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Industry Representative:	Alan Davis
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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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GROWER SUMMARY

Headline

The potential for LEDs to enhance the monitoring of certain pests in protected crops without any effect on biological control agents has been demonstrated and warrants further development to make the use of LEDs with sticky traps more practical within protected cropping systems.

Background

Protected crops require significant pest management inputs in many cases, particularly with edible crops where insecticide use is discouraged where possible, and the use of biological control agents (BCA) is most often undertaken (e.g. tomatoes, cucumbers, peppers). To obtain the most efficient pest management using insecticides or BCAs (or in combination) requires precise timing of application to the crop and an assessment of their effectiveness post-application, to determine whether any further applications are required.

Currently, sticky traps (often coloured) are used to detect the presence of many pests (e.g. thrips, whitefly, various aphid species, leaf miners, sciarid flies) and a decision on whether to begin application of insecticides and/or introduction of BCAs is often taken based on whether pests are being found on the traps. The efficacy of traps relies on their attractiveness to these pests, and exploits the behavioural attraction of the pests to their colour. It has been known for many years that specific colours are attractive to specific pests, such as blue for thrips, yellow for whitefly, white for sciarid flies. Recent research has indicated that traps can be made more effective through the use of light emitting diodes (LEDs) incorporated with the trap. For example, the capture of tobacco whitefly (*Bemisia tabaci*) was enhanced by 100% through the addition of a lime-green LED (530 nm wavelength) to the trap. Similarly, a 250% increase in trapping efficiency for Western flower thrips (*Frankliniella occidentalis*) was obtained on blue sticky traps that had a blue LED (465 nm wavelength) incorporated with the trap.

Various researchers have looked at the use of LEDs to enhance the efficacy of insect trapping, particularly of biting pests such as mosquitoes, but there is relatively little work on exploiting this on a commercial scale to enable growers to incorporate these traps into their IPM programmes.

This project aimed to identify the light spectra that are most attractive to a range of protected crop pests and their biological control agents; screened LEDs of specific light wavelengths that can be used with traps to enhance the attractiveness of traps to pests; and evaluated the efficacy of LED/trap combinations for their use in trapping pests under protected crop conditions with a small group of growers.

Summary

A total of six relevant species were captured in sufficient number for statistical analyses (Table 1).

Table 1. Species captured across all trial sites.

Species	Common name	Relevance to crop growing
Bradysia difformis	dark-winged fungus gnat	Pest species
Frankliniella occidentalis	western flower thrips	Pest species
Trialeurodes vaporariorum	glasshouse whitefly	Pest species
Plutella xylostella	diamondback moth	Pest species
Encarsia formosa	No common name	Biological control agent (parasitoid of whitefly)
Kleidotoma psiloides	No common name	Biological control agent (parasitoid of shorefly)

Bradysia difformis

The main findings were a significant increase in the capture rate of *B. difformis* on yellow sticky traps equipped with green (540 nm) LEDs, and a small increase on those equipped with blue (480 nm) LEDs. This increase varied between the sites.

Overall green (540 nm) was the more effective colour, with a difference of +37.5% at site 1, +23% at site 2, and +350% at site 3 (Figure 1).
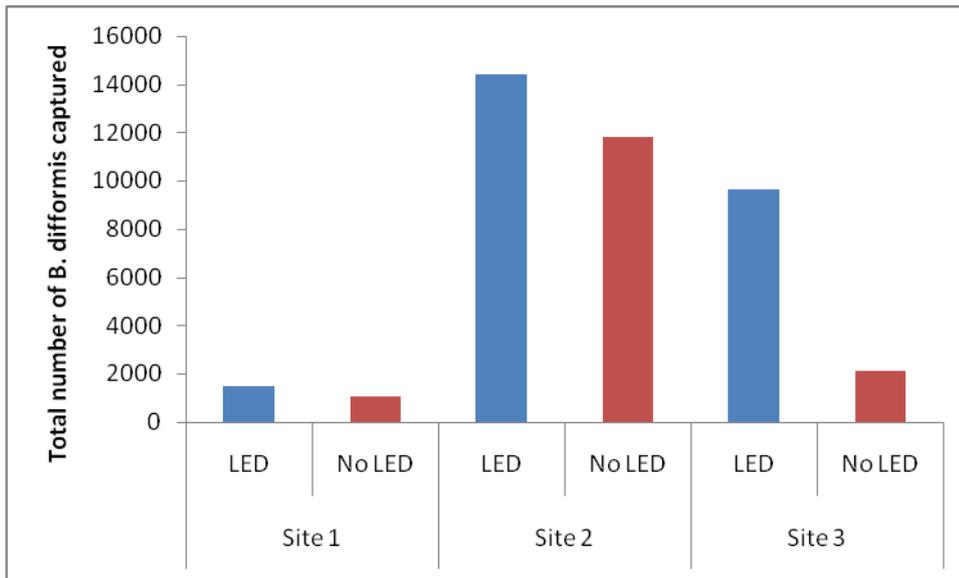
Figure 1: Total number of *B. difformis* captured on green (540 nm) LED equipped yellow sticky traps and standard yellow sticky traps at sites 1, 2 and 3 over the study period in 2012.

Frankliniella occidentalis

Laboratory behavioural experiments determined three wavelengths which may be effective for attracting this species; these are 360 nm (UV), 420 nm (violet/blue), and 480 nm (blue). When comparing yellow sticky traps to those equipped with green (540 nm) or blue (480 nm) LEDs, no significant differences were found. In the case of the blue LEDs this result is unexpected, and is likely due to the use of yellow sticky traps. Greater success may be had using blue sticky traps with the blue (480 nm) LEDs.

Trialeurodes vaporariorum

Laboratory behaviour experiments determined four wavelengths which may be effective for attracting this species; these are 320 nm (UV), 340 nm (UV), 380 nm (UV), and 480 nm (blue). Wavelengths in the green region were roughly equivalent in their level of attractiveness.

A small increase in capture rate was found in sites 5 and 7 for traps equipped with green (540 nm) LEDs, but no differences were found in comparisons using blue LEDs. The combination of the field work and behaviour experiments suggests that either green (540 nm) or blue (480 nm) are effective at increasing the attractiveness of sticky traps to *T. vaporariorum*. Although a peak in relative spectral preference was seen at 480 nm, it should be noted that this is in comparison with 520 nm, a wavelength to which *T. vaporariorum* does not appear to exhibit a strong preference.

Plutella xylostella

The main findings were a significant increase in the capture rate of *P. xylostella* at site 3 for yellow sticky traps equipped with green (540 nm) or blue (480 nm) LEDs (Figure 2). It is unusual to capture *P. xylostella* using sticky traps, and the addition of either of these LEDs makes the yellow sticky trap more viable as a monitoring method for this species.
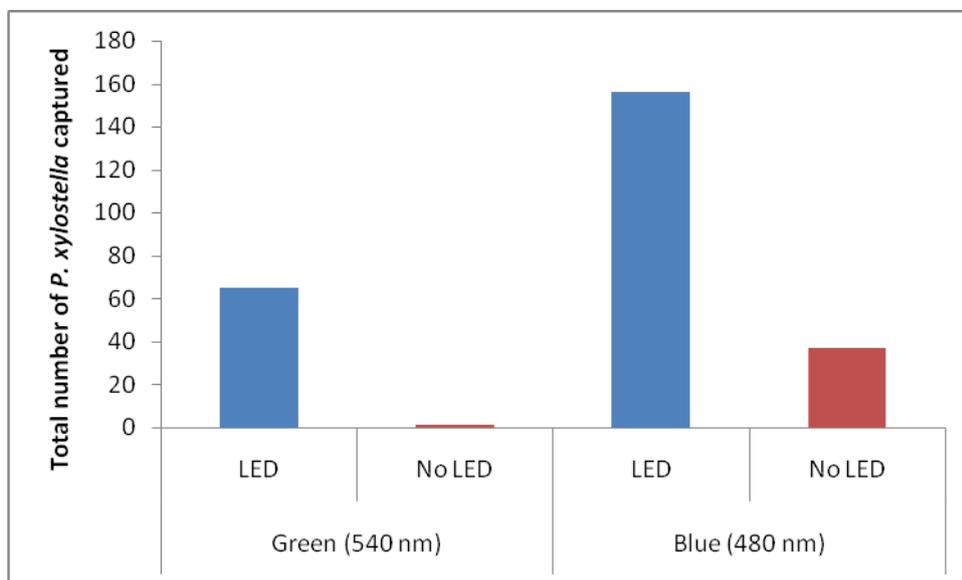

Figure 2. Total number of *P. xylostella* captured on green (540 nm) and blue (480 nm) LED equipped yellow sticky traps and standard yellow sticky traps at sites 3.

Encarsia formosa

The main findings of this study were that there were, in general, no differences in the attraction of the whitefly parasite *E. formosa* to sticky traps equipped with green (520 nm or 540 nm) LEDs and standard yellow sticky traps. A significant effect was observed in the second batch of traps from site 1, where a greater number of *E. formosa* were captured on green (540 nm) LED equipped yellow sticky traps. This result was not replicated in the other batches of traps from this site, or results from site 3 where LED equipped traps captured fewer *E. formosa.* Given these results it is clear that the addition of LEDs to yellow sticky traps, are unlikely to have a negative impact on the use of *E. formosa* as a biological control agent.

