonisation occurred in the last week of May. Soon after this, eggs were laid and the population rose rapidly through June and July reaching over 200 eggs per plant in August. Crop colonisation occurred earlier than described previously in the literature and it was believed that the adults emerging from the first eggs laid in the year were responsible for first colonisation of crops (Butler, 1938a). However, in the present study, although colonisation of the new plots occurred in late May, the first emergent adult of the first generation was not observed on overwintering Brussels sprouts until late July. So it is highly likely that the first coloniser was an overwintering female. This investigation is still on-going, populations will be monitored until early 2014. Further analysis will be conducted on data collected from this experiment such as, differences in the size and structure of populations on kale and Brussels sprouts, and whether the size of the initial infestation has any bearing on either the rate of population growth or the final pest load.

Financial Benefits

Contamination of fresh produce by pest insects and associated damage can lead to rejections by retailers. Improved control of whitefly will have considerable financial benefits for growers through an improvement in crop quality.

Action Points

There are no action points for growers at this early stage in the project.

SCIENCE SECTION

Introduction

Historically the cabbage whitefly (*Aleyrodes proletella*) has been a minor pest of *Brassica* crops (Butler, 1938a), but recently it has become an increasing pest in Europe particularly of Brussels sprout and kale (Nebreda *et al.* 2005). The cause of this is not fully understood, but is believed to be due to a combination of climate change, removal of certain active ingredients from use and later harvest times of crops. Effective control of cabbage whitefly with insecticides is difficult due to the adaxial positioning of the nymphs, and the leaf structure of the most susceptible crops (Brussels sprout and kale) further adds to the difficulty of achieving good coverage with insecticides. Currently, the most effective pesticide for the control of this species is the systemic insecticide Movento® (spirotetramat) (Richter, 2010; Collier, 2012). Resistance to pyrethroid insecticides has been documented in *A. proletella* (Springate & Colvin, 2011), indicating that resistance management is very important.

In the scientific literature, whiteflies (Aleyroidae) are a particularly under-represented taxa, including 1556 described species, with potentially many more unknown to science (Martin & Mound, 2007). Research has focused mainly on two species: *Bemisia tabaci* and *Trialeurodes vaporariourm.* This is due to their significant economic importance, and very few other species have been studied to such an extent. As relatively little is known about the family as a whole, care should be taken not to generalise the findings from these species to all members of the Aleyroidae, as these species are unlikely to be typical for the family (Gerling, 1990).

The basic biology of *A. proletella* was investigated during the 1930's and this gave one of the first insights into this species (Butler, 1938a; 1938b). Females begin laying eggs when temperatures rise in the spring and increasing temperatures are responsible for stimulating egg laying after a winter diapause (Iheagwam, 1978). The cabbage whitefly is a multivoltine species and between 3 and 5 generations occur in England. Field temperatures have the largest influence on the number of generations in a season (Butler, 1938a; El Khidir, 1963, Al-Houty, 1979). The first generation is believed to develop on the overwintering host and then the emergent adults migrate to summer hosts. This is believed to be the case as new colonisation by whitefly on crops usually occurs when the adults of the first generation emerge (Butler, 1938a; Al Houty, 1979; El Khidir, 1963). Reproduction continues until late September. Diapause is elicited when the second instar develops in a decreasing photoperiod of less than 15¾:8¼ (L:D), which occurs in late July. This generation of adults emerges in late September and consists of adults that overwinter (Adams 1985a; 1985b). Females that emerge at this time no longer have fully-developed ovarioles, and egg laying ceases (El Khidir, 1963). Overwintering is achieved primarily by these females who can tolerate temperatures as low as -18°C for short periods of time. Adult males have been shown to have a considerably lower tolerance of cold, and after mating they have a life expectancy of only 10 days (Butler, 1938a; 1938b). A suggestion that the later nymphal instars can overwinter was made by Iheagwam (1977a) and this is supported by the fact they can withstand sub-zero temperatures, which would be experienced through winter (Butler, 1938b). The degree to which this occurs has not been substantiated, as most pupae are likely to perish when the plant sheds its older leaves late in the winter (El Khidir, 1963). The factors leading to the termination of diapause in *A. proletella* have not been elucidated. Chilling has been shown to shorten diapause and temperatures exceeding 25°C to prevent diapause (Iheagwam, 1977a). It is likely that a number of factors interact to bring females out of diapause. If a phenological model was to be developed for this species, factors involved in the termination of diapause and the lower threshold temperature for egg laying must be determined.

