Project title:	Activity patterns in the western flower thrips and their manipulation to enhance control measures
Project number:	CP 10
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Location of project:	Keele University
Project co-ordinator:	Dave Abbott
Date project commenced:	1 October 2001
Date project completed:	31 December 2004
Key words:	western flower thrips, *Frankliniella occidentalis*, light intensity, visible light, ultra violet light, glasshouse, chrysanthemums, cucumber

CONTENTS

Grower Summary

Headlines

- Experiments have revealed how light intensity, wavelength and temperature affect take-off, flight and egg-laying in the western flower thrips.

- The light threshold for take-off and flight activity was about 34 Wm^{-2} (PAR) and thrips were found to fly mostly during daylight hours. This was found both at constant temperature and under glasshouse conditions although the light threshold for take-off was about 7 Wm^{-2} (PAR) at constant temperature. Above the light threshold, there was no significant increase in take-off or flight with increasing light intensity. It was found, however, that thrips could distinguish and walk towards light intensity as low as 0.001 Wm^{-2}.

- Although light stimulated take-off, thrips were able to take-off in the dark. Human visible light without UVA stimulated take-off and UVA light alone stimulated a greater take-off rate than in the dark.

- At constant temperature, the take-off rate of adult female thrips increased significantly through the day to a peak one or two hours before scotophase.

- Under full spectrum light, thrips did not take-off at 15° C and take-off rate increased between 20° and 30° C. Take-off ceased at 45° C due to high mortality.

- There was no significant difference between take-off rates under five spectral filters although thrips were able to distinguish between most of the filters in a walking bioassay.

- Western flower thrips laid eggs mostly during daylight hours and there was no significant difference between the egg-laying rates under a range of low light intensities.

- Oviposition rate over 48h increased when thrips were placed under a UV-Opaque spectral filter compared with a UV-Transparent filter.

Background and expected deliverables

The western flower thrips (*Frankliniella occidentalis* Pergande) is a major pest of protected crops in the UK. The insect is resistant to many pesticides and has the habit of remaining hidden in small recesses on the plant and thus evading control agents such as chemical sprays and biological controls. Novel approaches are thus required to improve control methods. In addition, developments in horticultural techniques, such as the use of brighter supplementary lighting, the use of specialised spectral filters and temperature integration techniques, may all have some effect on thrips.

A better understanding of their behaviour and the factors affecting thrips could lead to ways of manipulating activity to enhance current control techniques and could help to predict the effects of glasshouse regime changes. Previous work has shown that the behaviour of western flower thrips is affected by environmental conditions such as light and temperature. Work at Keele showed that both walking and oviposition in adult females responded rapidly to changes in lighting level. Studies in other climates have shown that both wavelength (Costa *et al.*, 2003) and temperature (Shipp & Zhang, 1999) have affected flight behaviour and may lead to enhanced control measures.

The project could lead in the short term to simple and cost-effective ways of enhancing control measures for thrips in protected ornamentals and edible crops. For example, when glasshouses are sprayed or fumigated at night, extra lighting at this time could increase activity and so increase the effectiveness of the insecticide or microbial biological control agent by increasing pick-up rate. An understanding of the effect on thrips of changes in the internal environment could help in predicting, for example, population growth rate and flight activity.

The project used laboratory and small-scale glasshouse conditions to show whether activity can be manipulated. Before any results can be implemented, large-scale glasshouse trials would be necessary to test whether increased activity improves the efficiency of control measures. This was beyond the scope of this project.

Summary of the project and main conclusions

The factors affecting thrips behaviour were investigated under laboratory and glasshouse conditions.

The daily pattern of oviposition

The daily pattern of egg laying was measured, since knowing the time when thrips lay their eggs is an important step towards understanding the factors which affect oviposition. It was found that thrips lay their eggs mostly during the day. It was also found that the pattern did not change when thrips were moved from a long-day light regime at constant temperature to a short-day regime under glasshouse conditions. Thus, although photoperiod affected egg laying, the response was to both current and previous conditions. Since there was no rapid response to environmental change, oviposition could prove difficult to control.

The daily pattern of flight within a commercial cucumber glasshouse

As well as carrying out experiments to determine the effect of various environmental factors on take-off and flight, it was necessary to determine the pattern of flight found in "natural conditions" which in the UK would be within a glasshouse, in order to show that the behaviour observed in the laboratory is not atypical. It was found that the number of thrips trapped, increased through the day to a peak just before noon over two days. Activity then decreased through the afternoon. Both male and female adult western flower thrips flew predominantly during the day above a light intensity threshold of about 34.3±1.7 Wm^{-2} (PAR). Once above this light threshold, there was no significant increase of flight activity with increasing light intensity (up to 240 Wm^{-2}). There was a positive correlation with temperature (between 17° and 32 °C) but this was not significant contrary to results obtained in the laboratory, suggesting that the situation in glasshouses is more complex.

The daily pattern of take-off under constant temperature

A commercial glasshouse has a changeable environment and many different factors could influence the flight behaviour of thrips at the same time. Take-off was measured under laboratory

conditions where each environmental factor could be controlled in order to determine the relative importance of the different factors. At constant temperature and with full spectrum light, adult female thrips took off significantly more in the day than the night. This was similar to the daily pattern of flight activity in a glasshouse population.

It was important to understand whether thrips were responding quickly to the changing light intensity or whether the pattern of take-off was influenced by the previous conditions under which the thrips were cultured. It was found that both immediate changes in lighting and the influence of the previous light regime affected take-off behaviour. Rapid changes in the glasshouse, therefore, such as switching on a light at night, could affect take-off rate.

The effect of light intensity on take-off under constant temperature

This experiment was designed to test whether light intensity affected take-off rate either by providing a threshold level above which take-off occurred or by increasing take-off rate as it increased. It was found that the take-off rate of adult female thrips was significantly greater above a light threshold of about 7 Wm^{-2}. This threshold figure is lower than that measured for thrips under more natural, glasshouse conditions. This could be due to several reasons but as both threshold figures are very low (similar to those found at dawn or dusk) they are, from a practical point of view, very similar.

Above this threshold there was no significant increase in take-off rate with an increase in light intensity. This would suggest that increasing the brightness of supplementary lighting may not have an affect on thrips take-off activity once above the flight threshold.

In an experiment to investigate the walking response of adult female thrips to a range of light intensities, western flower thrips were found to walk towards a very low light source (0.001 Wm^{-2}) in preference to darkness. Thrips can, therefore, detect light at a much lower intensity than the threshold for take-off and flight.

The effect of wavelength on take-off under constant temperature

Developments in the use of alternative cladding materials alter the spectral composition of light inside glasshouses including the proportion of UVA present. UVA light has been shown to affect

insect behaviour and this experiment was designed to determine the affect on take-off rate under four different lighting conditions: full spectrum light; human visible light without UVA; UVA light without human visible light and no light. There was no significant difference between take-off rates under light with and without UVA. UV-absorbing plastics used as cladding should have no effect on thrips take-off activity within a glasshouse. However, the effect on flight duration and landing are not known.

Thrips are stimulated to take-off by UVA as well as by human-visible white light. This suggests that UVA may be able to be used at night to stimulate take-off and perhaps lure thrips towards a trap or natural predators.

The effect of temperature on take-off

Temperature varies within a glasshouse and an understanding of how temperature affects take-off could lead to improved control either through directly manipulating glasshouse temperature, if practical, or by predicting the effect of the ambient temperature on thrips flight activity. It was found that adult female western flower thrips did not take-off at 15° C. Take-off rate then increased from 20° to 30° C to a maximum. There was no further increase in take-off rate between 30° and 40° C and at 45° C, take-off ceased due to high mortality.

The temperature range over which take-off rate increased with temperature, 20° – 30° C, encompasses the range commonly found within commercial glasshouses. However, no significant correlation was found between temperature and trap catch in a commercial glasshouse over a similar range during two days trapping. This suggests a more complex situation in a glasshouse.

Some preliminary assessments of the effects of spectral filters on adult females

The effect on take-off

This experiment was designed to investigate the effect of spectral filters since a change in take-off rate could alter the efficacy of control measures. There was, however, no significant difference in the rate of take-off under each of four specialised spectral filters compared to a standard control film: a) UV-opaque plastic, b) UV-transparent plastic, c) Luminance THB (standard diffusing film) and d) Solatrol (red / far red modified film).

These films, supplied by the manufacturer (BPI Agri, Stockton on Tees) were chosen to represent a range of commercially available films with a range of properties that influence crop growth. This suggests that the use of these plastics as glasshouse cladding would not affect take-off rate inside the glasshouse and therefore control measures that require thrips to be in flight.

The effect on oviposition

An effect by spectral filters on oviposition rate could affect the rate of population growth. An initial experiment showed that thrips laid more eggs under a spectral filter with no UVA (UV-Opaque) than under a filter with high UVA (UV-Transparent). This experiment needs to be repeated to see if the effect is maintained or is just a temporary effect of changed conditions.

The effect on walking

This walking bioassay was designed to test whether adult females could distinguish between the light transmitted by the control plastic and that of four spectral filters. Thrips were able to distinguish between the control plastic and three of the spectral filters, UV-Opaque, Solatrol and UV-Transparent. There was no preference made between the control and Luminance THB.

Although there was no significant difference in the rate of take-off under the spectral filters compared to the control, this was not because thrips could not distinguish between them.

The effect of light intensity on oviposition

There was no significant difference between the rates of oviposition under a range of three light intensities in constant temperature. Given that temperature remains the same, an increase in light intensity will not increase the amount of eggs laid by female thrips.

Financial benefits

No recommendations can be made as yet, because large-scale field trials would be needed first.

Action points for growers

No action recommended for growers.

Suggested large-scale glasshouse field trials:

- The effect of temperature integration on the efficacy of a) insecticide or biopesticide spray, b) application of biological pathogen
- The effect of combining the use of low intensity UVA light source at night with a biological predator such as *Neoseiulus cucumeris* (Oudemans)
- The effect of time of day on the efficacy of a) insecticide or biopesticide spray, b) application of biological pathogen.

Science Section

1. Introduction

1.1. Background to the project

Since its spread around the world in the 1980s, the western flower thrips (*Frankliniella occidentalis* (Pergande)) has become one of the most important insect pests of many edible and ornamental crops (Robb *et al.*, 1995; Bennison *et al.*, 1999). It has caused substantial economic losses through direct physical damage to crops and by spreading plant viruses (Ullman *et al.*, 1997). The western flower thrips is not easy to control as it is resistant to chemical pesticides (Robb, 1989; Helyer & Brobyn, 1992) and its preference for remaining hidden within recesses in the plant host reduces the chance of contact with chemical pesticides. Integrated pest management has been used in glasshouse crops since the 1980s (Wardlow *et al.*, 1992), but the success of biological control of western flower thrips on ornamentals has been variable (Bennison *et al.*, 1999).

A better understanding of the behaviour of western flower thrips could be used to enhance the effectiveness of current management techniques. For example, if the manipulation of glasshouse conditions increased thrips activity, this would increase contact with chemical or biological control agents, which could improve their efficiency. An improved understanding of the biology of the pest species would be of benefit in several ways.

- The knowledge could be exploited to apply control measures at an appropriate time to improve effectiveness or reduce application rate.
- In addition it may prove possible to manipulate the glasshouse environment directly to affect thrips behaviour to enhance control measures.
- Thirdly, it could lead to a better understanding of how changes in the glasshouse environment, made to improve crop growth, will affect thrips behaviour and therefore their impact on the crop.

Very little is known about the patterns of behaviour in western flower thrips or the environmental factors that control their behaviour. Adult western flower thrips display a diel periodicity being generally more active during daylight hours than in the dark. This has been observed for several types of activity pattern including oviposition (de Kogel, 1997; Kiers *et al.*, 2000; Suzuki *et al.*, 2004); walking (Cho *et al.*, 2000; Suzuki *et al.*, 2004) and flight (Mateus *et al.*, 1996; Pearsall, 2002). Environmental factors that have been shown to affect these patterns of behaviour include photoperiod (Brødsgaard, 1994; Suzuki *et al.*, 2004) and temperature (Shipp & Zhang, 1999). If factors such as light intensity, wavelength or temperature affect behaviour then small changes in the glasshouse environment such as changes in the lighting regime, the use of spectral filters (PC 170 and CP 19) or the implementation of temperature integration techniques (PC 190) could affect the efficacy of integrated pest management (IPM).

The western flower thrips, in common with other thrips, has the habit of crawling into narrow, enclosed spaces within the host plant structure and effectively hides from predators and chemical pesticides. Any environmental influence that increases walking and flight activity could increase contact with predators and chemicals and therefore increase mortality. Under glasshouse conditions, an increase of air temperature from 21-23° to 26-28° resulted in an increase in flight activity of western flower thrips and a corresponding increase in mortality from insecticide of 23-25% (Shipp & Zhang, 1999). By investigating the effects of light and temperature on activity patterns in western flower thrips, it may be possible to produce similar results by artificially increasing light intensity. Alternatively, it may be possible to reduce oviposition or predict an increase in oviposition with changes in the photoperiod.

The glasshouse environment is constantly under review either with the aim of controlling pests and diseases or to improve crop yields. In recent years, there has been much development of cladding plastics with different spectral properties to manipulate crop growth. The HDC Project CP 19 led by Dr R Jacobson of Stockbridge Technology Centre, has been investigating five modified plastics, which represent the range of properties exhibited by plastics currently available and their effects on a range of indicator crop species. In this study, the same plastics were used to carry out some preliminary investigations on how thrips behaviour could be affected by commercial spectral filters.

The results of this project are relevant to practical applications in the pest management of this serious pest of protected crops.

1.2 Project aims

The aim of the HDC Studentship Scheme is to support the training of new research staff for the horticultural industry. The aim of the project is to understand the factors that influence the behaviour of the western flower thrips with a view to exploiting this knowledge to develop means of enhancing control measures in glasshouses. The specific objectives of this project were agreed in advance with the Horticultural Development Council. At the start of the second year of the studentship, these objectives were adjusted in line with the restrictions of time within the PhD studentship and the potential overlap with a new DEFRA funded project (HH3102TPC) "Exploiting knowledge of western flower thrips behaviour to improve the efficacy of biological control measures". The amended aims and objectives are:

1. To record the daily patterns of oviposition by adult females under glasshouse conditions and under constant temperature.
2. To record the daily patterns of flight (trap catches) by adult thrips under glasshouse conditions.
3. To record the daily patterns of take-off under constant temperature.
4. To quantify how lighting (brightness and wavelength) affects take-off by adult females under constant temperature.
5. To quantify how temperature affects take-off by adult females.
6. To conduct some preliminary assessments of the effects of spectral filters on the take-off and oviposition of adult females.
7. To quantify how lighting (brightness and wavelength) affects oviposition by adult females under constant temperature.