Kleidotoma psiloides

The main findings of this study were that there was a significant decrease in the number of *K. psiloides* captured on yellow sticky traps equipped with green (540 nm) LEDs (Figure 3). This indicates that the addition of green (540 nm) LEDs at sites where *K. psiloides* are naturally present, may have a positive effect on their ability to control shore fly, when compared to using standard yellow sticky traps.
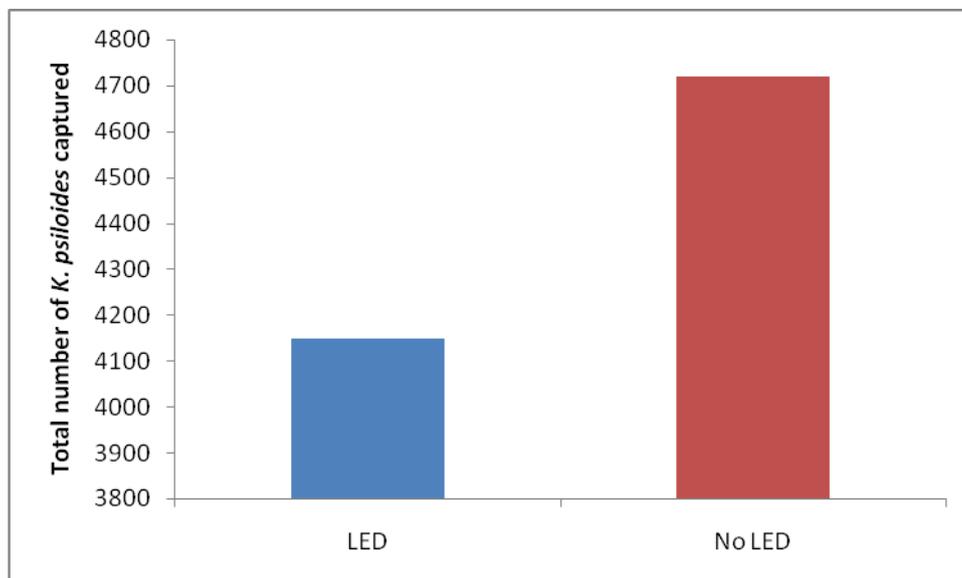

Figure 3. Total number of *K. psiloides* captured on green (540 nm) LED equipped yellow sticky traps and standard yellow sticky traps at sites 1.

Financial Benefits

LEDs are now relatively cheap (~£0.10 to £0.30 per unit, depending on wavelength and output) and have a very long life (>50,000 hours). If powered from the mains within a protected crop, the cost is estimated to be in the region of £0.08 per LED, per week, as the LEDs do not require much power to work. In the absence of mains power, LEDs can be powered by batteries, but this does increase the cost.

By using LEDs in conjunction with yellow sticky traps to enhance the monitoring and particularly the early detection of specific pests of protected crops, the improvement in timing of use of insecticides and/or release of biological control agents would be of economic benefit to the grower.

Action Points

1. Development of a simple method of attaching LEDs to yellow sticky traps, either by the grower or as a supplied product would facilitate the deployment of these traps for pest monitoring within protected cropping. The issue of power needs to be addressed – mains power is cheaper, but battery packs are possible but cumbersome and require waterproofing.

2. Individual LEDs such as the type used in this work are cheap to buy and power, and would be re-usable over several years, particularly if a simpler method of attachment/removal to/from traps can be developed.

3. The advantages of using LED enhanced traps would be evident in facilitating the improved timing of pest management within protected crops, and further testing/development is required to evaluate their role across a range of crop/pest situations, particularly where early detection and management of the pest is required.

SCIENCE SECTION

Introduction

Integrated Pest Management

Control of pest species is ordinarily required in the management of protected crops. Crop pest is a broad term encompassing arthropod pests, weeds, pathogens, and non-arthropod pests. Here the focus will be arthropod pests; these pests cause damage in numerous ways, for example via direct feeding (Moorhouse *et al.*, 1992), oviposition (Allsopp, 2010), and the spread of crop diseases, e.g. tomato spotted wilt (German *et al.*, 1992; Culbreath & Srinivasan, 2011). Currently North America and the majority of countries within northern Europe apply some form of integrated pest management (IPM) when controlling insects (Kogan, 1998; Finch and Collier, 2000; Puente *et al.,* 2011). Broadly, IPM is the co-ordination of management strategies, knowledge of pest biology and ecology (e.g. life cycle), and pest control methods. The primary goal of IPM is to maximise the benefits of chemical pesticides, while minimising any harmful side-effects (Kogan, 1998). This is particularly desirable in edible crops where the use of pesticides is discouraged (Garthwaite *et al.*, 2009). However, while social and moral concerns are of importance to crop growers within developed countries (Mzoughi, 2011), there is the additional incentive of the reduction in costs associated with the implementation of IPM. This reduction in costs can come as a result of the direct reduction in the use of pesticides; for example Filipino onion growers trained in IPM spent ~£74 less on chemical pesticides per ha than untrained growers (Yorobe *et al.*, 2011). Furthermore, by reducing the usage of chemical pesticides the potential for resistance to these chemicals is reduced, potentially averting large economic losses like those seen in Californian celery crop in the 1980's, where the leafminer *Liriomyza trifolii* developed a resistance to all available chemical pesticides, resulting in a loss of around $20 million (Reitz *et al.*, 1999). IPM can also result in an increase in net profit; experimental celery plantations (Trumble *et al.*, 1997) comparing standard chemical pesticides practices against IPM found that plantations using IPM generated net profits of $600-$1400 (~£368-£860 at the time; £540-£1264 at the time of writing) per hectare than those using standard chemical pesticide practices.

A key component of IPM is the effective monitoring of pest species. The detection of these pests is either direct, e.g. the presence of insects on traps, or indirect, e.g. damage to crops as a result of pest activity. The decisions to use chemical pesticides of biological control agents (BCA) are often based on the presence of pests within traps, the most common of which is the sticky trap. These are coloured and rely primarily on their visual attractiveness to the pest. Certain trap colours are known to be more attractive to specific pests; for example blue are typically used to attract thrips (Vernon & Gillespie, 1990), although red was demonstrated to be more successful for common blossom thrips (*Frankliniella schultzei*) (Yaku *et al.,* 2007). Yellow traps are attractive to a myriad of species; for example multiple species of whiteflies and aphids (Byrne *et al.*, 1986; Moreau & Isman, 2011). Yellow is frequently used as a general purpose trap colour, as many phytophagous insect species show a preference for yellow over other colours (Bernays & Chapman, 1994). This may be due to a super-normal foliage-type stimulus, i.e. the green wavelength (~520-570 nm), which would be expected to attract phytophagous insects, is reflected at a greater intensity by the colour yellow than by green (Prokopy & Owens, 1983). This does not fully account for this yellow preference, as a white sticky trap will also project more strongly in the green wavelength and thus would also be expected to preferentially attract phytophagous insects, which is not the case. This may be due to a colour opponent mechanism (Döring and Chittka, 2007).

Visual Cues in Host-finding

Despite the wide, and successful, use of coloured sticky traps as a method of monitoring insect pests, vision has been assumed to be of little importance in host-finding in insects when compared against chemical cues (Reeves, 2011). There are undoubtedly numerous factors behind this, but the most important are likely the assumptions that: 1. Insects have poor visual acuity, and; 2. Insects are unable to differentiate between plant species using visual cues.

Increasing the Attractiveness of Traps by Using an Active Light Source

The capture efficiency of a trap can be increased with the addition of an active light source. The Centre for Disease Control (CDC) have long used incandescent bulbs in the field to attract insect disease vectors for monitoring, although over the past

ten years they have been switching to light-emitting diode (LED) bulbs (Cohnstaedt, 2008).

This increase in capture efficiency using LEDs has been demonstrated with sticky traps; for example Chu *et al.* (2003) were able to increase the capture of *Bemisia tabaci* by 100% by equipping plastic cup traps with a lime-green (530 nm) LED. A greater increase in trap capture efficiency (250%) of *Frankliniella occidentalis* was found when equipping blue sticky traps with blue LEDs (465 nm) (Chen *et al.*, 2004), with later work by Chu *et al.* (2005) demonstrating that UV wavelengths (398 nm) are even more effective than blue (465 nm). It should be noted that these studies do not appear to have accounted for the spectral sensitivity of the subject species where it is known; for example Chen *et al.* (2004) appear to have made no use of the previously determined spectral sensitivity of *F. occidentalis* (Matteson *et al.,* 1992). Rather, with the exception of Nakamoto & Kuba (2004), previous studies appear to have either used a green LED (530 nm) (Chu *et al.*, 2003; Nombela *et al.*, 2003), perhaps to simulate the colour of plants, or used the colour previously found effective as a trap colour (Chen *et al.,* 2004).

Nakamoto & Kuba (2004) performed a preference test to determine which LED light wavelength to equip their traps with to attract the West Indian sweet potato weevil (*Euscepes postfasciatus)*. However, this relied on the simple presentation of four different light wavelengths of varying broadness. In order to more effectively determine LED colour for enhancing the capture efficiency of traps, as well as for acquiring a better understanding of why these colours are attractive to the pest species, it is important that the spectral sensitivity of these species be determined prior to preference testing.

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Properties of Light-emitting Diodes and their Advantages and Disadvantages

An LED is a semiconductor which produces light. It is composed of a silicon semiconductor chip possessing a positive side (anode) and negative side (cathode) the gap between these two sides is named the p-n junction (Figure 4). As with all semiconductors the voltage will flow in one direction, from the p-side to the n-side, it is not ordinarily possible for a reverse flow of voltage. This property creates limitations is the powering of an LED in that direct current (DC) must be used, as

with alternating current (AC) the flow of electrons will periodically reverse direction and the LED will not be powered for this period. Fortunately batteries use DC, and mains power is easily converted from AC to DC using a converter, for example a laptop charger possesses an AC-DC converter.
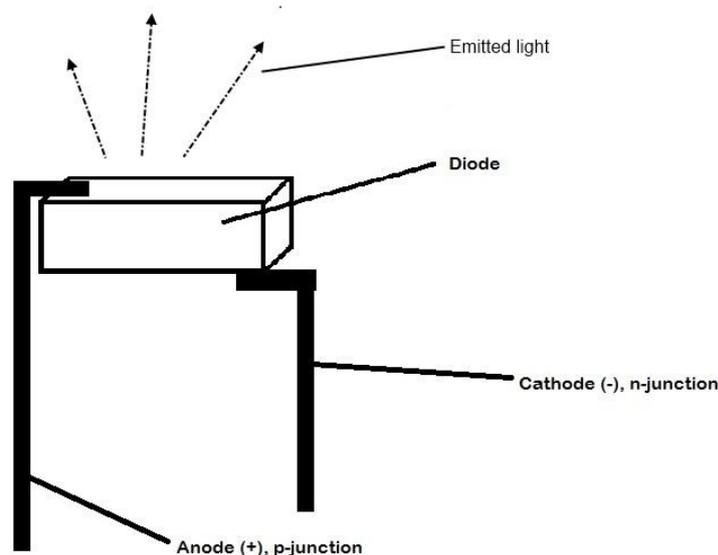

Figure 4. A simplified diagram showing the construction of an LED. The emitted light can be focused, or dispersed, using an epoxy casing.