It is very important to understand the pattern of crop colonisation by *A. proletella*. As the immature stages of whiteflies are sessile, dispersal and therefore colonisation of new crops is achieved by the winged adults. Females show a vastly higher rate of dispersal than males (El Khidir, 1963). It is likely that males respond to a cue from females, as males have been recorded 'waiting' for females to emerge from their puparia (Butler, 1938a). Dingle (1996) considered that there are two distinct forms of dispersal; trivial flight and migration. Trivial flights can be regarded as short duration flights, usually between hosts, where flight is directed to host plants and elicited by attraction to green/yellow light wavelengths (400-600nm). Migration is undistracted flight, whereby the insect ignores vegetative cues and is attracted to others such as sky light, causing the insect to fly up, out of vegetation. The distribution of captured whiteflies from a source follows a bimodal distribution supporting the notion of trivial and migratory flight morphs (Bryne *et al.* 1996). Two seasonal morphs of *Aleyrodes proletella* have been discovered, that differ in their dispersal behaviour. The summer morph has been shown to be reluctant to fly and, when it does fly, this is only for short durations, and it quickly returns to vegetation. It has been shown that the summer morph of *A. proletella* is attracted to yellow-green light (500-600nm), which is close to the wavelength of light reflected from vegetation and this has been documented for other whitefly species (Bulter, 1938a; Mound, 1962). This information suggests that during the summer, whiteflies stay within a localised region with minimal immigration from long distances into crops. This 'morph' can be regarded as performing mainly trivial dispersal. The autumn diapausing morph has shown increased flight behaviour with long flight durations, potentially reaching up to 40m in height. Diapausing individuals have shown positive phototaxis to an overhead light source, which was not observed in non-diapausing individuals (Iheagwam, 1977b).

Differences in phototactic responses between migratory and non-migratory morphs of whitefly have been observed in *Bemisa tabaci.* Migratory morphs have shown a clear attraction to 'Sky light', specifically wavelengths towards the ultraviolet part of the spectrum. This is believed to attract the whitefly to fly upwards toward the sky eliciting the higher flights needed for migration (Mound, 1962). The distance of migration by cabbage whitefly has not been quantified. Whitefly have been shown to migrate distances over 2km and this is likely to be a conservative estimate, as prevailing winds influence their migration (Bryne *et al.* 1996). Although whitefly migration is likely to be aided by prevailing winds, it should be noted that it is not regarded as a passive migration, as dispersal does not follow a diffusive pattern that would be predicted if this were the case (Bryne *et al.* 1996). It seems that active flight to achieve height, along with prevailing winds, suggests the potential for an individual to travel vast distances. This longer range migration is likely to be achieved by the overwintering females. The lower threshold temperature for flight for this species has been found to be 9°C (El Khidir, 1963). As a result, overwintering females stay within the same location once temperatures fall in November and are unlikely to take flight again until temperatures warm in spring. Being able to predict peaks of this migration by developing a phenological model would be invaluable to the Brassica industry allowing a targeted timing of control to eradicate the first colonisers to a new crop. Knowledge of the window of immigration of the pest into the crop would could be invaluable as control may be best held back until immigration has stopped, allowing the control of whitefly without the risk of new colonisers occurring afterwards.

The overall aim of this project is to understand population trends of *Aleyrodes proletella* in the most vulnerable crops, Brussels sprout and kale. This includes understanding the key times of population/generation increase and colonisation of new crops. This information will be used to indicate periods when the application of control methods would be most effective in reducing the overall pest load. This report describes experiments to:

1.1. Develop an effective method for trapping active adult whitefly in the field
1.2. Survey wild host plants for whitefly in an uncultivated field.
1.3. Survey a commercial oil seed rape crop for whitefly.

1.4. Egg laying rate and duration on three different *Brassica oleracea* crops: Brussels sprout, kale and Cauliflower.

1.5. Monitor whitefly on overwintering Brussels sprouts

1.6. Monitor whitefly on newly-planted vulnerable field crops (Brussels sprouts and kale) throughout season.

Materials and methods

Study Site

All field studies were conducted at or near Warwick Crop Centre, Wellesbourne, England, CV35 9EF (UK Grid reference SP 27320 56936).

Experiment 1.1 Developing an effective method for trapping active adult whitefly in the field.

This experiment was undertaken to investigate the preferences of the cabbage whitefly for landing on sticky traps of different colours (yellow/blue), heights (ground/1m high) or orientation (upwards/downwards). A small plot of Brussels sprout plants (3m x 10m, 30 plants) with a heavy infestation of cabbage whitefly was used to investigate any preferences of colour, height and orientation. Replicate treatments (4) were set out in a randomized-block design. The sticky traps (22cm x 10cm) were either yellow or blue (BHGS Ltd, UK). The traps close to the ground were placed upon a plastic base (9cm diameter) to suspend them approximately 1cm above soil level. The traps at 1m above ground were attached between two 1m bamboo canes to secure them horizontally .All sticky traps were placed perpendicular to the ground. Traps were set out on 26th October 2012 and collected on 29th October 2012. The numbers of whitefly caught were recorded on the day of collection.