The western flower thrips is a pest of protected crops in the UK and can be found in both glasshouses and plastic covered tunnels. The results of this project are relevant to both and for clarity the term "glasshouse" is used throughout to indicate a protective structure of either type.

2. Materials and methods

2.1. Previous reports

Some of the techniques used in this project have been presented in detail in two previous reports (Annual Report September 2002 and Annual Report September 2003). These include the following:

a) Environmental monitoring of temperature, relative humidity, visible and ultra-violet A (UVA) light intensities,
b) The culturing of a laboratory population of western flower thrips,
c) The use of oviposition tubes and humidity tanks to carry out experiments on the factors affecting oviposition rate,
d) The use of time-lapse videography and a carousel to observe the diel pattern of oviposition,
e) Experimental lighting using full-spectrum fluorescent tubes,
f) The measurement of environmental conditions inside commercial glasshouses,
g) The use of a suction trap and sticky traps to monitor flight inside a commercial cucumber glasshouse.

Some of these techniques were used during the final year. These and additional techniques are described below.

2.2. Western flower thrips culture

A culture of western flower thrips has been reared at Keele University for about nine years as described in Annual Report 2002 section 2.2. By July 2003, certain changes had been made to the culture technique, namely:

a) Each lighting array was replaced with four 5' (58 W) Sylvania Activa 172 Professional full-spectrum fluorescent tubes to provide simulated daylight with a UVA component. In addition, the roof of each culture cage was replaced with a UVA transparent plastic. Thrips reared after this date were, therefore, reared in the presence of UVA similar to that found in natural daylight.

b) The culture lighting regime was changed to L16:D8 (from L18:D6). The lights came on at 0500 GMT and went off at 2100 GMT.

c) The vermiculite base within each cage was replaced with capillary matting.

d) As well as chrysanthemums grown at Keele (*Dendanthema grandiflora* Tzvelev "Yellow Princess Anne") other varieties of chrysanthemum were used in the culture, including the variety "Swingtime" which was provided by ADAS, Boxworth.

2.3. The daily pattern of oviposition by adult females under glasshouse conditions and constant temperature.

The carousel apparatus described in the Annual Report 2002, section 2.4, was used to measure the pattern of egg laying by adult female western flower thrips over a period of 2 days under glasshouse conditions and constant temperature. Thrips of mixed age were collected from the laboratory culture (described in Annual Report 2002, section 2.2) 24h prior to setting up the carousel and kept in a small culture pot with bean pods and excess pine pollen, to acclimate the thrips to the pine pollen, a rich food source which increases egg laying rate (Kirk, 1985; Whittaker, 2002).

For the trial conducted in constant temperature, the apparatus was set up in a constant temperature room directly under a light array of four 24"(18W) and four 5' (58W) Sylvania Activa 172 Professional fluorescent tubes with a light regime of L16:D8 as used for the culture. Mean light intensity was 5.5 Wm^{-2}. Temperature was maintained at an average of 27 ± 0.5°C.

Placing the apparatus inside a north-facing window of a large laboratory simulated glasshouse conditions. Lighting was restricted to natural daylight for the duration of the experiment and was measured using a datalogger (see Annual Report 2002, section 2.1). The temperature ranged between 19.6 and 23.5°C with a mean of 21.2 °C. Light intensity during the middle of the night (between one hour after sunset and one hour before sunrise) ranged from 0.04-0.5 Wm^{-2}. Daytime was therefore defined as hours above 0.5 Wm^{-2}, which was between 0700 and 1700 GMT. This coincided closely with the times of sunrise and sunset.

2.4. The daily patterns of flight (trap catches) by adult thrips under glasshouse conditions

A Johnson and Taylor insect suction trap (Burkard Manufacturing Co.Ltd., Herts, England) (Taylor, 1951, 1955; Johnson & Taylor, 1955) was used to collect western flower thrips over two days (17th and 18th September 2003). The trap mechanism segregated the catch by hour. In order to compare the results from the suction trap with the results from other workers who have used sticky traps, blue sticky traps were placed in four positions around the suction trap starting at 0000 GMT on the 17th September 2003 and were replaced every 2h for a 24h period. See Annual Report 2003 (section 2.4) for a detailed account of the materials and methods.

2.5. The measurement of take-off

2.5.1. Introduction

Take-off is an indication of the tendency of thrips to fly as opposed to hiding or other activities. There are many factors that affect insect take-off, including temperature (Lewis, 1963), relative humidity (Haufe, 1963), light and physiological state (Haufe, 1962). Under natural conditions, several factors may act together to affect take-off (Johnson, 1969) and it is necessary to take these into consideration when testing the effects of a single factor such as light. Experiments on the effect of light on take-off, for example, were therefore carried out here under constant temperature.

The effect of light intensity and wavelength on take-off in the western flower thrips has not been investigated although there has been some work on cereal thrips (Lewis, 1963). In common with most insect species, the compound eye of western flower thrips is highly sensitive to UVA light (350 –380 nm) (Matteson *et al.*, 1992). Antignus (2000, 1996, 1998)and Costa *et al*. (1999, 2002) found that the numbers of western flower thrips trapped inside polytunnels can be reduced by the use of UV absorbing spectral films. Although these experiments have shown that thrips behaviour is affected by the spectral composition of the light inside the glasshouse, the mechanism is not yet understood. The results could be due to the effect on the numbers in flight or instead, on landing preferences. The trials presented here aim to investigate how light (intensity and wavelength) affects take-off as a component of flight.

Initial trials showed that take-off behaviour is very variable and experiments were therefore conducted to investigate the effect of other variables including temperature and time of day. Developments in horticultural techniques could have an effect on thrips behaviour. For example, a change in temperature regime with the use of temperature integration techniques may reduce take-off activity at lower temperatures. According to Shipp & Zhang (1999), improved insecticide efficacy was achieved at higher temperatures with increased flight activity. The effect of temperature on take-off was investigated under constant light intensity.

2.5.2. The take-off bioassay

All trials were conducted in a constant temperature room maintained at 25±1°C with an ambient relative humidity of 35–60%. Experiments on the effect of temperature were conducted inside an incubator (detailed below) and all other experiments were carried out on a laboratory bench, covered with black card to reduce reflection. Mixed-age, adult female western flower thrips were collected from the culture, three at a time, for immediate use. Each thrips was placed directly into a gelatin capsule, 0.68 ml (size #0, Harvard Apparatus, USA), which was then placed into a release chamber (fig 2.1 and fig 2.2). Previous experiments had shown that thrips require an edge from which to take-off. Each release chamber provided a structure, simulating a large upturned flower, with an upper edge from which they could take-off. The release chambers were then placed in position for 2 min (light experiments) or 10 min (temperature experiments) for acclimation. The release chambers were placed in a shallow layer of distilled water to prevent thrips from escaping by walking. The gelatin capsules were opened carefully using forceps to minimise disturbance and the time until take-off was recorded up to a maximum of 360 s. Dead, missing or escaped thrips were discounted. The process was recorded on video and illuminated using infra-red LEDs (see Annual Report 2003, section 2.1). This allowed observation of the take-off behaviour in the dark, on the video monitor. Trials conducted in the dark were illuminated briefly with a low intensity of red light (λ_{max}= 676nm), which is undetectable by the thrips (Matteson *et al.*, 1992; Walbank, 1996) so that the capsules could be positioned and opened accurately in the dark. A minimum of nine thrips was used per treatment for each replicate and the sequence of treatments was assigned randomly. Initial trials showed that take-off activity increased through the day. Take-off experiments were therefore, conducted between 1200 and 1900 GMT (unless specified otherwise) during peak take-off activity. The measured

time for each thrips to take-off from the release capsule was converted to an index of take-off rate by subtracting the time to take-off from the total time available to take-off (360 s). This gave an index from 0-360, with the higher values indicating a higher take-off rate.

2.6. The daily patterns of take-off under constant temperature

The pattern of take-off throughout a 24 h period (midday to midday) was measured using the take-off bioassay described previously. A bioassay was completed every three hours through a 24h period at: 1300, 1600, 1900, 2200, 0100, 0400, 0700, 1000, 1300 GMT. Twenty-one mixed age female, adult thrips were collected directly from the culture, three at a time and used for each bioassay. Temperature was kept constant. The process was repeated over four separate 24h periods using two light regimes for the bioassay:

1) LL test conditions.

In the first regime, the test arena was illuminated using the standard full-spectrum light array of four, 2' fluorescent tubes for every test, in order to detect any pattern of take-off behaviour through 24 h. This was completed twice.

2) LD test conditions.

The second regime involved the use of the same light array but it was only used to illuminate the test arena during the culture day (photophase). During the culture night (scotophase), take-off rate was monitored in the dark to determine whether the presence of light affected the take-off rate at night. This test was completed twice.

In addition, take-off bioassays were conducted at three or more different times of the day between 0700 GMT and 1900 GMT on eight separate days between 3.v.2004 and 18.vii.2004. The same protocol was used as that used to measure take-off rate during the day in the above experiment.

2.7. The effect of lighting (brightness and wavelength) on take-off by adult females under constant temperature

2.7.1. The effect of brightness (light intensity) on take-off

The apparatus as shown in figs 2.1 and 2.2 were used to investigate light intensity. Five levels of light intensity were used in the laboratory using 24" (18W) Activa 172 full spectrum fluorescent tubes as a light source transmitted through a Lee diffusing filter X (20 cm x 40 cm) to create an even light. Light intensity was varied by altering the number of tubes used and the bench to tube distance. The distance between the diffusing filter and the experimental arena remained constant at 27 cm. An extra light treatment of natural light was provided by setting up the apparatus inside a south-facing window to provide bright daylight of 30 Wm^{-2} and above. The area of the overhead light source was kept comparable by shielding the experimental arena on three sides with black card, leaving an open overhead area of 20 cm x 40 cm.

The light intensities used are shown in table 2.1.

Table 2.1 Light intensities used to investigate the effect of light intensity on take-off in adult female western flower thrips.

Light treatment	**Mean visible light intensity Wm^{-2})**	**Number of tubes**
1	0	0
2	0.05	1 @ 80 cm
3	2	4 @ 80 cm
4	7	2 @ 35 cm
5	16	4 @ 35 cm
6	22-40	Natural daylight

2.7.2. The effect of wavelength on take-off

In addition to the preliminary trials described in Annual Report 2003, Section 2.3, the effect of the presence or absence of UVA light was investigated using the methods described in section 2.5.2 above.

UVA light without human white light (-visible+UVA) was produced with the use of a 24" blacklight-blue fluorescent tube (Sylvania F18W BLB T8). The spectral composition of this light also includes a low intensity of blue light (below the light intensity threshold for take-off). Human white light without UVA (+visible-UVA) was achieved with the use of a UV-blocking filter (Sterilite HDF, XL Horticulture, Lincolnshire).

Light treatments are summarized in table 2.2.

Table 2.2 Treatments to investigate the effect of UVA on take-off

Light treatment	**Mean visible light intensity (Wm^{-2})**	**Mean UVA light intensity (Wm^{-2})**
+visible+UVA	16.12	0.372
+visible-UVA	17.84	0
-visible+UVA	0	0.372
-visible-UVA	0	0

Fig 2.1 Diagram of apparatus used in take-off experiments using infra-red videography and an overhead light source. Each thrips is released from the gelatin capsule and the time to take-off from the release chamber is recorded up to a maximum of 360 s.