LEDs are limited to monochromatic light output. This means that colours produced by combinations of, for example, pink, purple, or white, cannot be produced using a single die. These can be produced by either a combination of dies, for example white can be produced using a mix of red, green, and blue dies. Alternatively a phosphor coating can be placed over the die, which emits light when illuminated by the die; the combination of these light sources produces the colour, for example a blue LED with a red phosphor coating produces the appearance of purple light (Schubert, 2003; Held, 2009).

The narrow wavelength produced by LEDs is a great advantage for attracting insects for two primary reasons: 1. The absence of other light wavelengths prevents a reduction in attraction from a photonegative response to unwanted wavelengths. 2. Power is not wasted in producing unwanted wavelengths. It should be noted that it is possible that certain wavelength combinations result in a greater attraction than

monochrome light sources, if this is the case, LEDs can be combined while still maintaining these two advantages.

In terms of power consumption a standard 5mm LED uses 10-30mA, and are much more efficient than other light sources. For example, tungsten light bulbs have a luminous efficacy of 6%, with the remainder being output as heat. While there is great variance in LED luminous efficacy it would not be unusual for it to be over 15%, and a luminous efficacy of over 100% (~230%) was recently demonstrated using a non-standard LED which made use of environmental heat to increase the electrical efficiency, although this was performed at very low power level and efficiency should be expected to decrease as power level is increased (Santhanam *et al.,* 2012). A result of this combination of low power consumption and high luminous efficacy is that current LEDs produce far less heat, than other light sources, as a higher percentage of a smaller amount of power is used to produce light. In the case of the LED used by Santhanam *et al.* (2012) heat is absorbed. The advantage of this in a crop growing environment is that LEDs can be placed close to a plant than currently used light sources, which enables a much more compact growing environment as well as intercrop lighting.

Although LEDs consume very little power, they have a forward voltage which ranges from 1.5v to 3.4V. As a general rule the longer the wavelength the lower the forward voltage required, so a UV LED may have a forward voltage of 3.4v compared with 1.8v for a red LED. The forward voltage is the minimum voltage required to light up the LED. This creates difficulties when having to power LEDs without access to mains power, as high voltage batteries typically suffer from low capacity. The capacity of an alkaline 9v battery is around 500mAh, which would power a 20ma LED continuously for a period of 25hours (500mAh/20ma=25hrs). Conversely an alkaline D cell battery has a capacity of around 12,000-20,000mAh and a voltage output of 1.5v (Note: capacities are estimates as manufacturers no longer publish full battery specifications). Because of the relatively high forward voltage requirements of LED, in order to power an LED using D cell batteries, multiple batteries must be arranged in series to combine their voltages. This means that a minimum of three D cell batteries are required to power a single green (540nm, 3.2v forward voltage) LED. In situations where more than one LED must be powered by

a single source it is possible to wire the LEDs so that they all benefit from the full voltage of the power source (as illustrated in Figure 5); this applies to any number of LEDs, so very large numbers of LEDs can be powered from a single battery pack, although each LED will draw an additional 10-30ma and the power source will expire sooner. If a rechargeable power source is desired, it is preferable to use AA batteries instead of D cell, as although these have a much lower capacity (~500-1000mAh) they suffer far less from voltage drop, i.e. the reduction in voltage as the battery power depletes.
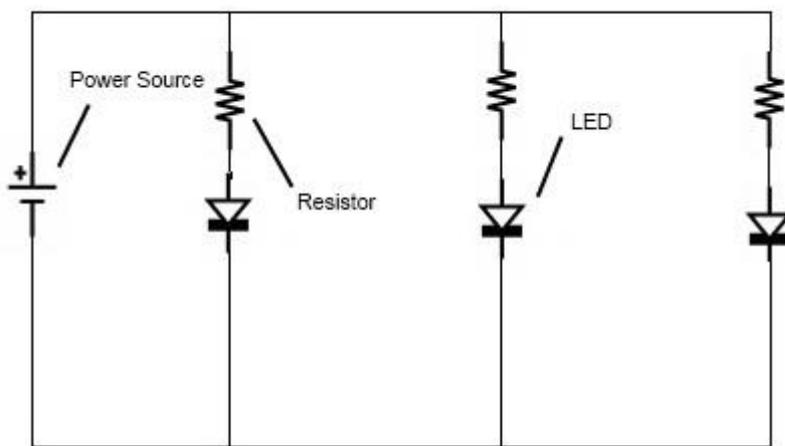

Figure 5. Circuit diagram demonstrating how to wire multiple LEDs to a power source which only produces enough voltage to drive a single LED. Here each LED is directly wired to the power source, so receives the full voltage.

LEDs are solid state, which is to say they are built of solid materials and have no moving parts. This gives them a high degree of durability. They also possess a very long half-life of around 11 years, so will theoretically lose only half of their brightness after this time period.

Properties of light and colour vision

Introduction to light

The nature of light is complicated by exhibiting the properties of both waves and particles. For convenience sake light will generally be treated as part of the electromagnetic spectrum within this report, except when measuring the brightness of light, where particles are more appropriate. As part of the electromagnetic spectrum light can be described as a wave, which has a wavelength (λ), a

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frequency, and an electrical and magnetic field, both of which are described by a vector. Light can be graphically represented using a sine wave, with the amplitude representing the magnitude of the electrical vector, and the distance between the wave crests, or troughs, the wavelength. If the velocity which the waves vibrate is increased the distance between the wave crests shortens, giving a shorter wavelength and a higher frequency. This relationship is described easily by the following formula: $V = \lambda . V$, where v is velocity, λ is wavelength, and v is frequency (Tilley, 2000). The magnetic vector will not be relevant to this project.

Refraction and dispersion

When light changes medium the direction of the wave is changed; this is termed refraction. The angle of refraction is determined by a number of factors, for example the velocity of light within that material, or the material density. Of relevance to this project is the effect termed 'dispersion'; this describes a relationship between the refraction of light and wavelength. Generally the index of refraction will increase as wavelength decreases, so blue light will refract at a greater angle than green, or red (Tilley, 2000). This is relevant to the calibration of the behaviour experiments to determine relative spectral preference, and it should be clear from this that although the number of particles in the centre of the chamber will be equal, inequality will exist between all other equal distances.

Colour vision

There are two types of photoreceptor, rods and cones. The cones are further subdivided: in the human eye these are divided into three classes termed red, green, and blue, although it would be more accurate to describe these as short, medium, and long wavelength receptors, for reasons that will become apparent. The rods have a lower response threshold so are more sensitive to light, and are used for low-light vision. The cones, while less sensitive to light, allow for the perception of colour by a comparison between the light wavelengths detected by the cones. The mechanism for this comparison is not fully understood and there are two current mechanisms proposed, these are the colour opponent mechanism and the complimentary colour theory (Lotto *et al.,* 2010; Pridmore, 2009 respectively).

Sensitivity to a broad range of wavelengths in no way implies the ability to see in colour. Within the human eye the rods posses a peak sensitivity around 500-510 nm (Lotto *et al.,* 2010); however, without additional receptors to compare against, the discrimination of colour is not possible, and only the intensity of the light is detected. As such vision at night time is represented in grey scale and two objects of the exact size and shape, but of different colours, will be indistinguishable from one another if they reflect light at the same intensity. It is for this reason that the naming of the cone photoreceptors in the human eye would be more accurately named after a length than a colour, as the wavelength in and of itself does not possess the attributes of a colour; rather, colour is a cognitive property (Skorupski & Chittka, 2009). Knowing this it becomes apparent that the simple detection of a light wavelength does not imply that the subject possesses colour vision. The species of insect being investigated in this project have not all been confirmed to possess colour vision.

While the healthy human eye is credited with being able to detect wavelengths between 380-400 nm (the colour violet) and 700-780 nm (the colour red), the wavelength detection abilities of insects varies from species to species (Arikawa *et al.* 1987; Briscoe & Chittka, 2001). Commonly three photoreceptors are present in insect eyes; these are typically located within the UVA, blue, and green wavelengths, although some species have red receptors. It is important to understand that this indicates that a colour perceived to be yellow to a human will not be yellow to an insect: for example the flower *Chrysanthemum coronarium* is yellow when viewed by a human, and green when viewed by a bee (FreD, 2011).

Health implication of artificial light sources

When using light to attract crop pests it is often the case that hazard to the human eye are not considered; for example Mutwiwa and Tantau (2005) experimented with the use of a UV lamp to attract the greenhouse whitefly (*Trialeurodes vaporiorum*), and made no mention of concerns of the irreversible damage that may be caused by exposure to UV light. This is concerning considering that the damaging effects of UV light are widely known.

Blue light is also known to cause damage to the eyes, with the photo-oxidative damage blue light causes being associated with the causation of age-related macular degeneration (Barker *et al.,* 2011; Kernt *et al.,* 2012). In some respects this is of greater concern as much less blue light is filtered by the lens when compared with UV, particularly in younger individuals.