Experiment 1.2 Survey of wild host plants for the presence of whitefly in an uncultivated field.

Potential wild hosts of cabbage whitefly were sampled within an field (approx. 1ha) for the presence of whitefly. The field had been removed from an arable crop rotation since 2008 when it entered management for the Entry Level Stewardship scheme for field margins, EF1 (Defra, 2005). Forty randomly generated co-ordinates were used as sample locations, where 0.5m^2 quadrats were used to survey for all known wild host plants (Mound & Hasley, 1978). These plants were checked thoroughly for the presence of cabbage whitefly. The survey was conducted on 20th May 2013. The percentage ground cover in each quadrat and the numbers of each host plant present were also recorded.

Experiment 1.3 Survey of a commercial oil seed rape crop for whitefly.

A commercial field of oilseed rape (OSR), *Brassica napus*, approximately 10ha in size, was surveyed for the presence of whitefly on three occasions during 2013: 20th April, 5th June and 17th July. A sampling grid 40m x 40m was used within the field. At each sampling point all plants within a 0.5m^2 quadrat were investigated for the presence of whitefly, an estimate of the percentage ground cover by OSR plants and the distance from field margin was also recorded.

Experiment 1.4. Egg laying rate and duration of egg laying on three different Brassica oleracea crops: Brussels sprout, kale and cauliflower.

Three types of *Brassica oleracea* crop were tested to determine the fecundity of female whitefly and the duration of egg laying. These were cauliflower (cv. Skywalker), Brussels sprout (cv. Revenge) and kale (cv. Reflex). All the whitefly used were reared in a controlled environment room at 20°C with a light regime of 16:8h (Light:Dark) on ~2 month old cauliflower (cv. Skywalker) plants. Newly-emerged whiteflies were collected by taking a sample of leaf from the laboratory culture, that contained pupae, and keeping it overnight in a closed petri dish to prevent newly emerged adults from escaping. The next day any adult whitefly that had emerged were sexed, males could easily be identified by the presence of two claspers on the abdomen. One adult of each sex was then placed onto a leaf using a fine paint brush. This was performed over ice, providing chilled conditions to prevent individuals flying. The newly-infested leaf was enclosed within a 'clip-cage' to prevent the whiteflies from escaping and to ensure feeding occurred on that particular leaf. All the leaves infested consisted of the second youngest leaf at time of infestation. The number of eggs laid was recorded every 2 days until the death of the female. Eggs were counted using a x10 magnification hand lens, care was taken to minimize disturbance to the female. Eggs were destroyed once counted. If the female was dislodged from the leaf, she was immediately placed back in the same location. Plants were kept at 20°C with a photoperiod of 16:8h (L:D). A total of 5 replicates were tested on each type of host plant. Females were moved onto new leaves if the leaves showed signs of senescence.

Experiment 1.5 Monitoring of whitefly on overwintering Brussels sprout plants.

A small plot of overwintering Brussels sprout plants (30 plants) was sampled for whitefly presence over the winter. Initial observations showed a distinct distribution of whitefly life stages across the leaf ages of the plants, showing surveys needed to incorporate this vertical distribution. The plot was attacked by birds and rabbits in December, considerably reducing the number of overwintering whitefly. The plants were then covered with bird netting to prevent further damage. The remaining population of whitefly was surveyed monthly until March when fortnightly samples were taken.

Experiment 1.6 Monitoring of whitefly on a newly-planted vulnerable field crop (Brussels sprout and kale) throughout season.

Plots of Brussels sprout and kale were planted on 2nd May 2013 to investigate natural colonisation and population increase of the cabbage whitefly over a season. Plants were sown in modules and raised in glasshouse conditions for 7 weeks prior to transplanting in the field. Plots consisted of 24 plants (3 x 8, 50cm spacing) of both kale (Reflex) and Brussels sprout (Revenge) (Figure 1). Five replicate plots were planted in different locations on the Wellesbourne site. Plots were covered in netting to prevent damage by pigeons. To determine the date of first colonisation to within a week, all leaves of all plants were surveyed weekly for a month after planting.