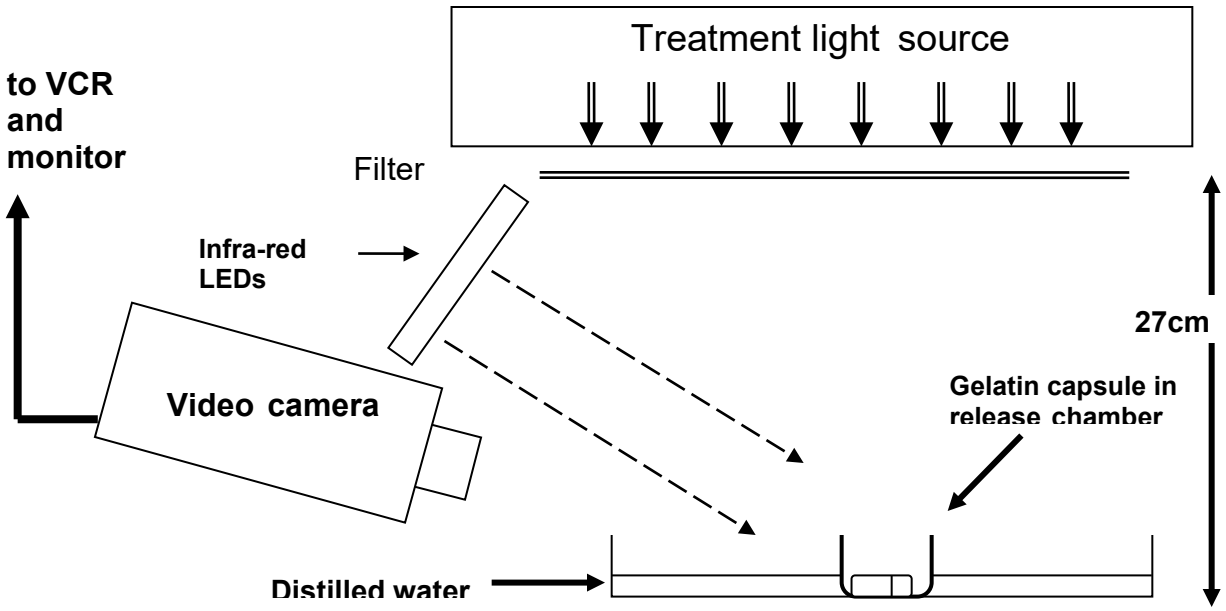


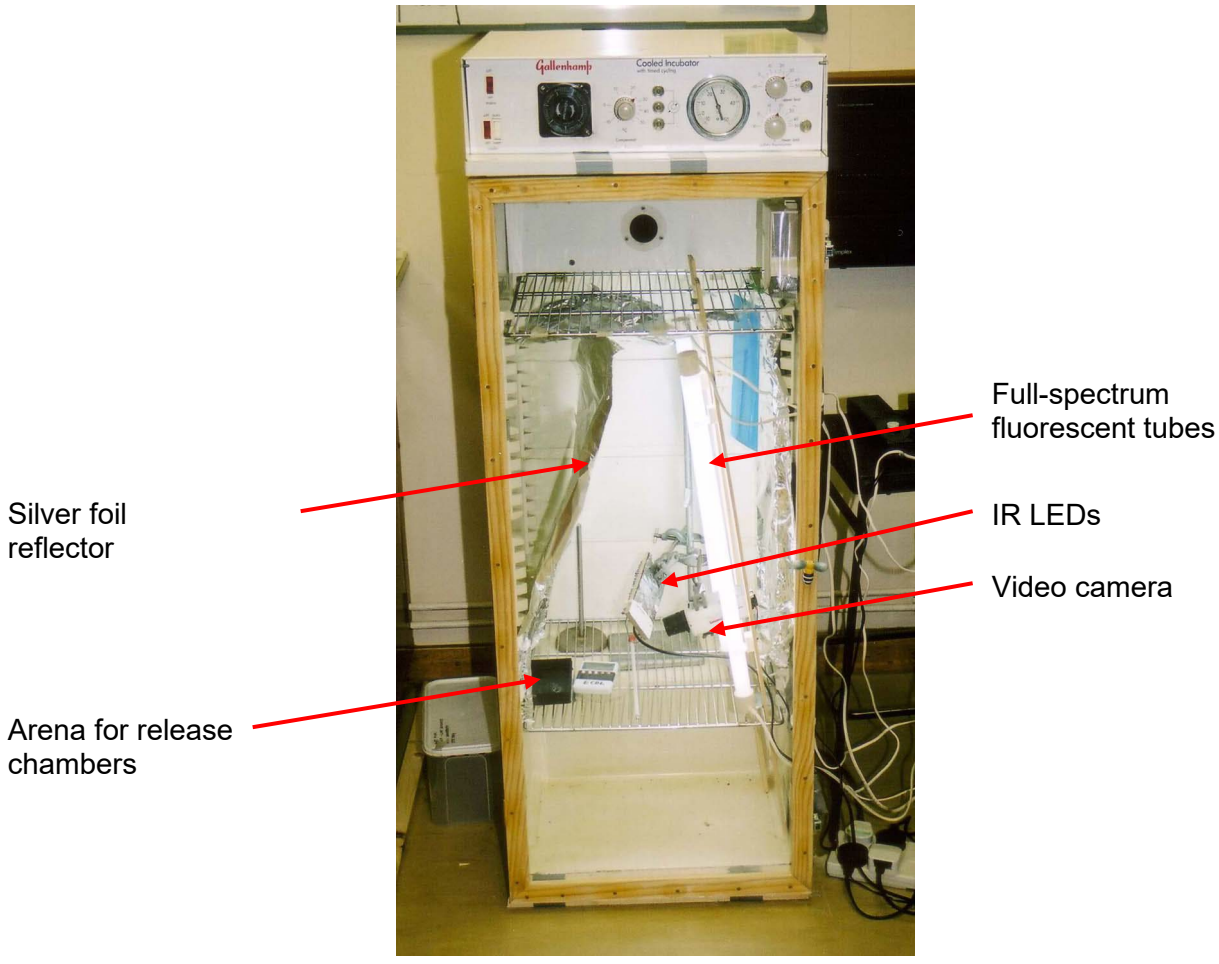
Fig 2.2 Three glass release chambers in position with gelatin capsules. Each release chamber is 25 mm across.

2.7.3. The effect of temperature on take-off

The apparatus was placed inside an incubator to control the temperature (fig 2.3). Due to the constraints of the incubator, the full-spectrum light source was positioned diagonally over the experimental arena. Treatments were applied in succession in a randomised block design and time was allowed between treatments for the temperature to stabilise inside the incubator.

Seven temperatures were used; 15°, 20°, 25°, 30°, 35°, 40° and 45° C.

Fig. 2.3 Incubator used to investigate the effect of temperature on take-off. A double layered perspex door allows the temperature to be maintained while the thrips are observed.



2.8. Some preliminary assessments of the effects of spectral filters on the behaviour of adult female western flower thrips

2.8.1. Spectral filters

The spectral composition of light inside a polytunnel enclosed by a modified spectral plastic, is different from that of natural daylight. The five commercial films and their spectral properties used in this project are listed in table 2.3 below. They are the same as the spectral filters used in HDC project CP 19 and were chosen to coincide with the work of other HDC projects. Samples of spectral filters were donated by the manufacturer (BPI Agri, Stockton–on-Tees, UK). See Appendix 1 for details of the spectral composition of light transmitted through the plastics.

Table 2.3 The spectral filters used to test the effect of spectral filters on thrips behaviour

Name of Spectral Filter	Spectral properties (% UVA transmitted)	Description
Control	3	Standard clear horticultural film
Luminance THB	1	Diffusing standard film
Solatrol	0	Red / far-red modified film (increases R:FR ratio)
UV - Opaque	0	Opaque to UV light
UV - Transparent	6	Transmits the full solar spectrum

2.8.2. The effect of spectral filters on take-off

Take-off was investigated using the method described in section 2.5.2. All five spectral filters were used in turn to filter the overhead light source in a randomised block design.

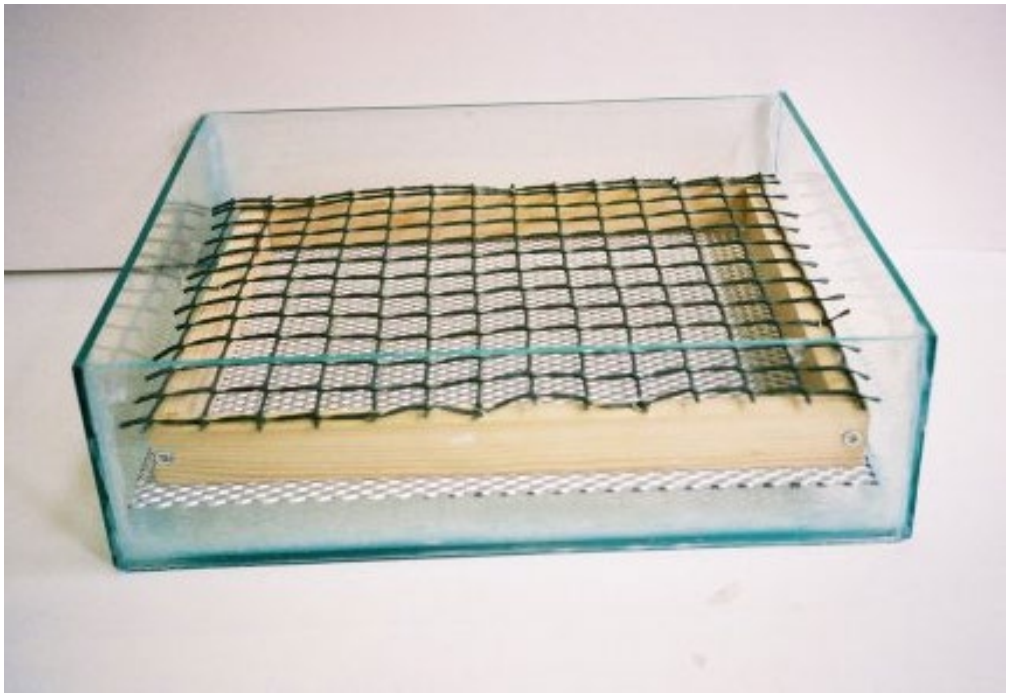
2.8.3. The effect of spectral filters on oviposition

The effect of spectral filters on the rate of oviposition in adult female western flower thrips was tested. The spectral filters altered the UVA component of the light to be above and below that of the control film. The percentage UVA was calculated from the amount of UVA (Wm^{-2}) divided by the amount of PAR (Wm^{-2}) and UVA (Wm^{-2}). They were:

- Control film 3% UVA
- UV – opaque 0% UVA
- UV – transparent 6% UVA

Three humidity tanks, 25 cm x 30 cm (fig 2.4) were set up each containing a layer, 1.5cm deep of saturated potassium tartrate solution. This solution served to maintain a constant relative humidity within the tank of 75% (Winston & Bates, 1960) when allowed to equilibrate with a glass lid fitted tightly over the top. The tanks were arranged in line under an array of four 5' full spectrum fluorescent tubes. Each was shielded on four sides by black card, leaving an area of 20 cm x 40 cm overhead, which was randomly assigned one of the test filters. Prior to placing the filters, light intensity was measured at each tank and modified as necessary to ensure that each tank received the same unfiltered light intensity of 5.0 Wm^{-2} with 4% UVA component. Mixed age, adult female thrips were collected from the culture prior to the trial and acclimated for 24 h with pine pollen. These were then placed, one thrips per oviposition tube, as described in Annual Report 2002. 35 tubes were prepared per humidity tank and left for 48 h under a light regime of L16:D8. After 48h, the number of eggs per tube was counted. Tubes with dead or missing thrips at the end of the experiment were discounted. The temperature was maintained at 26.4 ± 0.3°C.

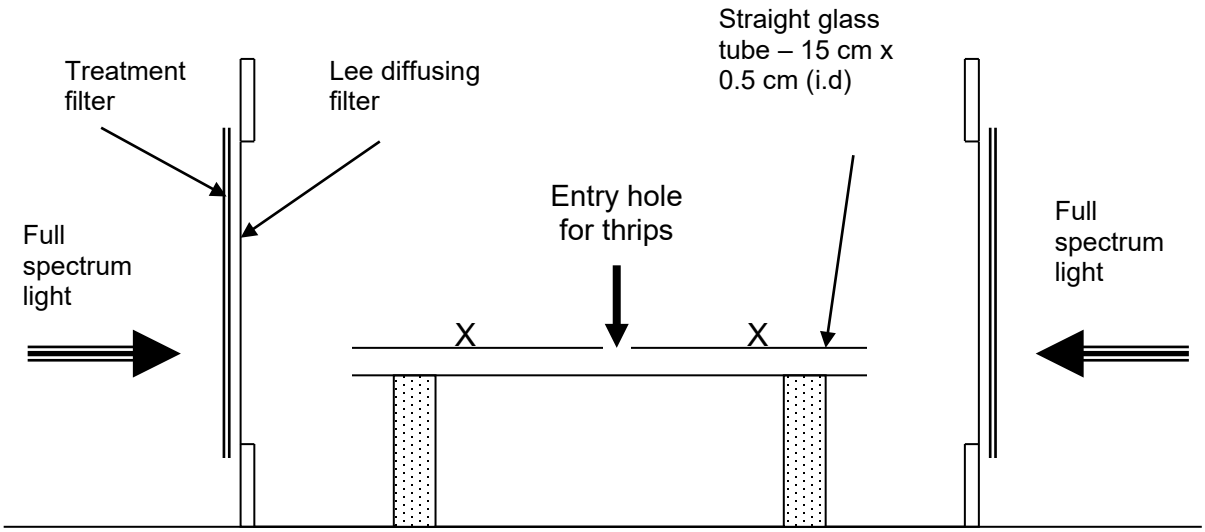
Fig 2.4 A humidity tank used to maintain humidity around the oviposition tubes used in oviposition experiments. Oviposition tubes were placed in the rack held above a layer of saturated potassium tartrate solution. A glass lid maintained a relative humidity of 75% within the tank.



2.8.4. The effect of spectral filters on walking

In this experiment the direction in which adult female western flower thrips walked was observed when they were given a choice between two different light sources. This gave a sensitive bioassay of walking response to differences in wavelength and intensity. A straight, horizontal glass tube, 15 cm long with a diameter of 0.5 cm was arranged with a 11cm x 11cm diffusing filter 3 cm from each end. A simulated daylight light source was then directed onto each diffusing filter to provide a diffuse light source at each end of the bioassay tube. The control spectral filter was placed over one screen and one of the other four spectral filters was placed over the other (fig.2.5). The bioassay tube was shielded with black card and the room lights switched off so that the only light source visible from the tube was through the filter screens at each end of the tube. Each thrips was tested only once by placing it inside the tube at the centre, using a mini-aspirator. The time and direction taken for the thrips to walk across a mark, 5 cm from either side of the entry hole, was recorded. Thrips that remained between the 5 cm marks for two minutes were counted as no-runs (NR) and discounted from the analysis. This was done to reduce any possible directional bias. After every 10 thrips, the tube direction was reversed. 60 thrips were used for each treatment replicate.

Fig. 2.5 Walking bioassay apparatus used to test the direction adult female thrips walked when given a choice between two light sources. Thrips were timed for up to 2 min or until they crossed one of the two marks, 5 cm either side of the entry hole. The direction chosen and the time taken to cross the mark, were recorded.



2.9. The effect of light intensity on oviposition by adult females under constant temperature

Three humidity tanks were set up as described in section 2.8.3. The primary light source was an array of four 5' full spectrum fluorescent tubes. Three light intensities were achieved as follows:

1) Low light intensity (0.2 Wm^{-2}) - two Lee neutral density filters

2) Medium light intensity (3.2 Wm^{-2}) – primary light source only

3) Bright light intensity (4.3 Wm^{-2}) – primary light source plus additional full-spectrum fluorescent tubes

Oviposition tubes were prepared as before with 40 in each humidity tank. The tanks were subjected to the normal light regime of L16:D8. The number of eggs per tube was counted after 48 h. Spot temperature readings were taken adjacent to each tank during the day and temperature was monitored throughout the 48 h period under the medium light intensity. Tubes with dead or missing thrips at the end of the experiment were discounted. A mean temperature was maintained of 26.5 ± 0.4°C.

2.10. Data analysis

Statistical analyses were performed using Minitab ver.13 (Minitab Inc., Pennsylvania) or SPSS ver.12 (SPSS inc., Chicago, Illinois). In most cases parametric tests were used initially followed by an Anderson-Darling test of the residuals. If residuals were not normally distributed, the equivalent non-parametric test was substituted with multiple comparisons using Holm's procedure (Holm, 1979) calculated with PEPI (Computer programs for Epidemiologists) version 3.01 (Abramson & Gahlinger, 1999)as recommended by Wright (1992).