Sources of blue light can be categorised into four different risk groups as defined by the European standard EN 62471 (Table 2). These exposure limits were determined by experiments involving monkeys and rabbits. These were exposure to light until a white lesion was observed on the retina, the amount of exposure to cause this was than multiplied by a safety factor of ten (Behar-Cohen, 2011).

Table 2. Risk groups which sources of blue light are classified under by EN 62471.

Maximum admissible exposure time (t)	Risk group
t ≥ 10,000s	Group 0
11s ≤ t 10,000s	Group 1 (low risk)
0.25s ≤ t < 100s	Group 2 (moderate risk)
T< 0.25s	Group 3 (high risk)

Behar-Cohen (2011) determined that a blue LED with an output of 0.07W would belong to group 1, and thus represent a low risk. As the blue LEDs used in this project do not exceed 0.01W these will likely be classified as group 0 and present very little risk. However, the potential for damage from these light sources should be considered as the potential for LED brightness increases with advancing technologies.

Aims and Objectives

There are two main experimental components.

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Relative attractiveness of light wavelengths

The relative attractiveness of light wavelengths to the subject insect species were determined using a simple choice test (Figure 6). The subjects were introduced into the centre of a tube, at either end of which is a light source. The source of light was filtered to a narrow wavelength using bandpass filters, one of which remained the same wavelength as a control. The amount of light (mmol) in the middle of the tube was equal. The subjects were left in the tube for 30 seconds, their choice, i.e. the wavelength they move towards, was considered their preference.
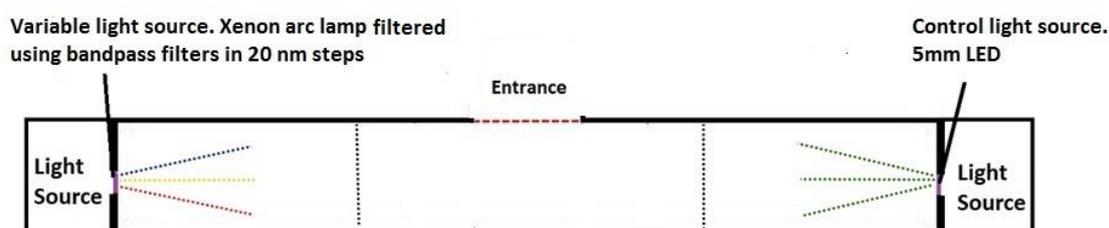

Figure 6. Chamber for choice test.

Effective sticky trap LED wavelength combinations

Using the information gained from the choice test outlined above, or the literature, the capture efficiency of sticky traps with and without LED attachments were compared. Comparisons were between the capture efficiency of the traps, i.e. total number of insects per species captured. Study sites were located around the UK (primarily in South England). Sticky traps were returned via post in order for the captured insects to be identified.

Materials and methods

Comparison of LED and standard yellow sticky traps

Yellow sticky traps equipped with LED attachments were compared against those without (Figure 7). LED attachments consisted of LEDs fixed into terminal blocks attached to curling clips. These were powered by either four D cell batteries or via a 9V ac/dc mains adaptor depending on the site. In sites which operate overhead irrigation or misting, battery packs were suspended within plastic containers (Figure 8), a silica satchel was included to reduce humidity.
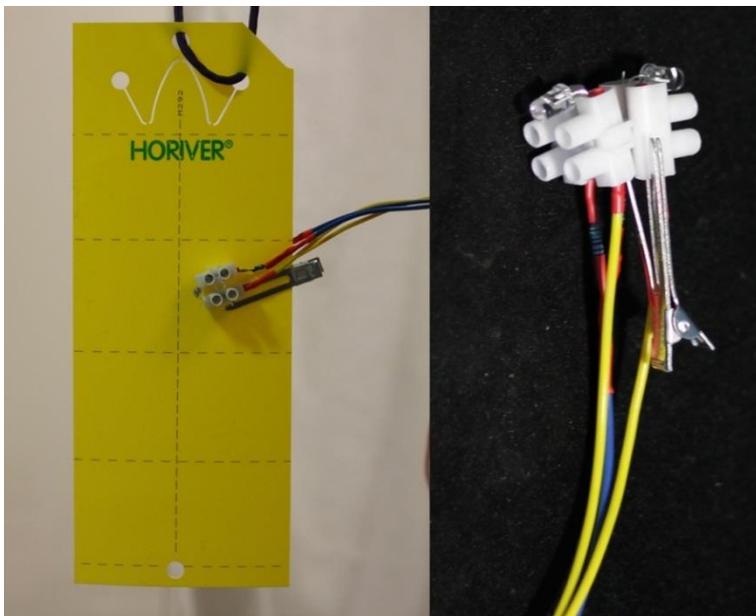

Figure 7. LED attachment.

Figure 8. Water resistant battery pack container.

Site 1

09/08/2012 – 23/08/2012

Yellow sticky traps were equipped with a single green LED (Avago Technologies, 5mm, 540 nm, 30° angle, power output 6.1mW) powered by battery packs. Experimental design was a randomised block design with 21 LED, and 21 standard (without LED) traps. One half of the trap was exposed for a week, this was then re-covered and the other half was exposed. Each half will be discussed as a separate batch (Table 3). The crop was poinsettia, and was grown on benches.

There were further batches in addition to these, but due to corrosion of the battery packs data from later dates are unreliable and will not be included here.

Table 3. Batch numbers and dates for comparison between green (540 nm) LEDs and standard yellow sticky traps at site 1.

Batch number	Batch 1	Batch 2
Batch date	09/08/12 – 16/08/12	16/08/12 – 23/08/12

12/09/2013 – 02/10/2013

Yellow sticky traps were equipped with a single blue LED (CREE, 5mm, 480 nm, 30° angle, power output 10.4mW) powered by battery packs contained within plastic enclosures. Experimental design was a paired treatment design with 10 replicates. One half of the trap was exposed for a week, this was then re-covered and the other half was exposed. Each half will be discussed as a separate batch (Table 4). The crops was poinsettia, and was grown on benches.

Table 4. Batch numbers and dates for comparison between traps equipped with blue (480 nm) LEDs and standard yellow sticky traps at site 1.

Batch number	Batch 1	Batch 2	Batch 3
Batch date	12/09/13–19/09/13	19/09/13–26/09/13	26/09/13–02/10/13

Site 2
29/10/2013 – 26/11/2013

Yellow sticky traps were each equipped with a single green LED (Avago Technologies, 5mm, 540 nm, 30° angle, power output 6.1mW) powered by battery packs. Experimental design was a paired treatment design with 17 replicates. One half of the trap was exposed for a week, this was then recovered and the other half was exposed. Traps were changed weekly (Table 5). Crops were a wide variety of herbs which are cycled e.g. basil, chive, and thyme, and were grown on benches.

Table 5. Batch numbers and dates for comparison between traps equipped with green (540 nm) LEDs and standard yellow sticky traps at site 2.

Batch number	1	2	3	4	5	6	7	8
Batch date	01/10/12	08/10/12	15/10/12	22/10/12	29/10/12	05/11/12	12/11/12	19/11/12

Site 3

11/10/2012 – 11/12/2012

Yellow sticky traps were each equipped with a single green LED (Avago Technologies, 5mm, 540 nm, 30° angle, power output 6.1mW) powered by battery packs. Experimental design was a paired treatment design with replicates differing with each batch as crops were sold or moved between locations on site. Traps were changed after differing time periods which were related to these same processes (Table 6). The crops were poinsettia on capillary matting covered by perforated plastic sheet. This site scales down their operations as crops are sold, so the number of traps decreases over time.

Table 6. Batch numbers, dates and number of replicates for comparison between traps equipped with green (540 nm) LEDs and standard yellow sticky traps at site 3.

Batch number	Batch 1	Batch 2	Batch 3
Batch date	11/10/12-08/11/12	08/11/12–22/11/12	22/11/12–04/12/12
Time (days)	28	14	12
Replicates	12	10	8

13/09/2013 – 15/11/2013

Yellow sticky traps were each equipped with a single green LED (Avago Technologies, 5mm, 540 nm, 30° angle, power output 6.1mW) powered by battery packs. Experimental design was a paired treatment design with replicates differing with each batch as crops were sold or moved between locations on site. Traps were

changed after differing time periods which were related to these same processes (Table 7). The crop was poinsettia on capillary matting covered by perforated plastic sheet. This site scales down their operations as crops are sold, so the number of traps decreases over time.

Table 7. Batch numbers, dates and number of replicates for comparison between traps equipped with blue (480 nm) LEDs and standard yellow sticky traps at site 3.

Batch number	1	2	3	4	5	6	7
Batch date	02/09/13-09/09/13	09/09/13-16/09/13	13/09/13-20/09/13	20/09/13-05/10/13	Unknown	01/11/13-08/11/13	08/11/13-15/11/13
Time (days)	7	7	7	15	N/A	7	7
Replicates	8	6	6	7	N/A	7	7

Site 5

LED attachments at this site were constructed to allow the LED to be changed without replacing the entire device.

21/08/2013 – 02/10/2013

Yellow sticky traps were each equipped with a single green LED (Multicomp, 5mm, 520 nm, 30° angle, luminous intensity 13cd) powered by battery packs. Experimental design was a paired treatment design with 6 replicates. Traps were changed every 2 weeks (Table 8). The plants were grown on benches.

Table 8. Batch numbers and dates for comparison between traps equipped with green (520 nm) LEDs and standard yellow sticky traps at site 5.

Batch number	1	2	3
Batch date	21/08/13-04/09/13	04/09/13-18/09/13	18/09/13-02/10/13

02/10/2013 – 31/10/2013

Existing LEDs were replaced with a single blue LED (CREE, 5mm, 480 nm, 30° angle, power output 10.4mW). Experimental design was a paired treatment design with 6 replicates. Traps were changed every 2 weeks (Table 9). The plants were grown on benches.