As the sampling effort increased significantly later in the season, due to increased numbers of leaves per plant and numbers of whitefly, a method to optimise sampling was developed. Whitefly has been found to have a distinct distribution on plants. Juvenile stages are sessile and age with their host leaves. Adults and eggs are found primarily on young leaves, while pupae are found on older leaves further down the stem (Gould & Naranjo 1999). Such a distribution requires sampling leaves of varied ages to sample all whitefly life stages without bias. Figure 2 shows a schematic of the sampling that took place on plants. Early studies showed the variance between plants was higher than that within plants indicating that replication at a plant level would gain better estimations of the population.

Figure 1. Study plot of Brussels sprout and kale covered in netting to prevent damage by pigeons.

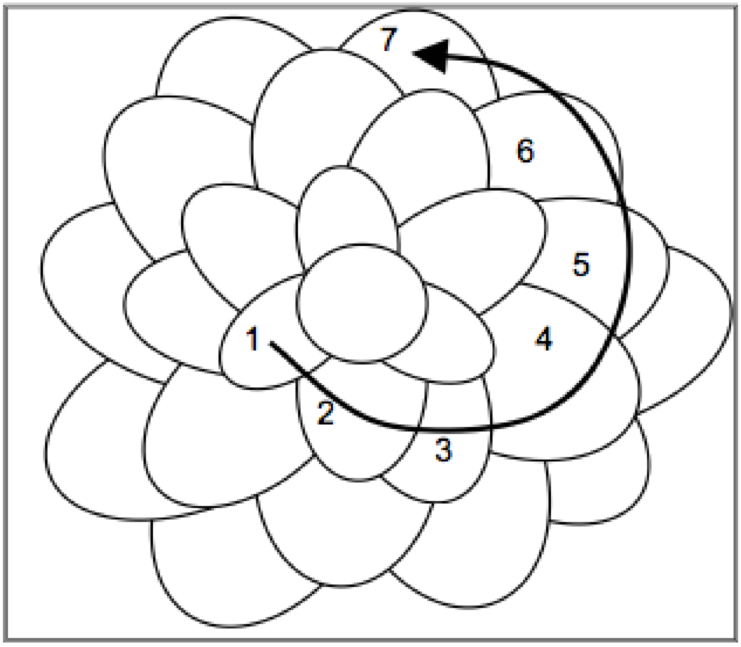

Figure 2. Schematic of sampling plan of plant to incorporate leaf-age distribution of whitefly. (From Schultz *et al,* 2010)

Results

Experiment 1.1 Developing an effective method for trapping active adult cabbage whitefly in the field.

Yellow sticky traps caught more adult whitefly than blue traps (ANOVA, F=18.6, n=4 P<0.001) and traps on the ground caught more whitefly than those positioned 1m above the ground (ANOVA, F=47.9, n=4, P<0.001).

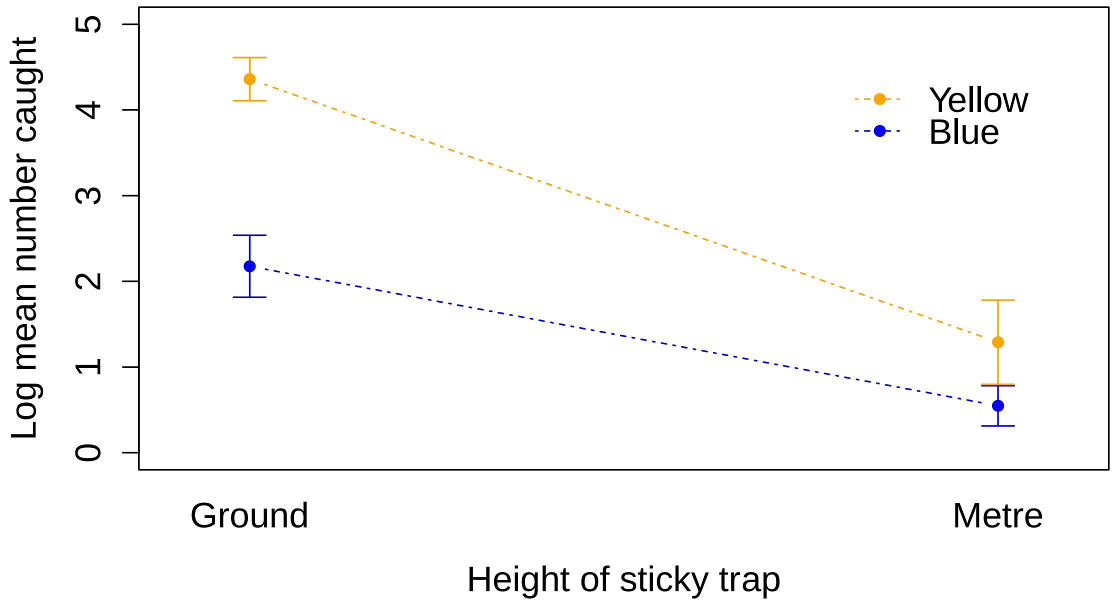

Figure 3. Log Mean number of whitefly caught for each colour of sticky trap (yellow/blue) at each height (ground/1m). (± 1 s.e.).