3. Results and discussion

3.1. Summary of results presented in year one and two

This summary describes the results of experiments not repeated or discussed in detail later in this report.

3.1.1. Environmental measurements

Measurements of visible and UVA light intensity; temperature and relative humidity were recorded from an unshaded position on the roof of a building, monthly for a full 12 months. Natural visible and UVA light reached much greater intensities than those achievable in the laboratory. For example, the maximum light intensity on a bright June day between 1200 and 1400 GMT reached a peak of over 500 Wm^{-2} visible and 30 Wm^{-2} UVA. This compares with a maximum achieved in the laboratory of 16 Wm^{-2} visible and 0.4 Wm^{-2} UVA. For this reason, the effect of high light intensity on take-off was tested using natural daylight. It is important to note, however, that thrips are often within flowers or underneath leaves where the light levels may be much closer to those in the laboratory. Also that the light intensity measured above the crop varies greatly and that the intensities used in constant temperature experiments are similar to those experienced by thrips in a glasshouse at certain times of day and under certain weather conditions. Although lower than the maximum intensities measured, the light intensities used in the laboratory were realistic compared to frequent glasshouse conditions.

3.1.2. Transmission of light through glasshouse cladding materials

Even when clean and unscratched, glasshouse cladding absorbs a certain amount of natural light. As well as reducing the overall light intensity, different materials absorb particular wavelengths to a varying degree thus changing the spectral composition of the light inside the glasshouse.

UVA light is particularly affected. The average percentage of UVA in natural daylight is 6% whereas under standard horticultural glass it is reduced on average to about 3%. This was the same as the percentage of UVA provided by the full spectrum lighting in the laboratory. Other

cladding materials such as polytunnel plastics displayed various absorption properties according to their designed purpose.

The use of full spectrum fluorescent tubes was thus further justified as providing a similar UVA percentage to that commonly found in standard glasshouses.

3.1.3. The effect of density on oviposition in western flower thrips

This experiment was carried out in order to determine the optimum number of thrips to place in each oviposition tube in the following oviposition experiments. It was found that the rate of oviposition and the total number of eggs laid by thrips, decreased with increasing thrips density. As a result of this finding, only one thrips per oviposition tube was used in all oviposition experiments in order to maximise oviposition rate. In a natural situation within a glasshouse, high density may initially lead to thrips walking or flying apart rather than a reduction in oviposition rate (Rhainds *et al.*, 2005).

3.2. The daily pattern of oviposition by adult females

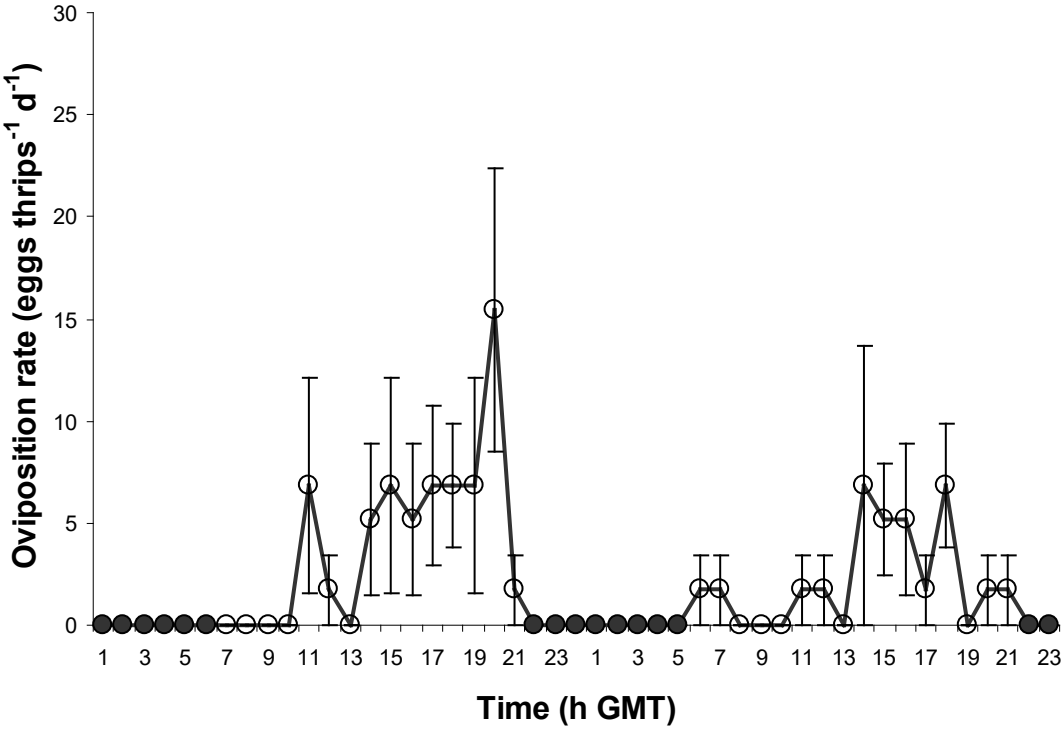
The daily pattern of egg-laying by female western flower thrips was measured since an understanding of this pattern and whether it is controlled by the immediate environmental conditions such as light or with an in-built rhythm affected by previous conditions could help to predict the effect of changes in the glasshouse environment. Fig. 3.1a shows the pattern of egg laying over a two-day period. In constant temperature, the mean oviposition rate of the adult female western flower thrips in the light (3.1 ± 0.6 egg thrips^{-1} d^{-1}) was significantly greater than in the dark (0 eggs thrips^{-1} d^{-1}) (two-way ANOVA, $F_{1,13} = 32.64$; $P < 0.001$). This result supports the findings of other workers that western flower thrips predominantly lay more eggs during the light than during the dark (de Kogel, 1997; Kiers *et al.*, 2000; Whittaker, 2002; Suzuki *et al.*, 2004). Under laboratory conditions, however, only the light changes and this is switched rapidly on and off unlike the gradual change of dawn and dusk. The pattern of oviposition was therefore, also measured under more natural simulated glasshouse conditions (Fig 3.1b). These results, however, showed an interesting departure from the results found at constant temperature. There was no significant difference between oviposition rate during the day (3.3 ± 1.4 eggs thrips^{-1} d^{-1})

(measured as the time when light intensity was above the night-time mean of 0.4 Wm^{-2}) and that during the night (1.3±0.6 eggs $thrips^{-1}$ d^{-1}) (two-way ANOVA, $F_{1,6} = 2.19$; P =0.189 ns). The thrips used in this experiment, however, were transferred directly from a light regime of L16:D8. When the pattern of egg laying in simulated glasshouse conditions was analysed according to the previous light regime (indicated on fig 3.1b) there was a significant difference between oviposition rate during the hours of the previous photophase (3.1±1.1 eggs $thrips^{-1}$ d^{-1}) and the previous scotophase (0 eggs $thrips^{-1}$ d^{-1}) (two-way ANOVA, $F_{1,6} = 8.11$; P =0.029). Although western flower thrips are influenced by direct changes in environmental conditions they are also affected by the conditions to which they were previously subjected. This would suggest that a sudden change in the light regime of a glasshouse such as decreasing the photoperiod with blinds, may not have an immediate affect on oviposition.

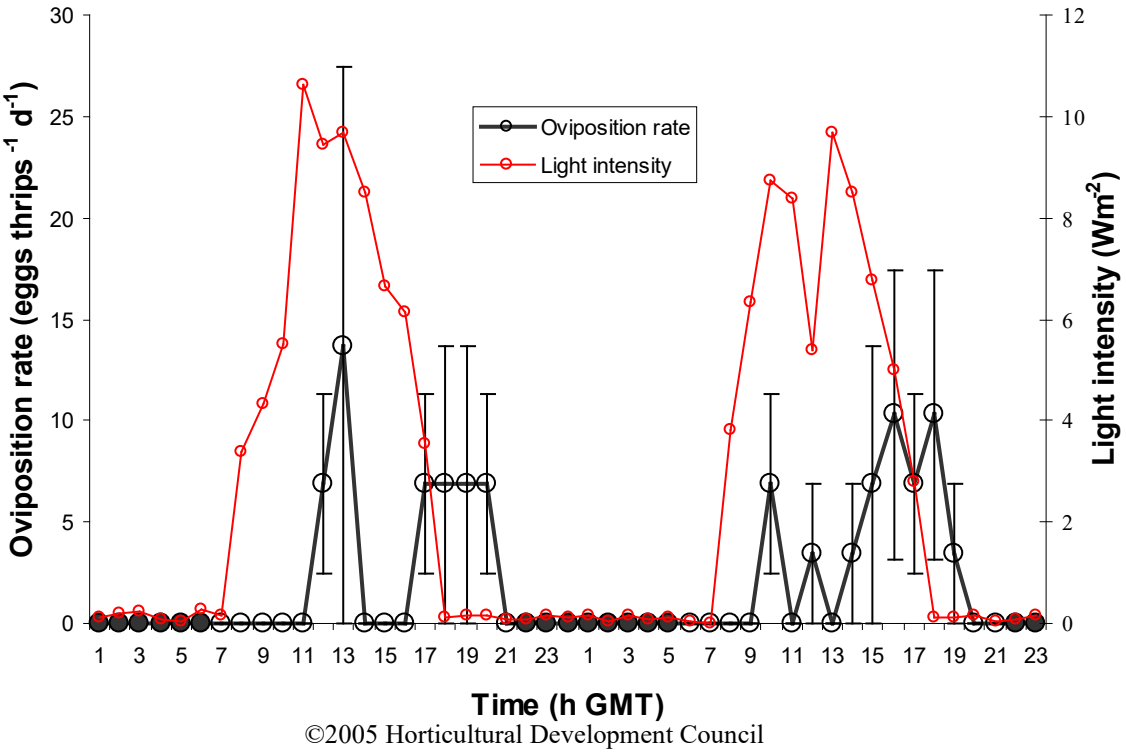
The effect of temperature on oviposition rate was not directly tested here but Teulon and Penman (1991) found that oviposition rate in a flower thrips (*Thrips obscuratus*) increased with temperature between 10° and 25° C. Katayama (1997) working on western flower thrips reared on chrysanthemum leaves, found little difference in average oviposition rate between 15° and 25° C and an increase in the oviposition rate between 25° and 30° C. The total number of eggs laid per female, however, was less due to reduced longevity. In a glasshouse, it may be only the oviposition rate in the first few days of female adult life that affect the population size, before control measures are implemented to kill the adults. Katayama (1997) found that in the first 10 days after emergence, daily oviposition rate increased with temperature between 15° and 30° C. Temperature may, therefore, have an important affect on oviposition rate in the glasshouse in young adult thrips.

Fig 3.1 Daily pattern of oviposition by adult female western flower thrips in: a) constant temperature and b) greenhouse conditions. Points represent mean ± SEM. Filled points represent the dark phase (scotophase) and empty points used for the light phase (photophase) maintained in the constant temperature laboratory (L16:D8).

a)



b)

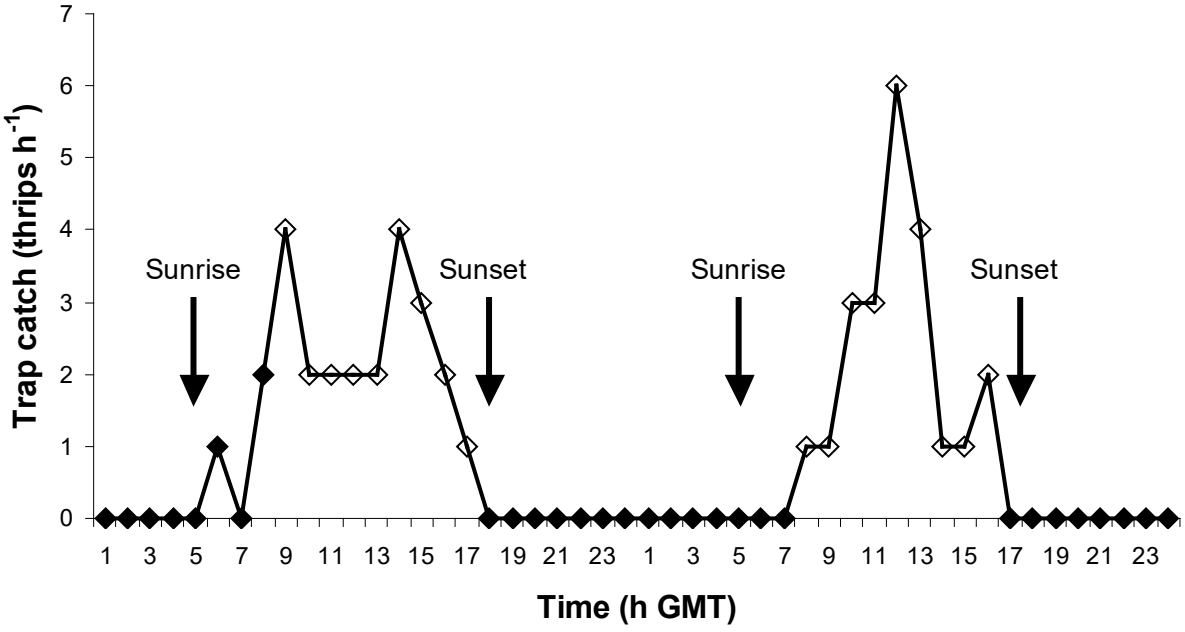


3.3. The daily patterns of flight (trap catches) by adult thrips under glasshouse conditions

Before it was possible to progress with flight experiments under controlled conditions, an infestation of western flower thrips in a commercial crop was investigated to determine the pattern of flight under more natural and variable conditions. In this way, the laboratory findings could be compared to glasshouse results to check that they are not atypical. The pattern of flight of western flower thrips in a cucumber crop is shown in figure 3.2. Male and female thrips flew significantly more during the day than the night (Mann Whitney, W=811.0, $P<0.001$). Daytime was defined here as sunrise to sunset.