Table 9. Batch numbers and dates for comparison between traps equipped with blue (480 nm) LEDs and standard yellow sticky traps at site 5.

Batch number	1	2	3
Batch date	02/10/1 16/10/13	16/10/13-31/10/13	31/10/13-04/11/13

Site 7

10/04/2013 – 27/04/2013

A mass release experiment was conducted at this site for the whitefly biological control *Encarsia formosa*. Yellow sticky traps were each equipped with a green LED (Avago Technologies, 5mm, 540 nm, 30° angle, power output 10.4mW) on each side of the trap powered by a 9V ac/dc mains adaptor. Experimental design was a paired treatment design with 6 replicates. Thirty cardboard strips, each with around thirty attached *E. formosa* pupae (Koppert Biological Systems, EN-STRIP), were suspended within the glasshouse on the 10th, and 17th May. Totalling around 1600 *E. formosa* over the study period.

Statistical methods for LED and standard yellow sticky trap comparisons

General statistical methods

Normality and homogeneity were tested using Shapiro-Wilk and Levenes tests respectively. Comparisons between trap capture rate were tested using either One-Way ANOVAs or Kruskal-Wallis H test. Where possible non-normal data were transformed to log10 to satisfy the assumptions of normality required for ANOVAs. Where transformations were performed any data point which was a 0, was changed to 1. Where Log10 data are used for analyses, actual data are presented in

graphical form. For comparisons across the study period, data were combined. All tests were conducted with 95% confidence (Dytham, 2011).

Site 1: statistical methods

Table 10. Species captured at site 1

Species	Common name	Relevance to crop growing
Bradysia difformis	dark-winged fungus gnat	Pest species
Frankliniella occidentalis	western flower thrips	Pest species
Trialeurodes vaporariorum	glasshouse whitefly	Pest species
Encarsia formosa	No common name	Biological control agent (parasitoid of whitefly)
Kleidotoma psiloides	No common name	Biological control agent (parasitoid of shorefly)

Bradysia difformis: *Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (09/08/12 – 23/08/12).*

The data from both batches and the combined data were non-normal in distribution. These data were transformed to Log10 to satisfy the assumption of normality required for ANOVAs. Comparisons were performed using One-way ANOVAs.

Frankliniella occidentalis: *Comparison of traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (09/08/12–23/08/12).*

The data from both batches and the combined data were non-normal in distribution. Comparisons were conducted using Mann-Whitney U tests.

Trialeurodes vaporariorum: *Comparison of yellow sticky traps equipped with* **blue** *(480 nm) LEDs and standard yellow sticky traps (12/09/13-03/10/13).*

The data from batch 3 were of a normal distribution. Batch 1, batch 2, and the combined data were non-normal in distribution, and were transformed to Log10 to

satisfy the assumption of normality required for ANOVAs. Comparisons were performed using One-Way ANOVAs.

Encarsia formosa: *Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (09/08/12-23/08/12).*

The data from both batches and the combined data were non-normal in distribution. Comparisons were performed using Mann-Whitney U tests.

Kleidotoma psiloides: *Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (09/08/12-23/08/12).*

The data from both batches and the combined data were non-normal in distribution. These data were transformed to Log10 to satisfy the assumption of normality required for ANOVAs. Comparisons were performed using One-way ANOVAs.

Site 2: statistical methods

Table 11. Species captured at site 2

Species	Common name	Relevance to crop growing
Bradysia difformis	dark-winged fungus gnat	Pest species

Bradysia difformis: *Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (01/10/12-26/11/12).*

The data from batch 6 were of a non-normal distribution, and were transformed to Log10 to satisfy to assumption of normality required for ANOVAs. The remaining batches were normal in distribution. Comparisons were performed using One-Way ANOVAs. The combined data from the project duration were non-normal in distribution, and the comparison was performed using a Mann-Whitney U test.

Site 3: statistical methods

Table 12. Species captured at site 3.

Species	Common name	Relevance to crop growing
Bradysia difformis	dark-winged fungus gnat	Pest species
Frankliniella occidentalis	western flower thrips	Pest species
Plutella xylostella	diamondback moth	Pest species

Bradysia difformis*: Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (11/10/12-04/12/12).*

The data from batches 1 and 3 were of normal distribution. The data from batch 2 were of non-normal distribution, and were transformed to Log10 to satisfy to assumption of normality required for ANOVAs. The combined data from the project duration were non-normal in distribution, and the comparison was performed using a Mann-Whitney U test.

Bradysia difformis*: Comparison of yellow sticky traps equipped with* **blue** *(480 nm) LEDs and standard yellow sticky traps (02/09/13-08/11/13).*

The data from batches 1, 2, and 3 were normal in distribution. Batches 4 and 6 were non-normal, and were transformed to Log10 to satisfy to assumption of normality required for ANOVAs. A comparison of the combined data could not be performed, as this site varied in the length of time each batch of traps were used, with batch 4 being used for 15 days and the remaining batches used for 7 days.

Frankliniella occidentalis*: Comparison of yellow sticky traps equipped with* **blue** *(480 nm) LEDs and standard yellow sticky traps (02/09/13-08/11/13).*

The data from all four batches were normal in distribution. Comparisons were performed using One-Way ANOVAs.

A comparison of the combined data could not be performed, as this site varied in the length of time each batch of traps were used, with batch 4 being used for 15 days and the remaining batches used for 7 days.

Plutella xylostella*: Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (02/09/13-08/11/13).*

The data from batches 1 and 2 were non-normal in distribution. The comparisons were performed using a Mann-Whitney U test. The combined data from the project duration were non-normal in distribution, and the comparison was performed using a Mann-Whitney U test.

Plutella xylostella*: Comparison of yellow sticky traps equipped with* **blue** *(480 nm) LEDs and standard yellow sticky traps (02/09/13-20/09/13).*

The number of *P. xylostella* captured was too low to reliably test for normality. The data were treated as non-normal and comparisons were performed using Mann-Whitney U tests.

Site 5: statistical methods

Table 13. Species captured at site 5.

Species	Common name	Relevance to crop growing
Frankliniella occidentalis	western flower thrips	Pest species
Trialeurodes vaporariorum	glasshouse whitefly	Pest species
Encarsia formosa	No common name	Biological control agent (parasitoid of whitefly)

Frankliniella occidentalis*: Comparison of yellow sticky traps equipped with* **green** *(520 nm) LEDs and standard yellow sticky traps (21/08/13-02/10/13).*

The data from batches one and two were of a normal distribution. Batch 1 and the combined data were non-normal in distribution, and were transformed to Log10 to satisfy to assumption of normality required for ANOVAs. Comparisons were performed using One-Way ANOVAs.

Frankliniella occidentalis*: Comparison of yellow sticky traps equipped with* **blue** *(480 nm) LEDs and standard yellow sticky traps (21/08/13-02/10/13).*

The data from all three batches were of a normal distribution. The combined data were non-normal in distribution, and were transformed to Log10 to satisfy to assumption of normality required for ANOVAs. Comparisons were performed using One-Way ANOVAs.

Trialeurodes vaporariorum: *Comparison of yellow sticky traps equipped with* **green** *(520 nm) LEDs and standard yellow sticky traps (12/09/13-03/10/13).*

The data from all three batches were of a normal distribution. The combined data were non-normal in distribution, and were transformed to Log10 to satisfy to assumption of normality required for ANOVAs. Comparisons were performed using One-Way ANOVAs.

Trialeurodes vaporariorum: *Comparison of yellow sticky traps equipped with* **blue** *(480 nm) LEDs and standard yellow sticky traps (12/09/13-03/10/13).*

The data from batches 1 and 3 were of a normal distribution. Batch 2 and the combined data were non-normal in distribution, and were transformed to Log10 to satisfy the assumption of normality required for ANOVAs. Comparisons were performed using One-Way ANOVAs.

Encarsia formosa: *Comparison of yellow sticky traps equipped with* **green** *(480 nm) LEDs and standard yellow sticky traps (21/08/13-04/09/13).*

The number of *E. formosa* captured was too low to reliably test for normality. The data were treated as non-normal and comparisons were performed using Mann-Whitney U tests.

Site 7: statistical methods

Table 14. Species captured at site 7.

Species	Common name	Relevance to crop growing
Trialeurodes vaporariorum	glasshouse whitefly	Pest species
Encarsia formosa	No common name	Biological control agent (parasitoid of whitefly)

Trialeurodes vaporariorum: *Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (10/04/13-27/04/13).*

The data from both batches and the combined data were non-normal in distribution. Comparisons were performed using Mann-Whitney U tests.

Encarsia formosa: *Comparison of yellow sticky traps equipped with* **green** *(540 nm) LEDs and standard yellow sticky traps (10/04/13-27/04/13).*

The data from batches 1 and 2 were normal in distribution; the comparisons were performed using a One-way ANOVA.

Maintenance of study species for choice tests

Frankliniella occidentalis

Frankliniella occidentalis (obtained from Clare Sampson, Keele University) were reared on chrysanthemums in plastic enclosures in an insectary maintained at 20±1°C. Florescent lighting was operated on a 16/8h light/dark cycle.

Trialeurodes vaporariorum

Trialeurodes vaporariorum were captured in a nearby glasshouse and maintained on moneymaker tomato plants and cucumber within a mesh enclosure in an insectary maintained at 20±1°C. Fluorescent lighting was operated on a 16/8h light/dark cycle.