A significant interaction of colour and height of trap was found (ANOVA, F=4.5, n=4, P<0.05). There was no statistically significant difference between the numbers caught on the upper or lower sides of the traps.

Experiment 1.2 Survey of wild host plants for the presence of whitefly in an uncultivated field.

Of the wild hosts of the cabbage whitefly mentioned in Mound and Hassle (1978) only *Sonchus*, *Taraxacum* and *Euphorbia spp* were found. No whitefly were found on any of these potential host plants. It is likely that the population of cabbage whitefly was too low for them to be detected from this study.

Table 1. Mean number of wild host plants and their percentage coverage per $0.5m^2$ from 40 x $0.5m^2$ surveyed quadrats from an uncultivated field at Wellesbourne.

Wild host plant	**Mean number $0.5m^{-2}$** (% cover)
Sonchus spp.	0.46 (1%)
Taraxacum spp.	0.24 (0.9%)
Euphorbia spp.	0.05 (0.2%)

Experiment 1.3 Survey of a commercial oil seed rape crop for whitefly

No whiteflies were found from surveys in April or June. The final survey in July showed an average of 0.1 adults $0.5m^{-2}$, a total of 4 adults were found from 40 survey quadrats (Table 1). Taking this as an estimate for the entire field, there is potential for the 10ha field to support approximately 40,000 adult whitefly [(0.1 x 4) x 100,000)]. It should be noted that all whitefly found during the survey were within 40m of the field edge.

Table 2. Mean number of OSR plants per $0.5m^2$ and number of whitefly at different life stages from 40 x $0.5m^2$ survey quadrats on three different survey dates.

Survey date	Mean number $0.5m^{-2}$				
	OSR plants	Cabbage whitefly			
	(% cover)	Adults	Eggs	Nymphs	Pupae
20.04.13	9.66 (10%)	0	0	0	0
05.06.13	5.67 (64%)	0	0	0	0
17.07.13	3.62 (66%)	0.10	3.25	0.15	0.20

Experiment 1.4. Egg laying rate and duration of egg laying on three different Brassica oleracea crops: Brussels sprout, kale and cauliflower.

The mean duration of egg laying was 33 days, with females producing a mean of 89 eggs in this time. There was no significant difference between the mean number of eggs laid per female over a 2 day period for the three crops tested (Brussels sprout, cauliflower and kale, ANOVA, $F=3.7$, $P>0.05$, Figure 4). Further analysis of this data set will be conducted, including analysis of the rate and duration of egg laying. Further replications will be conducted and included in this analysis.

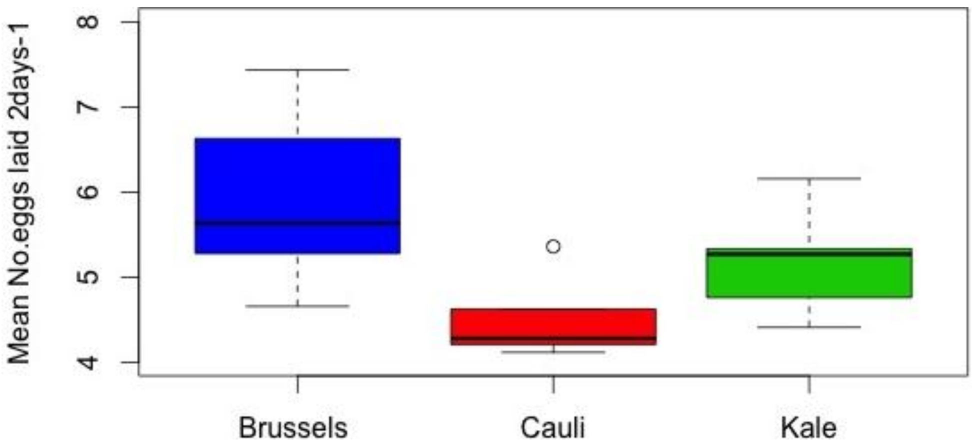

Figure. 4. Mean number of eggs laid per female in 2 days on three different host plants, Brussels sprout, cauliflower and kale. Initial analysis shows no statistically significant difference, n=5.

Experiment 1.5 Monitoring of whitefly on overwintering Brussels sprout plants.