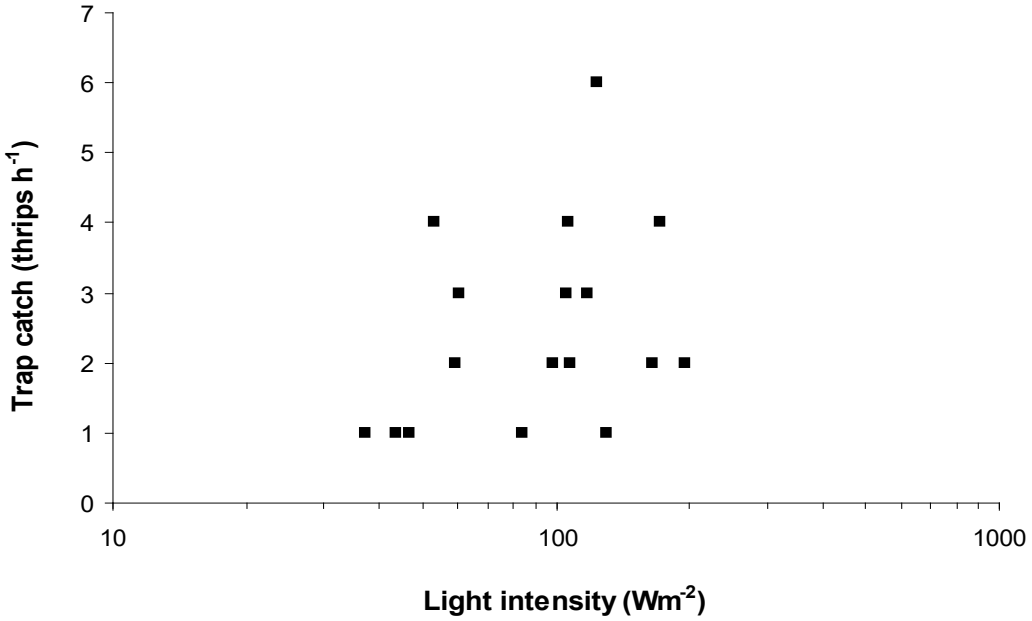
The light threshold for flight was 34.3±1.7 Wm^{-2} measured above the cucumber crop. This threshold was determined using a data test devised by Page (1957).

Fig 3.2 Graph of the number of female and male thrips caught per hour over a two-day period using a Johnson and Taylor suction trap positioned level with the top of a commercial cucumber crop located in Humberside, UK in September 2003. Shaded points: collection times when mean light intensity was below the calculated flight threshold of 34 Wm^{-2}. Clear points: collection times when mean light intensity was above the calculated flight threshold of 34 Wm^{-2}



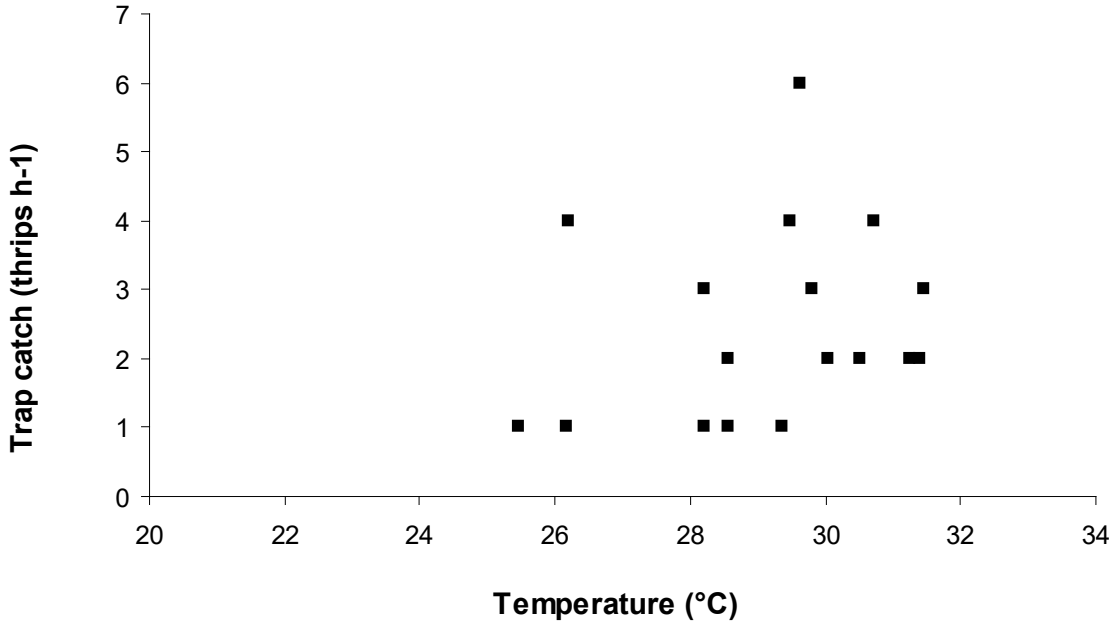
There was no significant correlation between light intensity and flight activity between the light threshold for flight of about 34 Wm^{-2} and the maximum light intensity achieved of 240 Wm^{-2}. ($F_{1,15}$= 1.22, *P*=0.286 ns) (fig 3.3).

Fig. 3.3 Light intensity against the number of male and female thrips caught per hour over a two-day period using a Johnson and Taylor suction trap positioned level with the top of a commercial cucumber crop located in Humberside, UK in September 2003. Only catch data above light threshold of 34 Wm^{-2} is included to show the relationship between light intensity and the number of thrips caught above the light threshold for flight.



The temperature in the glasshouse ranged from 23° to 32° C when the light intensity was above the flight threshold. The relationship between temperature and flight activity above this light threshold is shown in fig 3.4. The correlation was positive but a Spearman's Rank test showed no significant correlation (Spearman's rho=0.346, *P*=0.174 ns). Under laboratory conditions, there was an increase in take-off rate between 20° and 30° C (section 3.6). This apparent discrepancy could be due to the increased complexity of the glasshouse situation in which more variables are having an effect on the western flower thrips behaviour. It may also be because only two days data were collected in the glasshouse and a significant correlation between temperature and trap catch may not be apparent in such a small sample.

Fig. 3.4 Temperature against the number of male and female thrips caught per hour over a two-day period using a Johnson and Taylor suction trap positioned level with the top of a commercial cucumber crop located in Humberside, UK in September 2003. Only catch data above light threshold of 34 Wm^{-2} is included to show the relationship between temperature and the number of thrips caught above the light threshold for flight.



3.4. The daily patterns of take-off under constant temperature

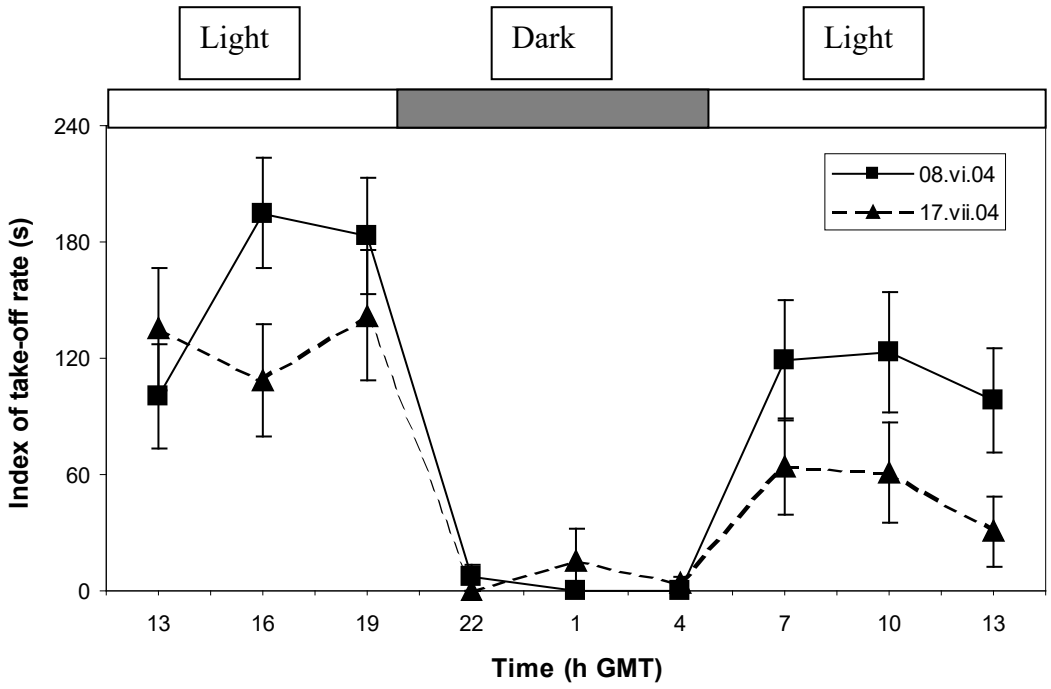
The daily pattern of take-off was tested under controlled conditions so that fewer factors varied through the test period and the effect of the test factor could be more accurately determined than under glasshouse conditions. Temperature was kept constant at 26±0.5° C so that the only changes were the progression of time and the presence or absence of light. The daily pattern of take-off of adult female western flower thrips tested under a light regime of L16:D8 (that is under full-spectrum light during the day and in the dark during the night) is shown in fig.3.5a. Take-off rate measured during the first trial was significantly different from that of the second (Mann Whitney, W=30978.0, *P*=0.208) and the data could not be combined. This probably reflects the day-to-day variability in take-off rate observed during this project. For each trial period, however, there was a significantly greater rate of take-off during the day (photophase) than during the night (scotophase) (Mann-Whitney, W=9145.5, P<0.001 and W=10003.0, P<0.001). At constant temperature, therefore, western flower thrips take-off at a significantly greater rate in the light compared with in the dark, which supports the findings of the daily flight pattern of a "wild" population in a commercial glasshouse (section 3.2).

The importance of previous environmental influences on western flower thrips is demonstrated in fig 3.5b. Thrips cultured in a light regime of L16:D8, but then tested under bright, full spectrum light both during the night and the day, showed a slightly different pattern of take-off. There was still a significantly greater rate of take-off during the day than the night (Mann-Whitney, W=40690.0, P=0.0115) but the difference was less than when the thrips were tested in the dark during the night. The higher take-off rate by day than by night was not solely attributable to the light level at the time of the bioassay. Thrips taken from the dark and tested in the light did not take-off as readily as those taken from the light. Take-off rate, therefore, is affected by both the immediate influence of light but also by the pattern of behaviour determined by previous conditions (in this case, the rearing light regime of L16:D8). In a glasshouse situation, this would suggest that a rapid change such as switching on lights in the night could affect take-off rate but that the effect might be tempered by the established predisposition to be less flight active at night.

Take-off rate increased significantly through the day (covariate analysis, $F_{1,13}$=29.67, P<0.001). This trend is shown in fig 3.6. The data from 12 days showed thrips take-off rate to vary from day to day but this was found to be not significant ($F_{11,13}$=2.31, P=0.076 ns). This trend supported general observations on thrips take-off behaviour and because of this, experiments on take-off rate were carried out between 1200 and 1900 GMT when thrips were likely to be most active.

Fig 3.5a The diel pattern of take-off of adult female western flower thrips measured a) in constant temperature and tested under the culture regime of L16:D8. and, b) in constant temperature and tested under the bright full spectrum light both during the photophase and scotophase. Dark bar represents the scotophase and clear bars, the photophase periods.

a



b

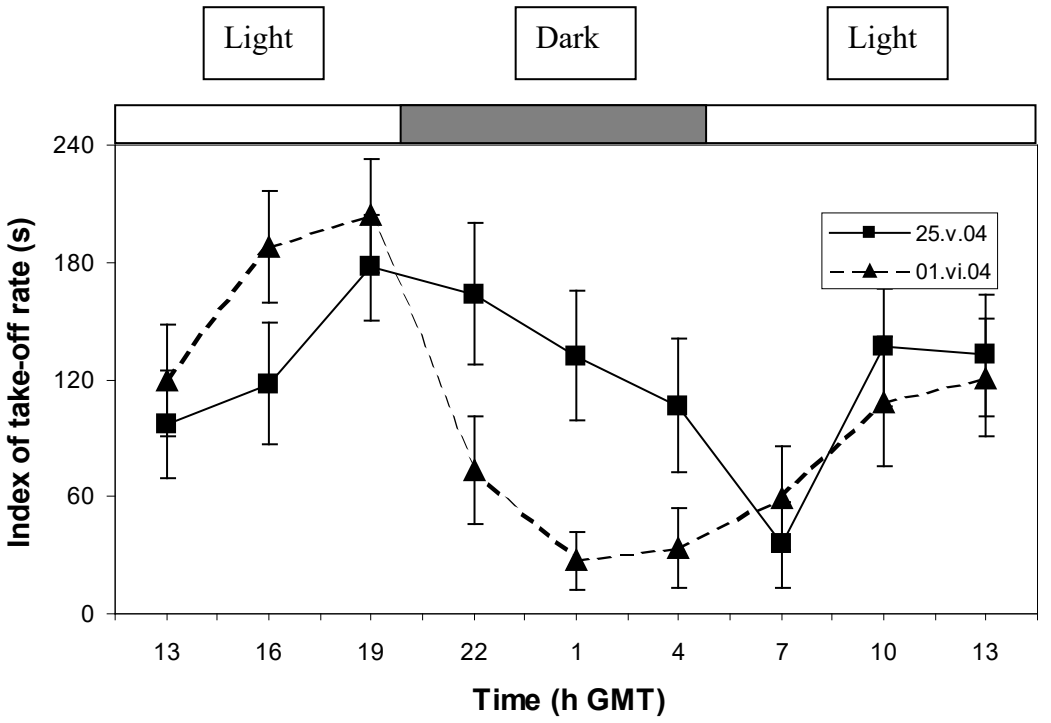
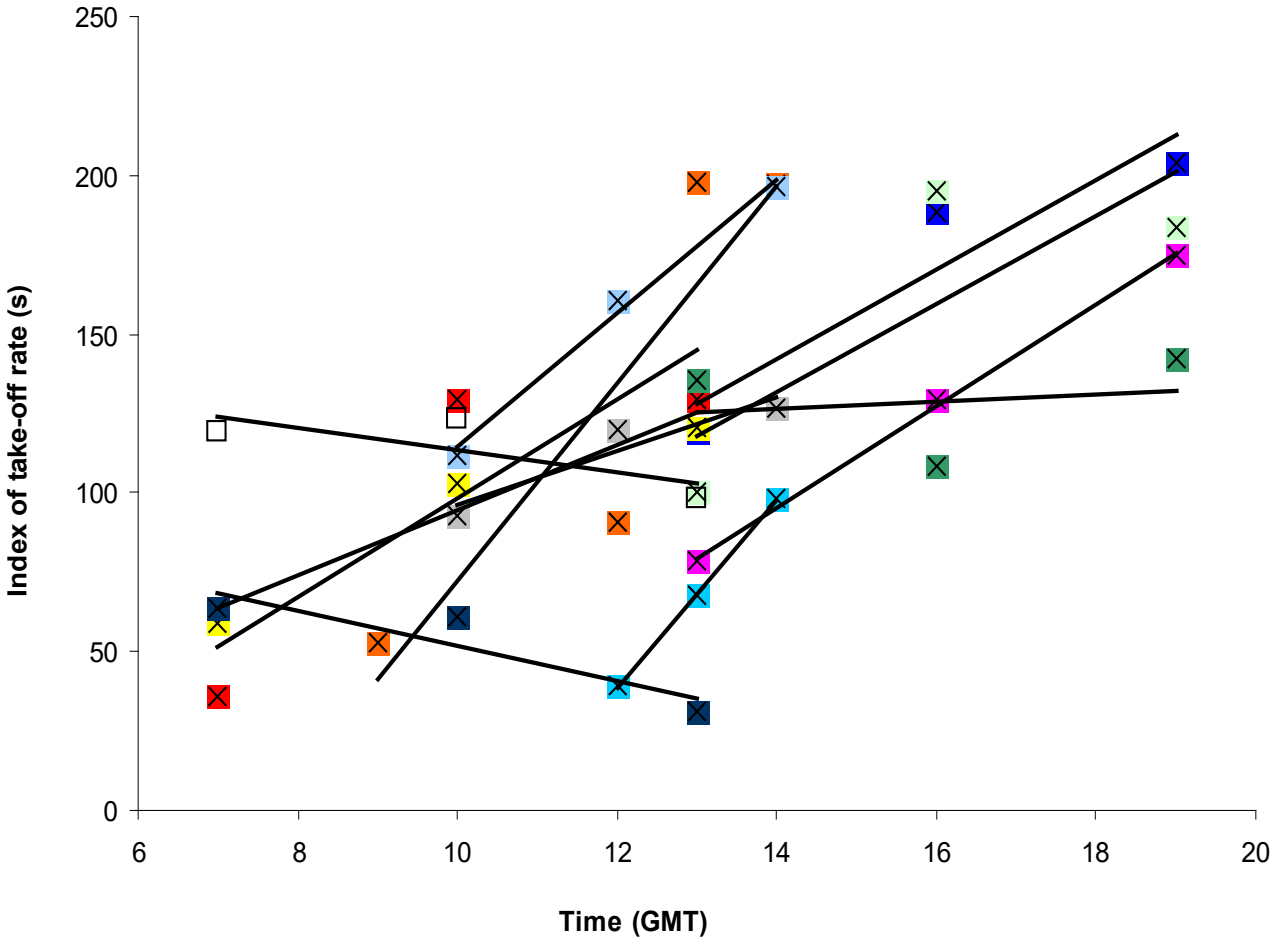