Relative spectral preference of insects

Relative spectral preference was measured by placing an individual within a linear clear plastic tube contained within a wooden box, which had a source of monochromatic light at either end (Figure 6). At one end a control light wavelength was produced via an LED, a wavelength the subject species was determined to be sensitive to via electroretinogram (from the scientific literature) was used. The other end of the test chamber (Figure 6) was illuminated by a test wavelength produced by a 100 W xenon arc lamp (Osram XBO100W/2 OFR) housed in a Xe-100 lamp housing device (UV- Gröbel, Ettlingen, Germany) filtered through band pass filters in 20nm steps and transferred by a liquid light guide. Wavelengths differed depending on the subject species. The power of the test wavelength was measured using a photodiode (Thor Labs, S120VC attached to a PM100USB compact console), this

was converted to photon flux, and the photon flux of the control wavelength was adjusted using an iris (Thor Labs, ID8 – Post-mounted iris diaphragm).

The plastic tube was 20mm long with an internal diameter of 5mm (Figure 6), and was marked into three equal sections. The subject was introduced to the centre of the tube through a hole in the top of the tube which was then sealed using a plastic square. After a period of time (differing by species) had passed the segment of the tube the subject was located in was recorded and considered to be their choice. Individuals which had not moved from the centre segment were not included in the statistical analysis. A maximum of 10 data points were collected for each wavelength. Statistical analyses were performed using Fisher's exact test.
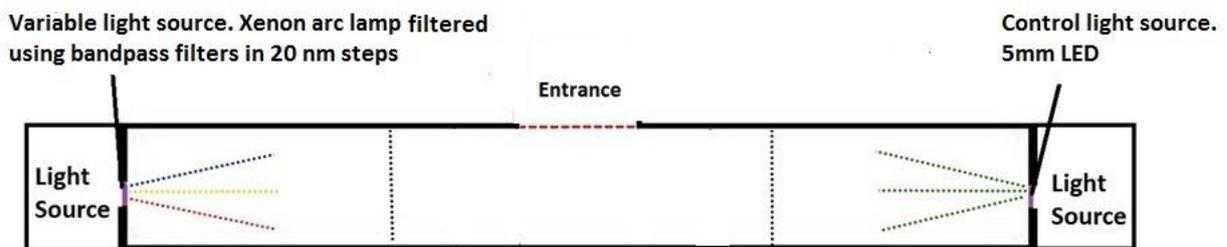
Figure 6. Choice chamber.

Frankliniella occidentalis

Subjects were placed into a 5mm internal diameter tube. The control light source was a green LED (Avango Technologies, 5mm, 540 nm, 30° angle, power output 10.4mW). The control wavelength of 540 nm was selected as *F. occidentalis* had a relatively high sensitivity to this wavelength (Matterson *et al.* 1992). The test wavelengths were in 20 nm steps between 340-620 nm.

Trialeurodes vaporariorum

Subjects were placed into a 5mm internal diameter tube. The control light source was a green LED (Multicomp, 5mm, 520 nm, 30° angle, luminous intensity 13cd). The control wavelength of 520 nm was selected as *T. vaporariorum* had a relatively

high sensitivity to this wavelength (Mellor *et al.*, 1997). The test wavelengths were in 20 nm steps between 320-620 nm.

Results

Comparison of LED and standard yellow sticky traps

Bradysia difformis

Site 1

Bradysia difformis using **green** (540 nm) LEDs (09/08/12-23/08/12)

LED traps captured significantly more *B. difformis* in batches 1 ($F_{1,40}$ = 4.138, P=0.049) and 2 ($F_{1,40}$ = 12.045, P=0.001). In batch 1 LED traps captured a median (Q1, Q3) of 39 (31, 57) and standard traps captured 33 (25, 41), an 18.18% difference (Figure 9). In batch 2 LED traps captured 25 (15, 32) and standard traps captured 14 (11, 17), a 78.57% difference (Figure 10). LED traps captured significantly more *B. difformis* across the study period ($F_{1,81}$ = 8.938, P=0.004), with LED traps capturing 31.5 (24.25, 39) and standard traps capturing 23.5 (14.25, 33), a 34% difference (Figure 11).
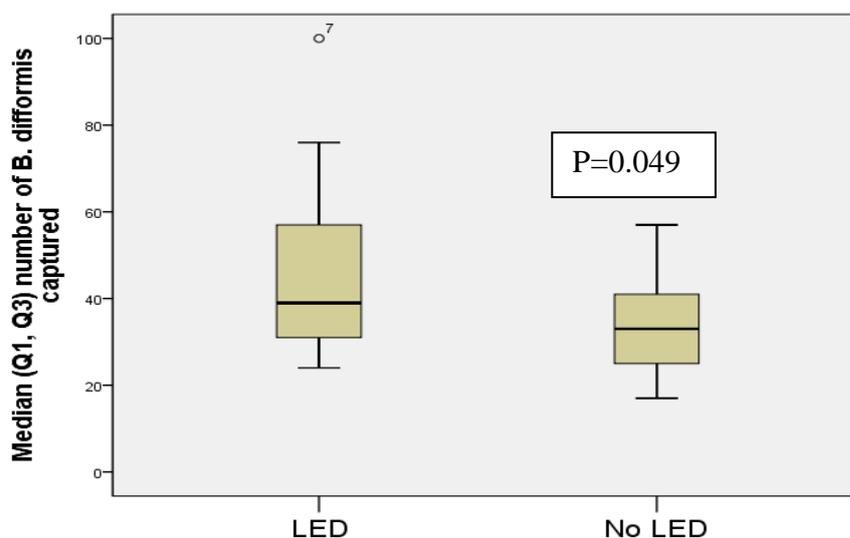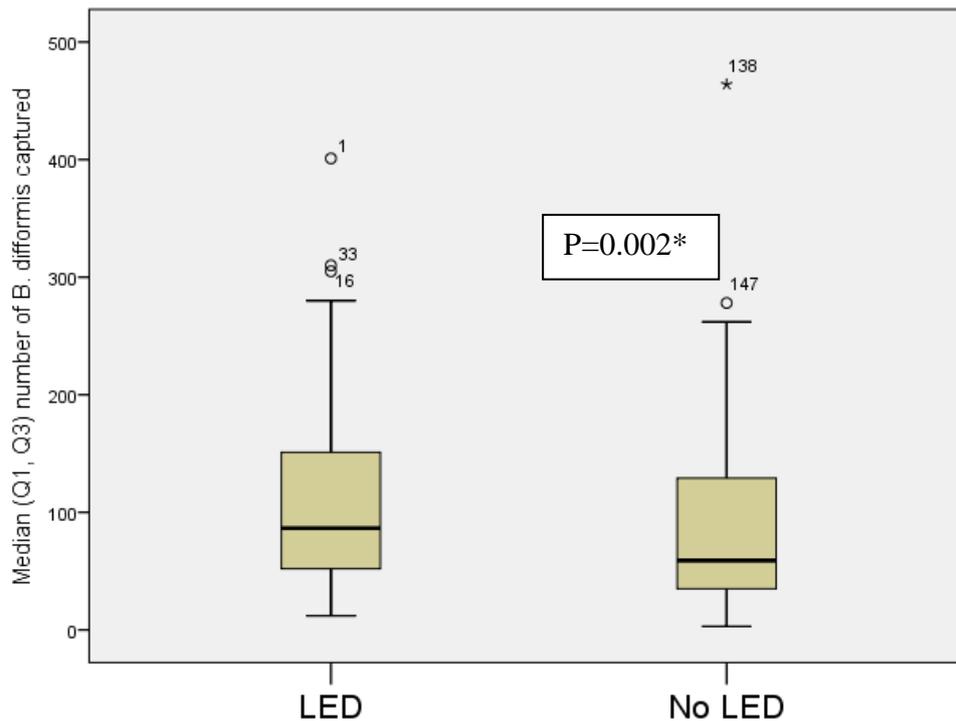