Figure 5 shows the mean number of each life stage of whitefly sampled from the overwintered plot from January to July. The first eggs were found in early February when mean temperatures rose. However, numbers did not increase any further during the colder temperatures of March. It was not until early April, when temperatures rose, that the egg numbers began to increase again. The numbers of adult whitefly and pupae fell during this period, until none were found in May. The first nymphs were present in May and the first generation adults that emerged from pupae were observed on 28th June.

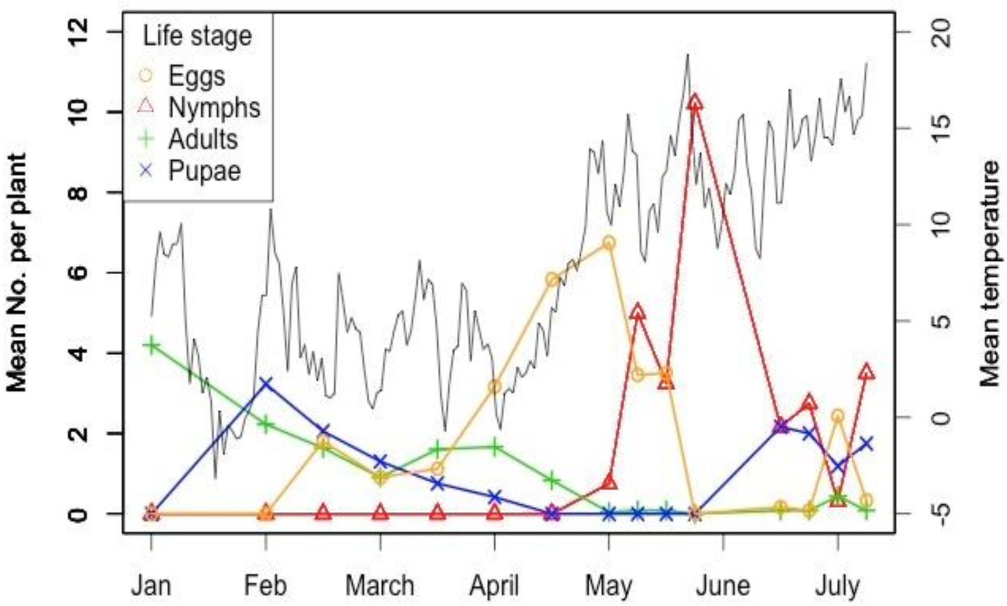

Figure 5 Results of sampling whitefly on a plot of overwintering Brussels sprout plants and the mean air temperature (black line) (°C).

Experiment 1.6 Monitoring of whitefly on a newly-planted vulnerable field crop (Brussels sprout and kale) throughout season.

This investigation is still on-going; populations will be monitored until early 2014, after which all data analysis will be conducted. Figure 6 shows the mean numbers of whitefly on Brussels sprout plants for the 5 study plots until August 2013. The first colonisation occurred during the last week of May. Soon after this, eggs were laid on plants and numbers rose rapidly through June and July, reaching over 200 eggs per plant in August.