Fig 3.6 Take-off rate of adult female western flower thrips at constant temperature, correlated against time. Data were collected at three or more times between 0700 and 1900 on twelve separate days.

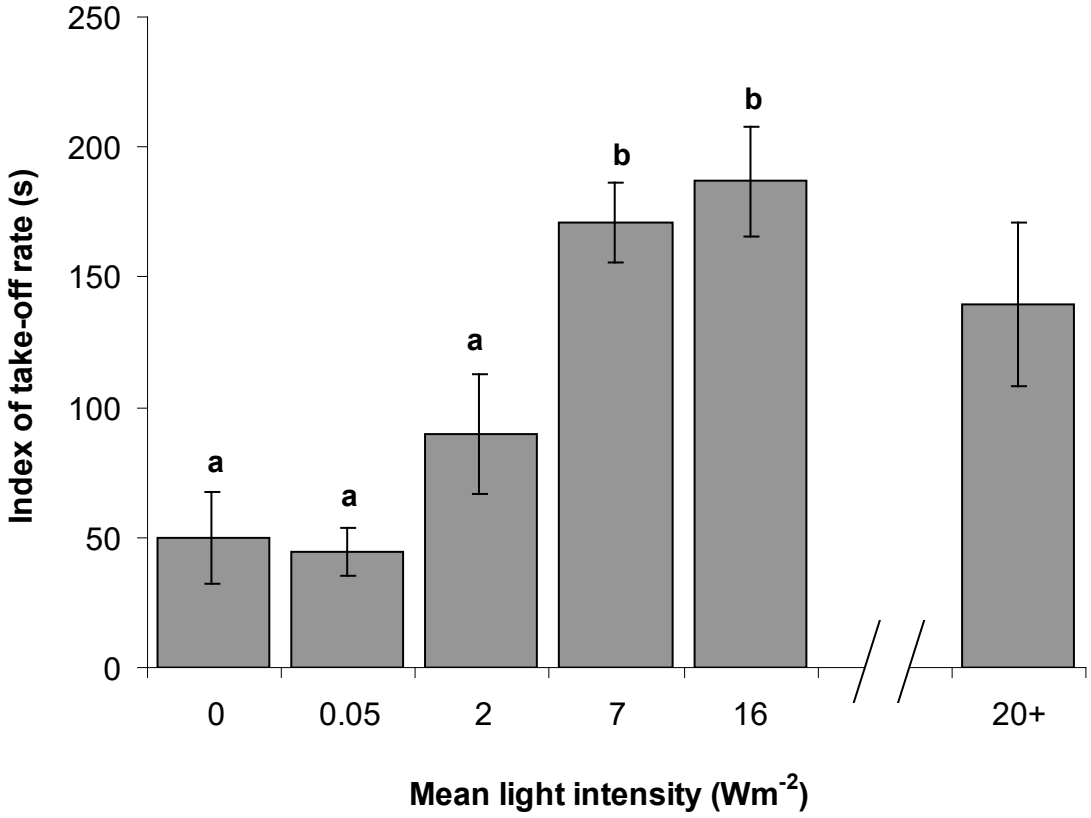


3.5. The effect of lighting (brightness and wavelength) on take-off by adult females under constant temperature

3.5.1. The effect of light intensity on take-off

With the implementation of brighter supplementary lighting, it was important to test the effect of light intensity on take-off since the level of flight activity may affect the efficacy of control measures. At constant temperature, the effect of light intensity was determined without the additional effect of increasing temperature as would occur in the glasshouse. It was found that the presence of light increased the take-off rate but that western flower thrips also took off in the dark (fig 3.7). Although thrips took-off in the dark under laboratory conditions and constant temperature, take-off rate was significantly greater above a light threshold, which was found to be about 7 Wm^{-2} (two-way ANOVA, $t_{(24)}$=3.329, adjusted P <0.001). This threshold of take-off was lower than the flight threshold calculated from trap catches in a glasshouse (section 3.2) for males and females. This could be accounted for by considering the solid angle of view measured by the light sensor. In the glasshouse, the sensor was measuring light over a full hemisphere whereas in the laboratory, the overhead light source was restricted to a rectangle of 788 cm^2. The same light intensity imposed over a full 180° hemisphere would provide a higher light reading. This could account for a lower laboratory threshold if thrips were responding to a bright light source and not integrating the overall light intensity over the whole area of vision. However, 7 Wm^{-2} and 34 Wm^{-2} are similar to the light intensity found near dawn and dusk and for practical purposes are very similar to each other.

Fig.3.7 The effect of light intensity on take-off rate of adult female western flower thrips at constant temperature. Bars with the same letter were not significantly different (adjusted $P > 0.05$) following two-way ANOVA test with Holm's adjusted P-values. Values show mean ± SEM. The take-off rate at light intensities of 30 Wm^{-2} and above was measured in natural daylight and was not be statistically analysed with the rest of the data.



Above the light threshold for take-off, there was no significant difference between light intensities of 7 - 16 Wm^{-2} (two-way ANOVA, $t_{(24)}$=0.6602, adjusted *P* =1.000 ns.) Under natural light which included higher light intensities than in the laboratory, mean take-off rate appeared similar to light intensities of 7 and 16 Wm^{-2}. There was no major increase as would be seen if take-off was proportional to light intensity. However, very bright light levels (>50 Wm^{-2}) were not tested. This supports the findings from trap catches in a commercial glasshouse. These findings suggest that increasing light intensity inside a glasshouse with the use of brighter supplementary lighting would have no effect on take-off rate or numbers of thrips in flight.

In an experiment to investigate the walking response of adult female thrips to a range of light intensities, western flower thrips were found to walk towards a very low light source (0.001 Wm^{-2}) in preference to darkness. This does not indicate a threshold light intensity but simply that thrips can detect light at a much lower intensity than the threshold for flight.

3.5.2. The effect of wavelength (UVA) on take-off

Developments in the use of alternative cladding materials alter the spectral composition of light inside glasshouses including the proportion of UVA present. UVA light has been shown to affect insect behaviour and this experiment was designed to determine the affect on take-off rate under four different lighting conditions: full spectrum light; human visible light without UVA; UVA light without human visible light and no light. The results of this trial are shown in fig.3.8. There was no significant difference in take-off rate under full spectrum light (+Vis+UVA) compared to human white light without UVA (+Vis-UVA)(two-way ANOVA, $t_{(18)}$=0.614 adjusted *P*=0.547 ns). This compares to the situation under a UV-absorbing polytunnel plastic, which has human white light but no UVA component. The loss of UVA had no effect on take-off rate.

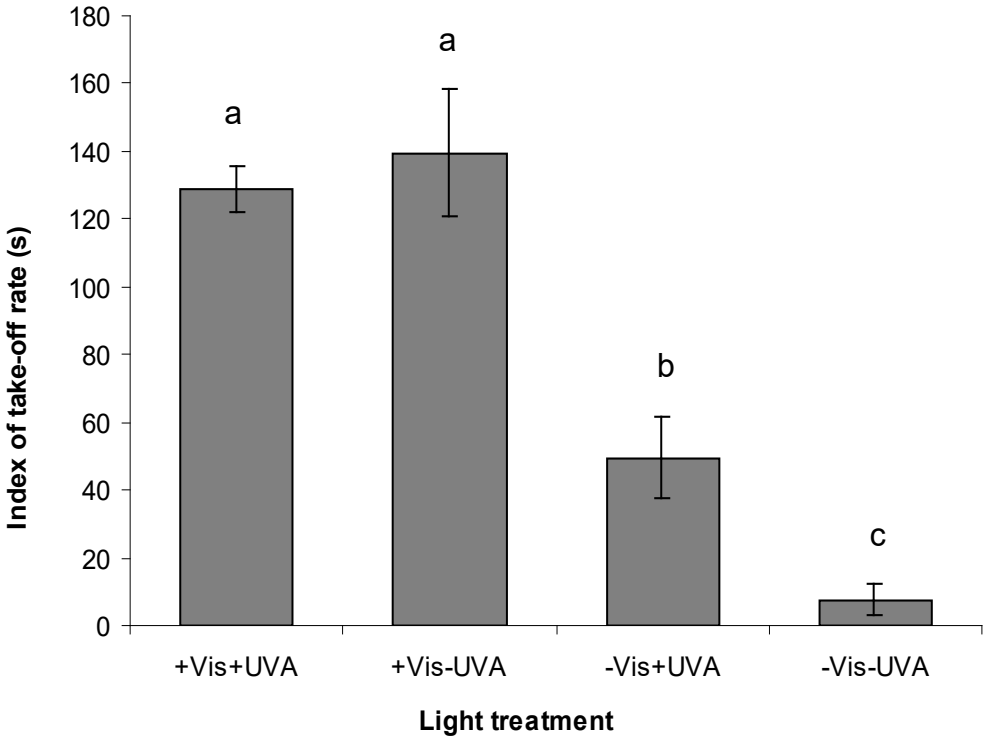
Below the measured light threshold for take-off, however, take-off rate was significantly greater in UVA light alone than in the dark (two-way ANOVA, $t_{(18)}$=-2.452, adjusted *P*=0.05). This suggests that a low intensity UV light source such as a blacklight blue fluorescent tube, could stimulate take-off in female adult thrips after sunset without affecting plant growth.

Take-off in the dark was significantly lower than under either full spectrum (+Vis+UVA) or human white (+Vis-UVA) (two-way ANOVA, adjusted $P<0.001$). Thrips can take-off in the dark and light is not necessary for take-off to take place.

Although UVA stimulates take-off, it is not essential for take-off to take place. Trials carried out to test the effect of UVA absorbing spectral films found that more thrips were caught under standard films than under the UVA absorbing spectral films (Costa & Robb, 1999; Costa *et al.*, 2002). Standard plastic will allow white with UVA light onto to the crop. If the thrips were taking off more readily under white light with UVA than under white without UVA, this would help to explain how more western flower thrips were trapped under the standard, UVA transmitting plastic film but this has not been found here. The difference in flight behaviour, which could explain the increased trap catches of western flower thrips under UVA transmitting plastics and therefore white with UVA light, may involve the duration and direction of flight activity after take-off. An alternative hypothesis could be that the spectral filters affect the appearance of the traps and may have an affect on their attractiveness. This could, therefore, affect the landing rate as trap colour and UV reflectance have been shown to be important in trap attractiveness (Vernon & Gillespie, 1990). Further glasshouse trials would require plant sampling to determine the numbers of thrips found under different spectral filters.

The results presented here show that UV-absorbing plastics used as a polytunnel covering would have no effect on the ability of thrips within the poyltunnel to take-off and fly.

Fig 3.8 The effect of wavelength on take-off rate of adult female western flower thrips at constant temperature. Values show mean ± SEM. Bars with the same letter were not significantly different (adjusted $P > 0.05$) following multiple Mann-Whitney tests with Holm's adjusted P.