Figure 9. Median, interquartile range, and 95% confidence intervals of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps in batch 1 (09/08/12-16/08/12). *significant at 0.05.
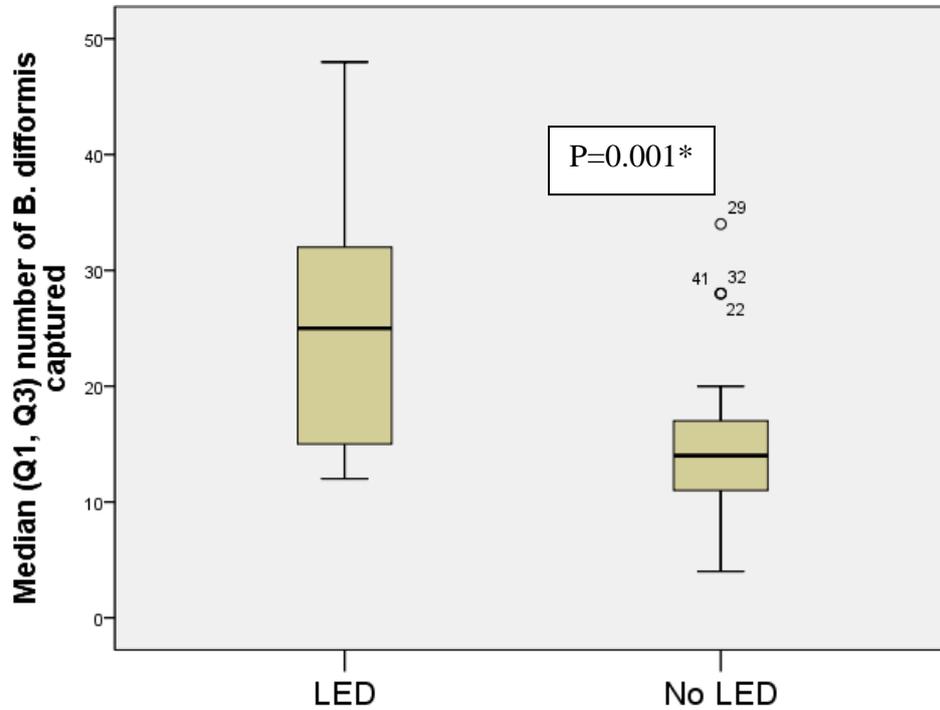
Figure 10. Median, interquartile range, and 95% confidence intervals of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps in batch 2 (16/08/12-23/08/12). *significant at 0.05.
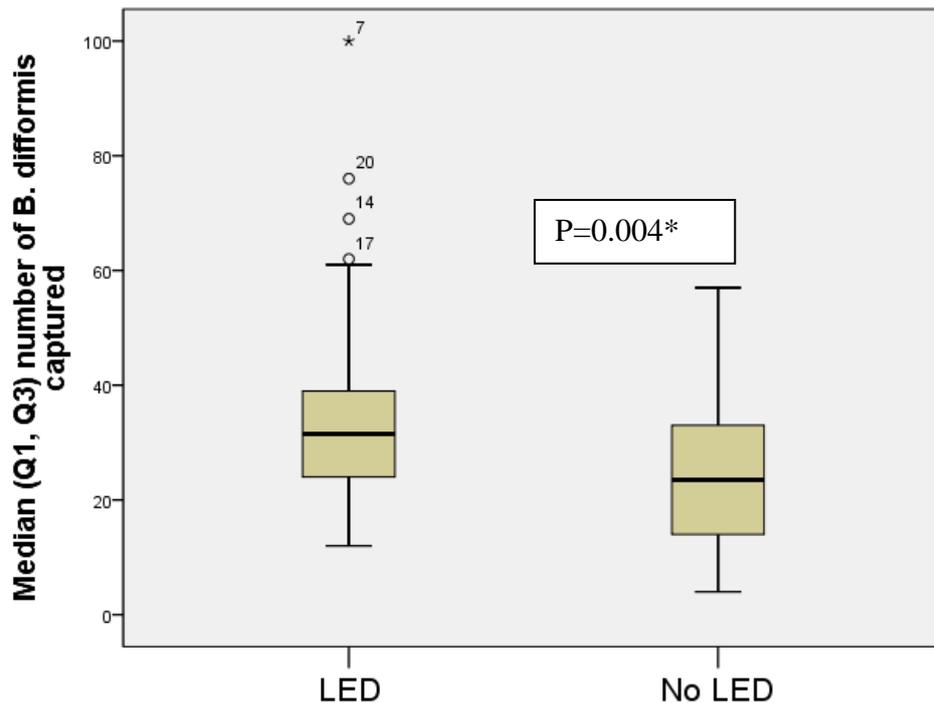
Figure 11. Median, interquartile range, and 95% confidence intervals of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps across study period (09/08/12-23/08/12). *significant at 0.05.

Site 2

Bradysia difformis using **green** (540 nm) LEDs (01/10/12-26/11/12)

LED traps captured significantly more *B. difformis* in batches 3, 7, and 8. In batch 3 LED traps captured a mean (± SE) of 122.24 (± 13.31) and standard traps captured 83.76 (± 10.15), a 45.94% difference. In batch 7 LED traps captured 61.12 (± 8.09) and standard traps captured 37.65 (± 5.21), a 62.34% difference. In batch 8 LED traps captured 62.53 (± 6.41) and standard traps captured 38.88 (± 8.95), a 60.83% difference. No significant differences were found in the remaining batches (Table 15, Figure 12).

LED traps captured significantly more *B. difformis* than standard traps across the entire study period (U = 7233, Z = -3.106 P=0.002) with a median (Q1, Q3) capture of 86.5 (52, 149.5) and 59 (35, 129) respectively, a 46.61% difference (Figure 13).

**Table 15.** Weekly analysis comparing the number of B. difformis captured by green (540 nm) LED and standard yellow sticky traps. *significant at 0.05.

Batch number	1	2	3	4	5	6	7	8
Batch date	01/10/12	08/10/12	15/10/12	22/10/12	29/10/12	05/11/12	12/11/12	19/11/12
P value	0.785	0.376	0.028*	0.703	0.403	0.087	0.021*	0.039*
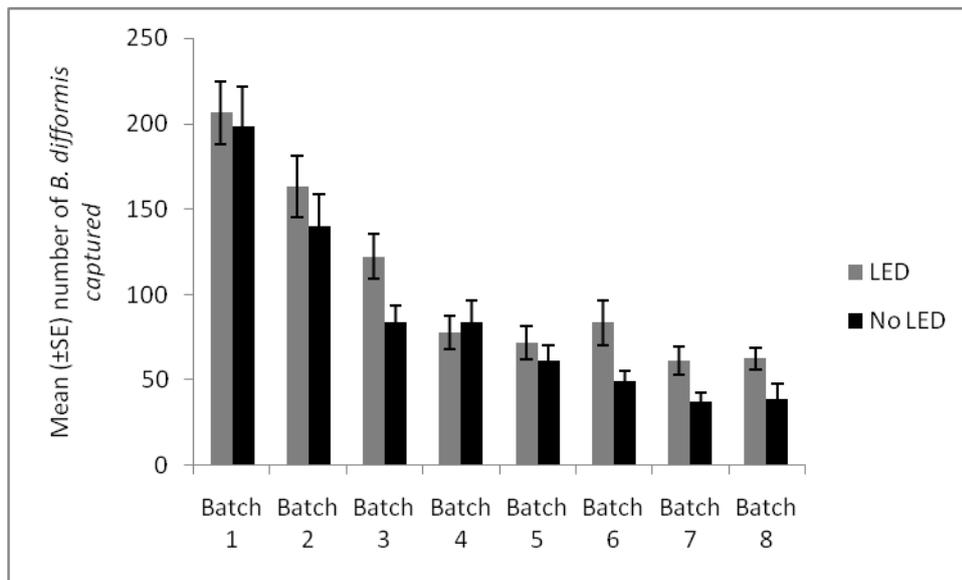
Figure 12. Mean (± SE) number of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps.
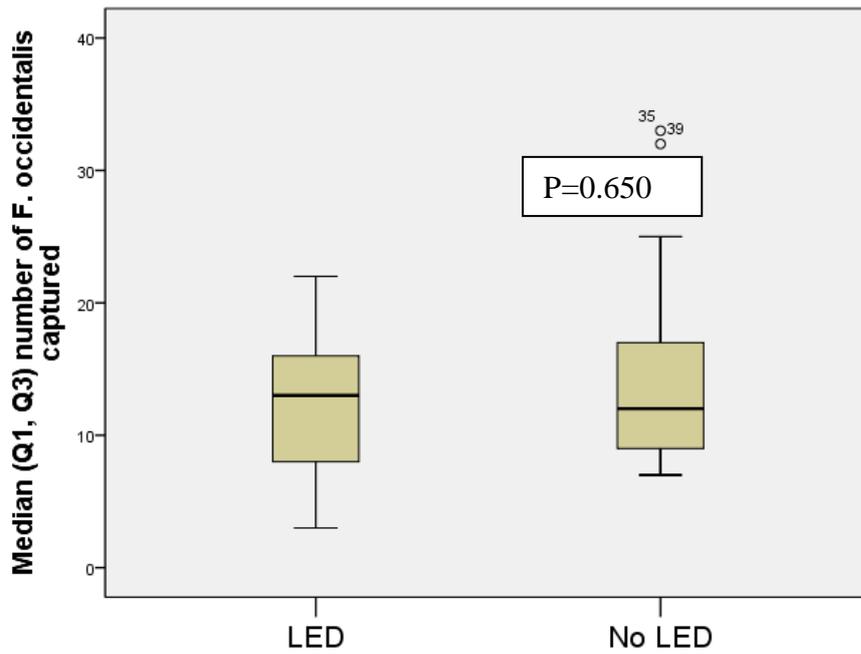
Figure 13. Median, interquartile range, and 95% confidence intervals of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps across study period (01/10/12-26/11/12). *significant at 0.05.

Site 3

Bradysia difformis using **green** (540 nm) LEDs (11/10/12 – 04/12/12)