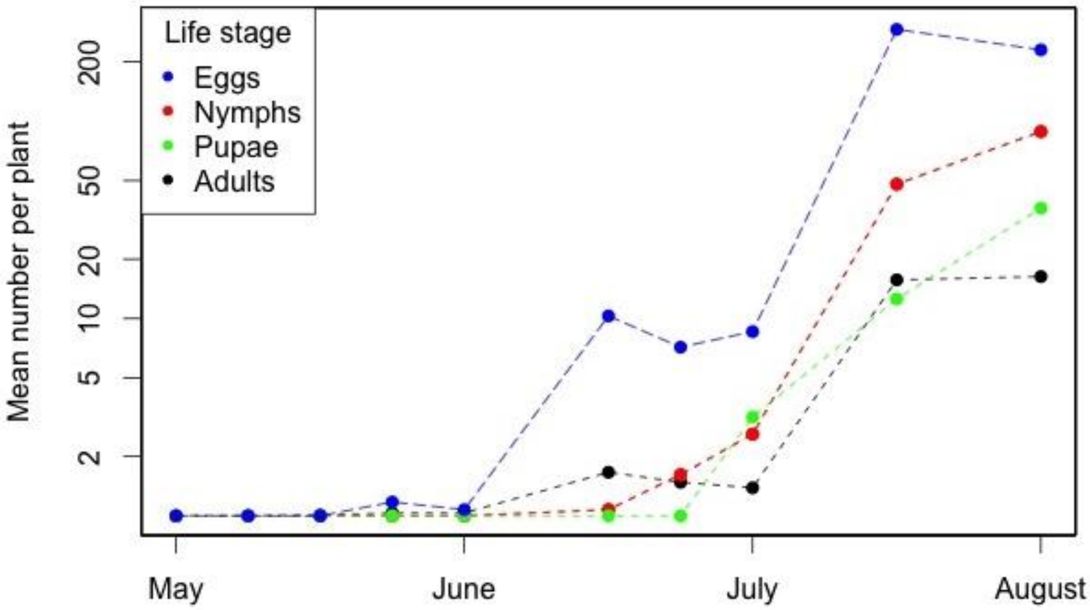

Figure. 6 Mean numbers of the different life stages of whitefly on Brussels sprout plants in the 5 study plots (log scale).

Discussion

Experiment 1.1 Developing an effective method for trapping active adult cabbage whitefly in the field.

Yellow sticky traps at ground level were the most efficient in catching adult whitefly. This technique was adopted for monitoring purposes, but this might be improved further and other trap orientations will be investigated. A downward facing 45° angle of inclination is most efficient for trapping carrot fly (*Psila rosae)* and has proved to be selective (Finch & Collier, 1989). A further study similar to Finch & Collier (1989) will be conducted to see whether an improvement in efficiency and selectivity can be made, providing more reliable information on adult activity. The interaction of colour and height suggests that blue is more efficient at greater heights above the ground. Future work will investigate a range of heights to see if this relationship persists. This might also give information on the migratory potential of cabbage whitefly at different times since *Bemisia tabaci* has been shown to have a preference for blue light when migrating (Mound, 1962). If this were the case, then migrating individuals of the cabbage whitefly may be more likely to be caught by blue traps at heights above 1m, which would be useful in determining times of long range dispersal.

Experiment 1.2 Survey of wild host plants for the presence of whitefly in an uncultivated field.

The results of the study suggest that in 2013-13, whitefly populations on wild hosts were at densities too low to be detected. In 2012, weather conditions were considered to be very unfavorable to the development and survival of whitefly populations and this may account for the generally low numbers of overwintering whitefly (Springate & Colvin, 2013). However, whitefly are present on wild hosts at Wellesbourne as spot checks of *Sonchus* plants near the car park in February found overwintering females. As the level of whitefly infestation on wild host plants was so low, it may be necessary to increase the size of the sampling quadrats to improve detection. The field used in this investigation had been uncultivated since 2008, all plants were the product of natural colonisation. Grass species seemed to dominate the area, which are not known to be hosts of the cabbage whitefly. Some of the most numerous wild host plants of cabbage whitefly found during this investigation were *Sonchus spp.. Sonchus spp. are* known to be one of the first colonisers of bare soil. Higher densities of this host plant are likely to be found if this study is repeated using land that was cleared approximately a year previously, or on ‘disturbed’ ground. Further work should investigate different habitats (i.e. woodlands, field margins, hedgerows, newly disturbed land) to see how these areas may differ in their potential as locations for supporting wild hosts of cabbage whitefly. Determining the density of wild host plants in different habitats will give an estimate of populations of whitefly that can be supported in these areas, which may be important reservoirs for females that could colonise newly planted vulnerable *Brassica* crops.

Experiment 1.3 Survey of a commercial oil seed rape crop for whitefly

No whiteflies were found within the sampling areas in April or June. This may be due to the high levels of herbivory by pigeons. In April, the percentage ground cover by OSR was incredibly low (10%), which was caused by heavy damage by pigeons early in the year. The field was nearly completely defoliated over the winter, providing few leaves that could support overwintering female whitefly, furthermore any whitefly that were overwintering on the OSR would have been disturbed by the pigeons. The adult whiteflies that were found within the field in July could have either have been immigrants from nearby wild hosts or there is the potential that they were the progeny of very few overwintering females within the crop. The estimate of a population of 40,000 whiteflies within this field is likely to be an over-estimation. Only 4 adult whiteflies were found from 40 quadrats and all of these were within 40m of the field margin. Thus multiplying the mean up to the whole field area might be incorrect as whitefly may only be present within 40m of the field margin. As such low numbers of whitefly were observed it was impossible to analyse the distribution of the whitefly statistically. The study should be repeated with the aim of finding more whiteflies. A way to increase the chances of achieving this would be to increase the quadrat size, perhaps to $1m^2$ or even more. This would be likely to create a more accurate estimate of the population of whitefly that could be supported by an area of OSR.