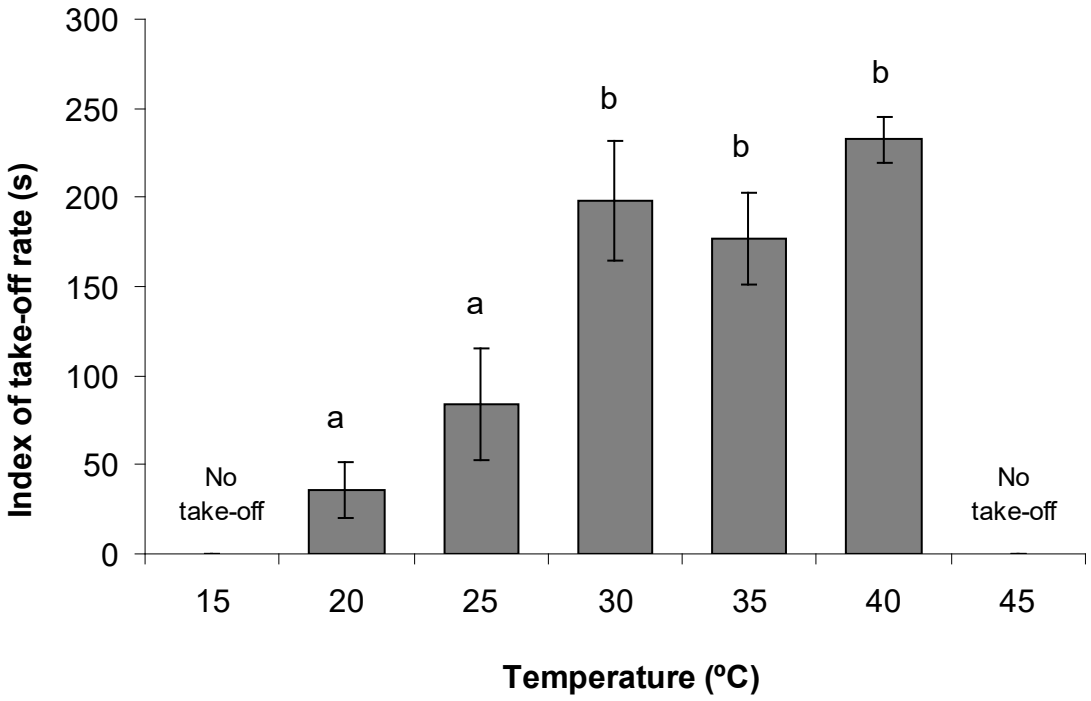
3.6. The effect of temperature on take-off

As well as light, temperature varies within a glasshouse and with the climate change levy making energy saving and temperature integration techniques increasingly important concerns in horticultural practice, the effect of glasshouse temperature on the flight activity of pest species is relevant. Changes in the glasshouse temperature may affect thrips activity and could therefore affect the efficacy of control measures. The results of this trial are shown in fig.3.9. There was no take-off at 15°C and at 45°C there was 100% mortality.

Take-off rate at 25° C was significantly less than at 30° C (two-way ANOVA, $t_{(16)}$=-3.605, adjusted *P*=0.012). However, no significant rise in take-off rate was found between 30° C and 40° C (two-way ANOVA, $t_{(16)}$=- 0.659 adjusted *P*=0.576 ns, $t_{(16)}$=-1.099 adjusted *P*=0.576 ns and $t_{(16)}$=-1.757 adjusted *P*=0.392 ns). This result, however, may be due to the inability of the bioassay to distinguish between very high take-off rates.

These findings support the results of Shipp and Zhang (1999) who found that raising the temperature inside a glasshouse from 21-23° to 26-28° resulted in an increase in flight activity of western flower thrips and a corresponding increase in mortality from insecticide of 23-25% . The effect of temperature on take-off may be particularly relevant in light of the latest development of temperature integration tchniques in commercial glasshouses (HDC report PC 190), (Anonymous, 2002, 2004). In brief, temperature integration works by allowing the temperature to vary about the desired average within computer controlled limits. This allows for a potentially higher daytime temperature with solar gain (free energy) and a lower night temperature (reduced energy input). A lower night temperature will have no effect on take-off since most flight activity takes place during the hours of light. A higher daytime temperature within the range of 20° – 30°C, however, will increase flight activity of thrips. This could be exploited to increase the efficacy of insecticide applied at the time of highest temperature if this was possible without detrimental effect on the crop.

Fig.3.9 The effect of temperature on take-off of adult female thrips under constant light intensity. Values show mean ± SEM. Bars with the same letter did not differ significantly (adjusted $P > 0.05$) following a two-way ANOVA test ns and Holm's adjusted P-values.



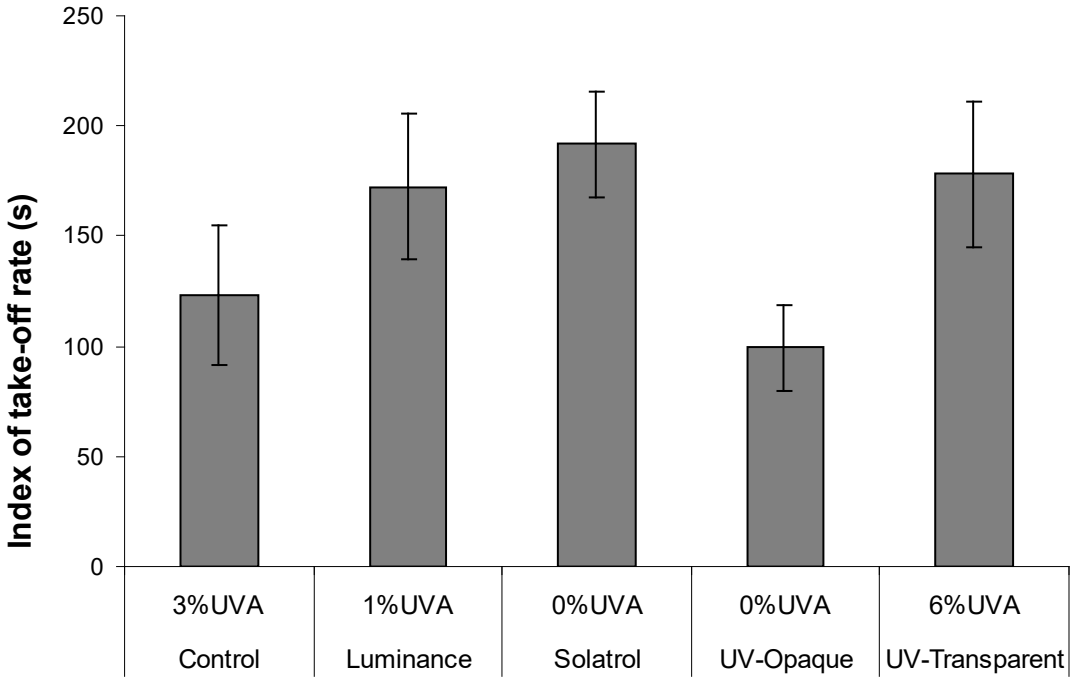
3.7. Some preliminary assessments of the effects of spectral filters on adult females

3.7.1 Effects on take-off

This experiment was conducted in order to compare the take-off activity of western flower thrips under a range of spectral filters. As pest control measures may be more efficient with either an increased or decreased flight activity, a change in take-off rate could affect the efficacy of control measures such as spraying with insecticide. The results of this trial are shown in fig.3.10. There was no significant difference in take-off rates under the four spectral filters tested when compared with the control filter (Dunnett's simultaneous comparison, $P>0.05$ ns).

This suggests that the use of one of these specialised spectral filters for polytunnels will not affect take-off activity of the thrips. Since it is generally desirable to increase thrips activity in order to increase the possibility of contact with pesticide or biological agents, the use of spectral filters should not reduce the effect of control measures. More behaviours need to be examined, however, before conclusions can be drawn about the overall effect.

Fig.3.10 The effect of spectral filters on take-off rate of adult female western flower thrips at constant temperature. Values show mean ± SEM. An ANOVA test with Dunnet's simultaneous comparisons showed there was no significant difference between the means. (P>0.05 ns).

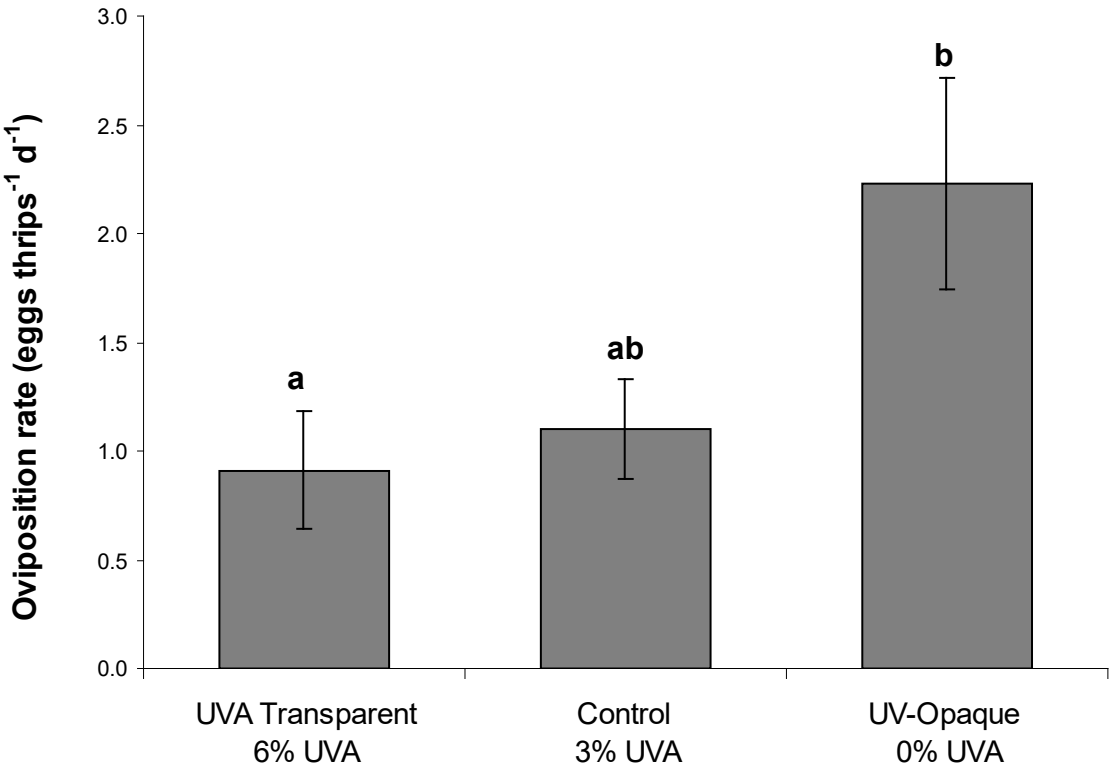


3.7.2 Effects on oviposition

The effect of spectral filters was investigated to determine whether the use of specialised filters as a glasshouse cladding might affect the rate of egg-laying and thus population increase. The results of this trial are shown in fig.3.11. There was no significant difference between the rate of oviposition under UV-Transparent and the control film (Mann-Whitney, W= 759.0, adjusted *P*=0.374 ns) nor between the control film and UV-Opaque film (Mann-Whitney, W= 711.0, adjusted *P*=0.168 ns). However, the mean oviposition rate under UV-Opaque film (2.2±0.485 eggs thrips^{-1} d^{-1}) was significantly higher than the rate under UV-transparent (0.91±0.27 eggs thrips^{-1} d^{-1}) (Mann-Whitney, W= 632.5, adjusted *P*=0.043).

This result suggests that the removal of all UVA from the light environment of a glasshouse would increase the rate of egg laying in the western flower thrips. This trial was designed as an initial experiment to investigate the effect of spectral filters on oviposition in western flower thrips and included just one replicate using a total of 83 thrips for a period of 48 h and the results should be viewed with caution. Thrips were moved from full-spectrum light to light without UVA and the observed effect on oviposition rate could be temporary. This experiment needs to be repeated with thrips kept under light without UVA for a longer period to validate this result.

Fig 3.11 The effect of spectral filters on oviposition rate of western flower thrips at constant temperature and a light regime of L16:D8. Values show mean ± SEM. Bars with the same letter did not differ significantly (adjusted $P > 0.05$) following multiple Mann-Whitney tests and Holm's procedure.



3.7.3 Effects on walking

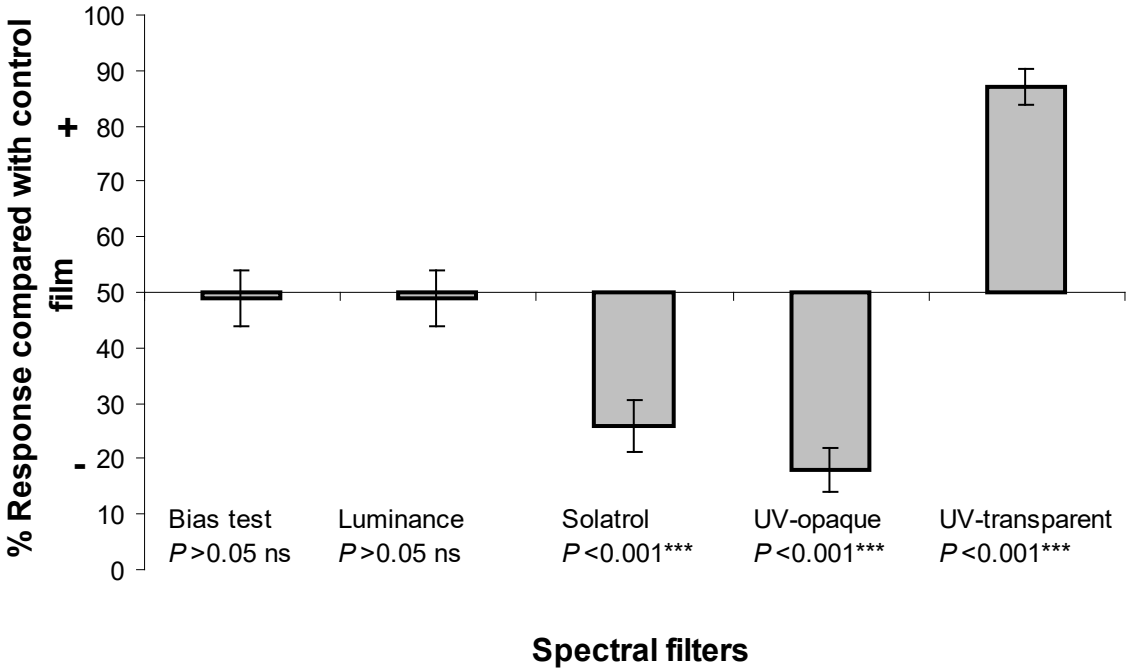
This bioassay was designed to determine whether western flower thrips could distinguish between the transmitted light from each of the four specialised spectral filters compared with the control film. If thrips were shown to be able to distinguish between the filters by walking towards or away from them, it may suggest that the use of a filter for cladding could affect their behaviour. The results of this trial are shown in fig.3.12. In the bias test and between the control and Luminance THB, there was no preference shown, with thrips walking equally to each filter (Binomial test, $P>0.05$ ns in both cases). Significantly more adult female western flower thrips, however, walked towards the control in preference to Solatrol and to UV-Opaque (Binomial test, $P<0.001$ in both cases) and significantly more thrips walked towards the UV-Transparent film than the control (Binomial test, $P<0.001$).

Both the total light intensity and the spectral composition of transmitted light varied with each filter. This is summarized in table 3.1 below:

Table 3.1 Summary of spectral properties of spectral filters used in the walking bioassay

Spectral Filter	**Visible light intensity (Wm^{-2})**	**UVA light intensity (Wm^{-2})**	**Total light intensity (Wm^{-2})**
Control	11.32	0.33	11.45
Luminance THB	9.26	0.25	9.27
Solatrol	10.12	0	10.12
UV - Opaque	8.57	0	8.57
UV - Transparent	11.38	0.71	12.09

Fig.3.12 The effect of spectral filters on the direction of walking of adult, female western flower thrips. Each test was conducted independently and consisted of a spectral filter (test) on one side of the bioassay tube and the control filter (control) at the other. The bias test had the control filter on both sides. The bars indicate the percentage of responding thrips that walked towards the test filter ± SE of proportion. Data were analysed with the binomial test.



If light intensity was the most important factor influencing thrips response then it could be expected that thrips would walk towards the control in preference to Luminance, Solatrol and UV-Opaque and towards UV-Transparent in preference to the control. This was found to be the case except for Luminance to which there was no preference shown. Total light intensity, therefore, was not controlling factor. The intensity of UVA light also varied and in order to determine the effect of UV light on walking, a bioassay was conducted using UV-Opaque against a control with full-spectral transmission. The light intensity was adjusted so that equal light intensity was transmitted through each filter. Significantly more adult female thrips walked towards the control filter with full spectrum light (binomial test, $P<0.001$). Thrips were, therefore, able to distinguish between full spectrum light and human visible light without UV and were attracted towards the full-spectrum light.

Thrips walked towards a light source with both human visible and UVA in preference to visible sources without any UVA.

Western flower thrips are able to distinguish between the transmitted light found under different spectral filters. These results support the findings of Antignus (2000, 1996, 1998) and Costa & Robb (1999, 2002, 2003) where a greater number of thrips were trapped inside polytunnels covered with standard plastic compared to polytunnels covered with UV-absorbing plastic. It has been shown, however, that take-off is not affected once under a covering of a UV-absorbing plastic and therefore the mechanism of why more thrips were trapped under full-spectrum light (standard plastics) has not yet been demonstrated. It is possible that thrips may fly towards an area with full spectrum light but equally, it is possible that the changed light quality under the spectral filters could affect the attractiveness of the traps used to monitor thrips numbers.

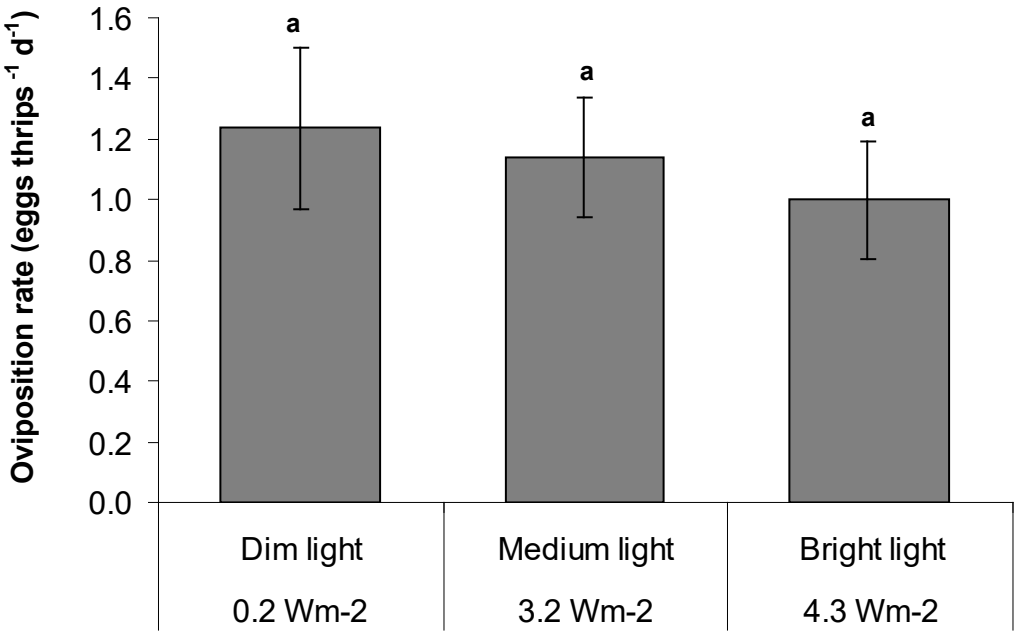
If it could be demonstrated that thrips will fly towards a UV light source as well as walking towards one, a potential use of this finding could be the use of a low intensity UV light source such as a blacklight blue fluorescent tube (e.g. Sylvania F18W BLB T8). Such a light source could be used after dark to attract thrips towards natural predators or a trap without affecting crop growth.

3.8 The effect of light intensity on oviposition

The results from this trial are shown in fig.3.13. There was no significant difference between the rates of oviposition under three light intensities: 0.17 Wm^{-2}, 3.21 Wm^{-2} and 4.27 Wm^{-2} at constant temperature (multiple Mann-Whitney, W=1133.0, adjusted *P*=1.000 ns, W=1095.5, adjusted *P*=1.000 ns and W=1193.5, adjusted *P*=1.000 ns).

These results are preliminary and show no effect of light intensity on oviposition rate over a narrow range of low light levels. To confirm that light intensity at higher levels equally has no effect on egg laying, the experiment should be repeated in a glasshouse with greater light intensity.

Fig 3.13 The effect of light intensity on oviposition rate in western flower thrips under constant temperature. Values show mean ± SEM. Bars with the same letter did not differ significantly (adjusted $P > 0.05$) following multiple Mann-Whitney tests and Holm's procedure.



3.9 General discussion

This project aimed to investigate several aspects of western flower thrips behaviour with a view to

- exploit the knowledge to improve the use of existing control measures,
- suggest new ways to manipulate thrips behaviour to enhance existing control efficacy,
- a better understanding of how protected crop management techniques may affect thrips populations

In order to enhance the efficacy of applications such as insecticide or biological pathogens, there needs to be an increased rate of contact between the insect and the control agent. This requires an increased rate of activity with the thrips moving out from the recesses of the crop and onto the leaf and flower surfaces or into the air. An increase in walking or take-off with short flights is likely to increase the contact rate with droplet applications and predators on the plant surface. More thrips in the air would allow a fumigant insecticide to work more efficiently.

Thrips take off and are in flight above the crop mostly during the day with a peak of flight activity that varies according to the weather conditions. The results presented here showed a peak of flight activity in cloudy conditions to be in the late morning, which would be the most efficient time to spray insecticide. Other workers, however, (Holmes, pers.comm., 2004) (*Mateus et al.*, 1996; Pearsall, 2002)*have* found that western flower thrips display two peaks of flight activity, in the early morning and the late afternoon. Western flower thrips flight behaviour is variable and efforts to model this activity are currently in progress (DEFRA funded project, HH3102TPC).

Any techniques used to modify thrips behaviour in the glasshouse environment must not have a negative impact on the protected crop. Light intensity above the threshold for flight had no significant affect on take-off or flight and are therefore unlikely to increase activity. Temperature did increase take-off between 20° and 30° C but raising the temperature within a glasshouse simply in order to increase flight activity may not be a practical consideration within an

integrated crop management schedule. Instead, applying the control measures at a time of high temperature as determined by the normal crop management, might increase efficacy of the control measure.

It was found that western flower thrips are attracted to a UVA light source. UVA light at a low intensity and for a short duration would have little or no effect on the crop but could stimulate take-off activity and attract western flower thrips if used after dark. It could be used either to increase flight activity before spraying or may work better as an attractant to lure thrips towards an insecticide impregnated trap or an area with natural predators. This would need field trials to evaluate effectiveness.

The use of novel crop management techniques may have negative or positive impacts on a western flower thrips infestation. The increased use of supplementary lighting and the use of brighter lights will have the effect of increasing mean light intensity inside a glasshouse. This may not have any effect, however, on either take-off activity or oviposition rate. The use of temperature integration techniques has been discussed previously and could be exploited to coincide the higher temperatures with spraying. On the negative side, very low temperatures would reduce or inhibit take-off. This might, for example, prevent the use of a UVA attractant.

Much work is in progress on the benefits of specialised spectral filters. Of the range of filters tested, none had any effect on take-off, so any techniques used to increase flight activity may not be hampered by the use of the spectral filter as a cladding. The possibility that the use of UV-absorbing filters will increase egg-laying rate in western flower thrips needs further investigation.

4 Conclusions

- Western flower thrips laid eggs mostly during daylight hours.
- Male and female adult thrips flew during daylight hours with a peak of activity around midday.
- The light intensity threshold for flight was about 34 Wm^{-2} (PAR).
- There was no significant correlation with light intensity or temperature above the flight threshold.
- At constant temperature, adult female thrips took off mostly during the photophase.
- At constant temperature, adult female thrips were able to take off in the dark.
- At constant temperature, the rate of take-off of adult female thrips increased through the day to a peak, one or two hours before scotophase.
- At constant temperature the light intensity threshold for flight was about 7 Wm^{-2}.
- The presence of UVA light was not necessary for take-off but UVA light increased take-off in the dark.
- Adult female western flower thrips walked towards light with UVA in preference to light without UVA and were able to distinguish between four spectral filters and standard control plastic.
- An increase in temperature from 20° to 30°C led to an increase in take-off.
- Thrips did not take-off at 15° C and take-off ceased at 45° C due to high mortality.
- There was no significant difference in take-off rate under the following four spectral filters: a) Luminance THB, b) UV-opaque, c) UV-transparent, d) Solatrol compared to the control standard plastic.
- Oviposition rate over 48 h increased when thrips were placed under a UV-opaque spectral filter compared with a UV-transparent filter.

Glossary

Term used	Definition
Human white light	Light visible to the human eye between 400 – 700 nm.
UVA light	Ultra-violet A light of wavelengths 315 – 380 nm.
PAR	Photosynthetically active radiation – light between 400 and 700 nm
Oviposition	The process of egg laying, in this case by an insect using an ovipositor – a piercing, tube - like organ at the tip of the abdomen.
Photophase	Light phase of a lighting regime – may or may not coincide with day time
Scotophase	Dark phase of a lighting regime – may or may not coincide with night time

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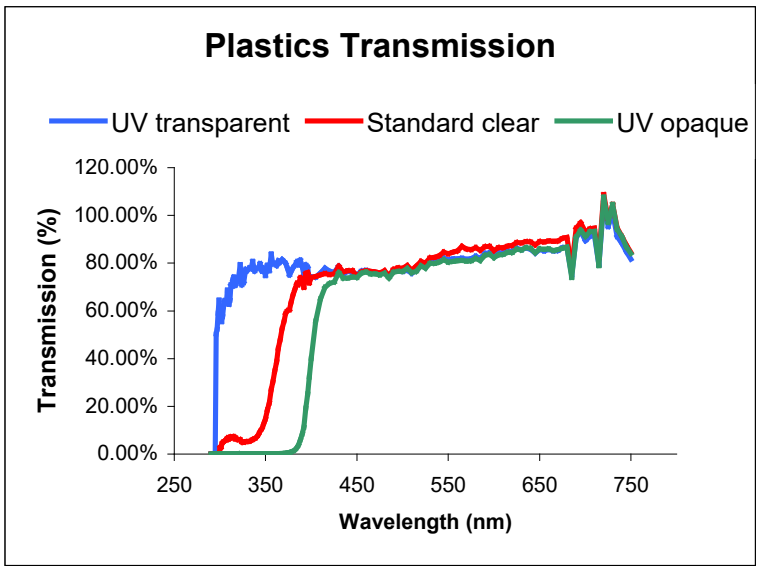
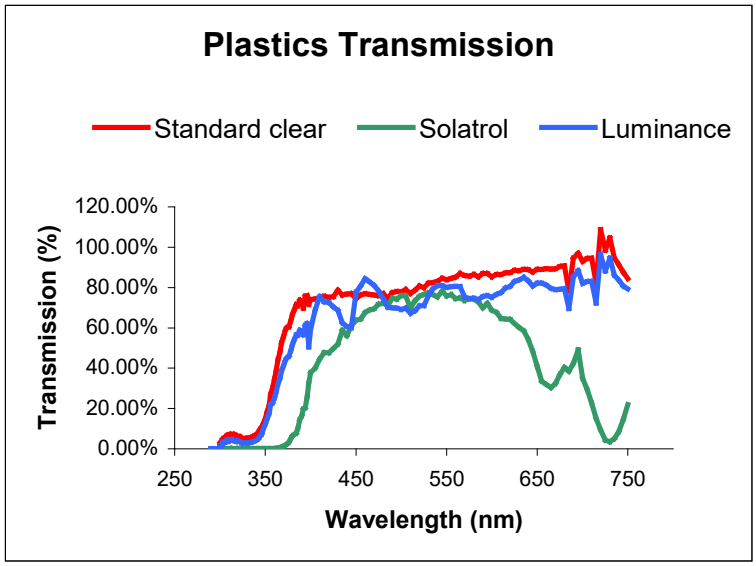
Appendix 1 – Measurement of irradiances of five spectral filters

Spectral irradiances measured within polytunnels at Stockbridge Technology Centre using two double monochromator spectroradiometers (S9910 – PC and SR9910 –V7, Macam Photometrics, Livingston, UK). (HDC Project CP 19)





Data from Dr Anna Taylor, Lancaster Environment Centre, Lancaster University and presented here with the kind permission of Dr Rob Jacobson, Stockbridge Technology Centre (CP 19)