This survey does not support that OSR was acting as a reservoir for overwintering females. It wasn't until July that whitefly were found on the crop, the whitefly present at this time likely entered the OSR field from nearby wild hosts Interestingly there is the potential that the OSR could reduce the overall whitefly load within an area if adult whitefly colonised these fields instead of vulnerable horticultural brassica fields and offspring from these individuals would more than likely die at harvest. There is potential that when harvest of OSR occurs there could be a dispersal of displaced adults causing an influx onto nearby vegetable Brassica crops. This hypothesis would need to be tested. Crops of kale, for example, should be surveyed before and after harvests of nearby OSR crops to see if there is noticeable increase in whitefly.

Experiment 1.4. Egg laying rate and duration of egg laying on three different Brassica oleracea crops: Brussels sprout, kale and cauliflower.

The average duration of egg laying was 33 days. The duration of egg laying in this species is long in relation to its generation time. At 20°C the length of time it takes for an egg to develop to an adult is 23 days, an adult female can then continue laying eggs for another 33 days or more. As such, a female can be continuing to lay eggs after her early eggs have emerged as adults. This study shows how generations of cabbage whitefly can overlap significantly. Further statistical analysis needs to be conducted to analyze rates of egg laying throughout a the life of a female along with duration of egg laying. Variation was high between the replications for Brussels sprout plants in this study. A repeat study will be conducted that will include replicates on different leaves on the same plant. The analysis can then take into account female to female variation (random variation) within cultivar adding statistical power.

Experiment 1.5 Monitoring of whitefly on overwintering Brussels sprout plants.

The initial 'spike' in egg numbers in early February was followed by a nearly month long period when egg number remained constant, which coincided with a reduction in the mean air temperate below that of early February. Air-temperatures may have fallen below the lower thermal threshold for egg laying and it is not clear whether the eggs laid in early February were still viable and were responsible for the appearance of nymphs in May. Further research will investigate the lower temperature thresholds for egg laying and egg survival. This information would allow the prediction of egg survival as well as the prediction of the period of egg laying in spring, which would be important in understanding the future size of infestations in crops. The number of adults decreased during May but it could not be determined whether this was due to their death or to dispersal from the plants. The reduction in the numbers of pupae, together with a reduction in the number of adults, suggests that new adults were not emerging from overwintered pupae, otherwise an increase in adult numbers would be expected. Previous research has shown that pupae can survive sub zero temperatures (Butler, 1938b) but thermal thresholds for survival have not been determined; future studies should investigate this. The first generation of adults appeared on overwintering Brussels sprout plants on 28th June. This is very similar to the timings recorded by Al-Houty (1979).

Experiment 1.6 Monitoring of whitefly on a newly-planted vulnerable field crop (Brussels sprout and kale) throughout season.

Data collection for this experiment is still on-going. Initial results show earlier colonisation of new crops by the cabbage whitefly than thought previously (Butler, 1938a). It was believed that first generation adults emerging from eggs laid by overwintered females were responsible for colonisation (Butler, 1938a). This seems not to be the case. On overwintering Brussels sprout plants the first generation of adults to emerge from pupae was not observed until late July, a date that is similar to that recorded in previous studies conducted within the UK (Al-Houty, 1979). The first adult within a newly-planted plot was found in late May and eggs appeared soon after. This suggests that this first colonisation was by an overwintering female. Further analysis will be conducted on data collected from this experiment such as, differences in the populations on kale and Brussels sprout plants, correlations between populations of each life stage and total pest load and whether the initial population size has any bearing on either the rate of population growth or the final pest load. This information will highlight aspects of the biology of the cabbage whitefly that are important in the management of the pest within a commercial crop.

Conclusions

- Yellow sticky traps are most effective at ground level. However, results suggest that blue traps may become more effective at greater heights.
- A commercial oilseed rape crop did not support a population of overwintering female cabbage whitefly in 2012-13. High levels of damage by pigeons may have reduced the potential.
- Female whitefly lay a mean of 89 eggs over a period of 33 days at 20^{o}C. The period of egg laying exceeds the duration of development at the same temperature, showing the potential for considerable overlapping of generations.
- Under field conditions, egg laying began in February and continued until April. Egg numbers did not increase during the very cold period at the beginning of March, suggesting a cessation of egg laying due to low temperatures.
- Colonisation of new crops occurred in late May, before the first generation of adults had emerged on overwintered Brussels sprout plants. It is highly likely this first colonisation was by overwintering females.

Knowledge and Technology Transfer

- October, 2012. Attended Brassica Growers Association R&D Group meeting
- March 2013 Abstract for University of Warwick student symposium
- August 2013 Poster presented at HDC student conference
- September 2013 Oral presentation at IOBC-WPRS Working group ‘Integrated protection in field vegetables. Bergerac, France

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