Significantly more *B. difformis* were captured by LED traps in batch 1 ($F_{1,22}$ = 66.080, $P<0.001$), with a mean (± SE) of 790.67 (± 70.07) captured by LED traps and 170.17 (± 30.28) on standard yellow sticky traps, a difference of 364.64%. No significant differences were found in batches 2 ($P=0.169$) or 3 ($P=0.184$) (Figure 14). No significant difference was found over the complete study period ($P=0.281$) (Figure 15).
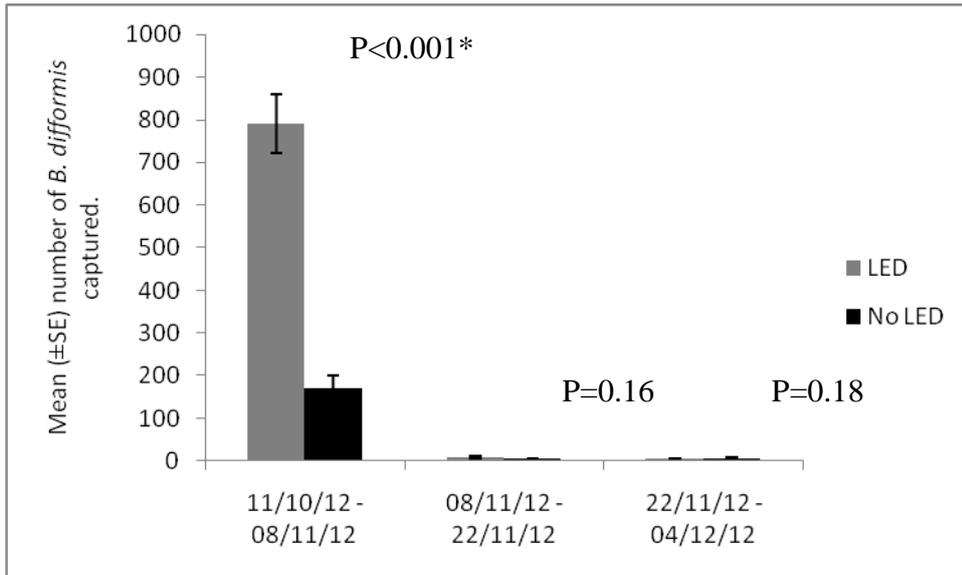
Figure 14. Mean (±SE) number of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps. *significant at 0.05.
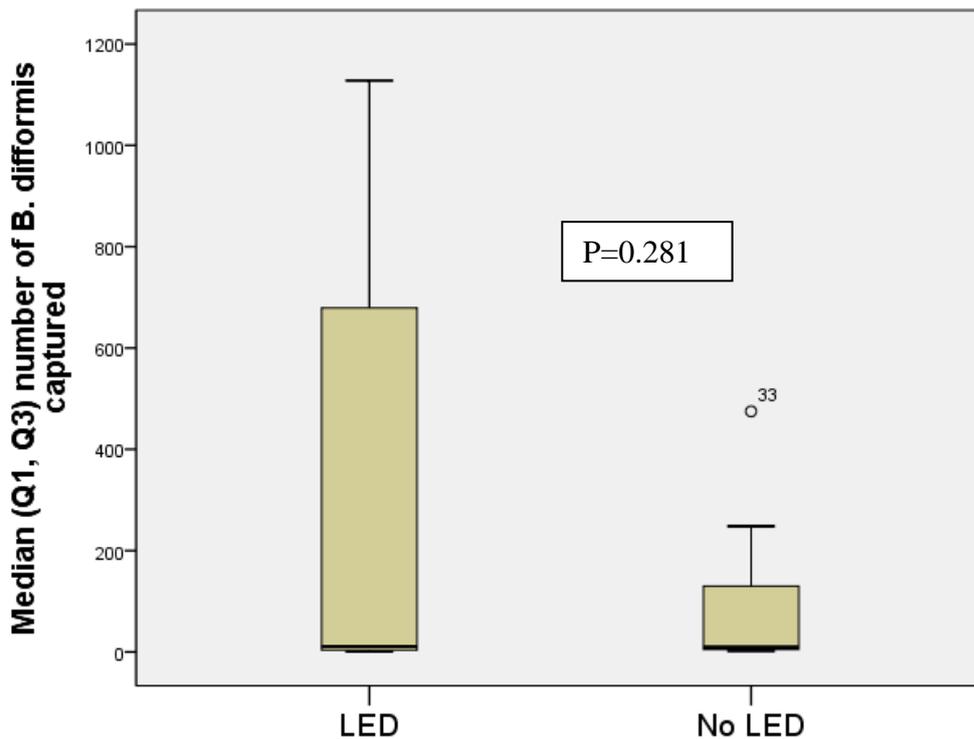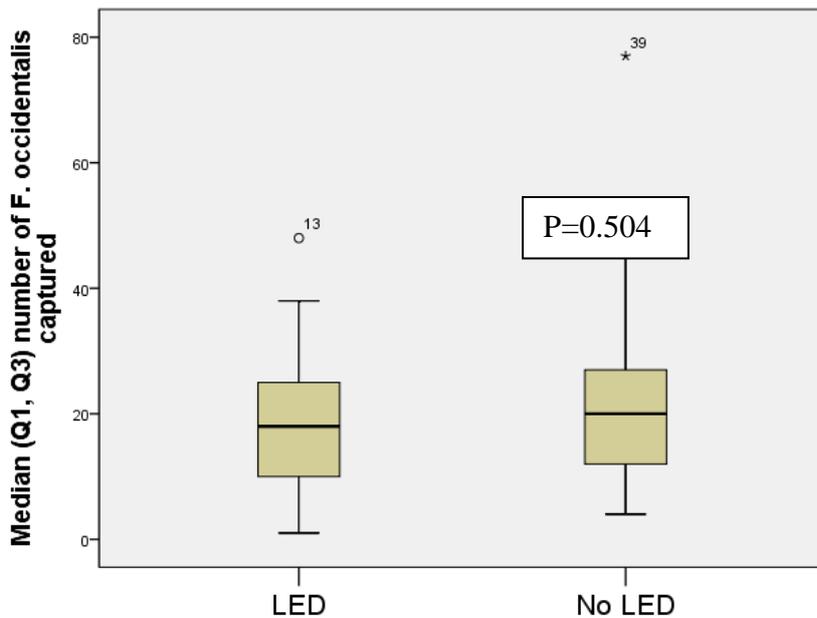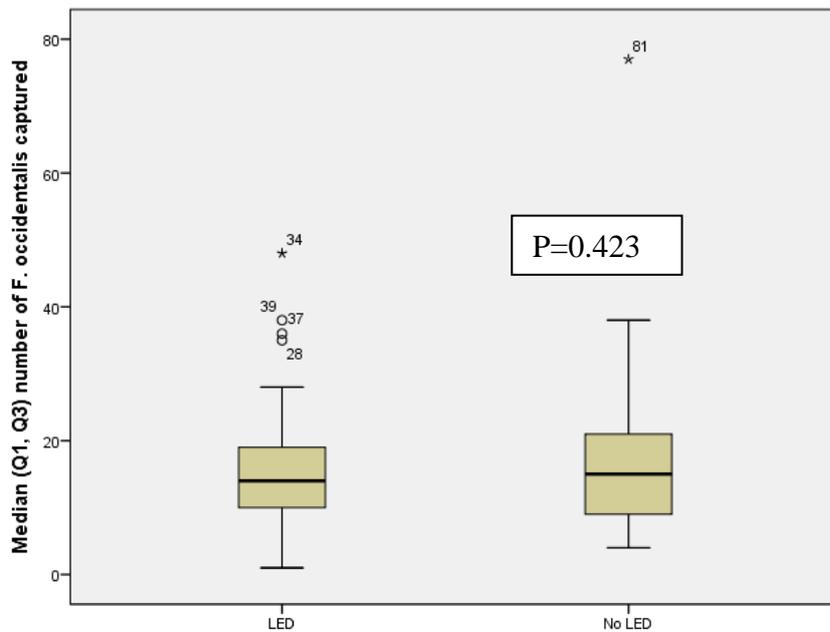

Figure 15. Median, interquartile range, and 95% confidence intervals of *B. difformis* captured on green (540 nm) LED and standard yellow sticky traps across study period (11/10/12-04/12/12). *significant at 0.05.

Bradysia difformis using **blue** (480 nm) LEDs (02/09/13-08/11/13)

LED traps captured significantly more *B. difformis* in batches 4 and 6. In batch 4 LED traps captured a median (Q1, Q3) of 28 (24.5, 66) and standard traps captured 16 (11.5, 26.5), a 75% difference. In batch 6 LED traps captured 4 (3, 10.5) and standard traps captured 1 (0, 1) (Figure 16).
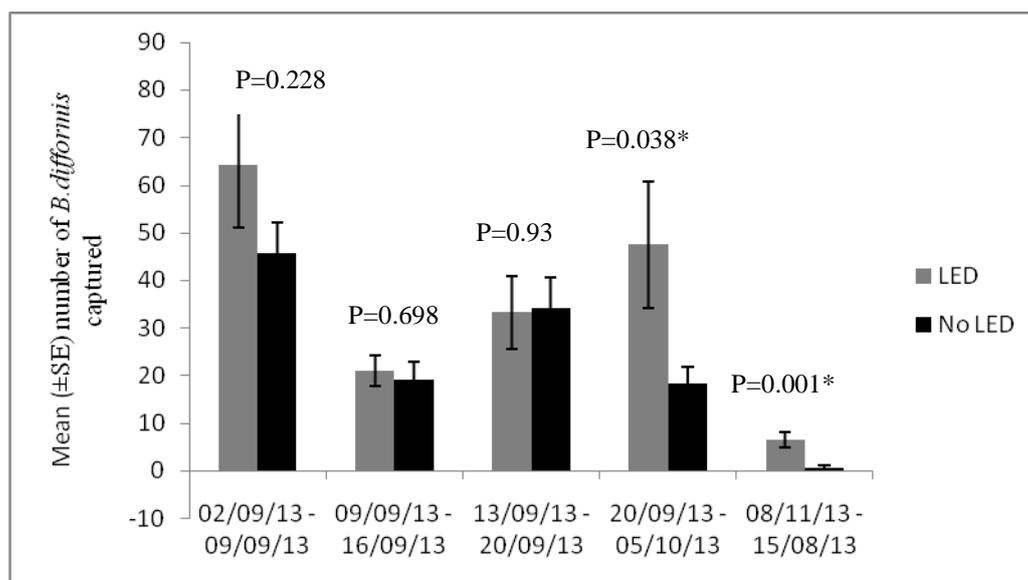
Figure 16. Mean (±SE) number of *B. difformis* captured on blue (480 nm) LED and standard yellow sticky traps. *significant at 0.05.

Frankliniella occidentalis

Site 1

Frankliniella occidentalis using **green** (540 nm) LEDs (09/08/12-23/08/12)

There were no significant differences in the capture rate in batches 1 (P=0.650) (Figure 17) or 2 (P=0.504) (Figure 18). No significant differences were found in capture rate across the study period (P=0.423) (Figure 19).

Figure 17. Median, interquartile range, and 95% confidence intervals of *F. occidentalis* captured on green (540 nm) LED and standard yellow sticky traps in batch 1 (09/08/12-16/08/12).

Figure 18. Median, interquartile range, and 95% confidence intervals of *F. occidentalis* captured on green (540 nm) LED and standard yellow sticky traps in batch 2 (16/08/12-23/08/12).


Figure 19. Median, interquartile range, and 95% confidence intervals of *F. occidentalis* captured on green (540 nm) LED and standard yellow sticky traps across study period (09/08/12-23/08/12).

Site 3

Frankliniella occidentalis using **blue** (480 nm) LEDs (02/09/13-05/10/13)

No significant differences were found between LED traps and standard yellow sticky traps for batches one to four (Figure 20).
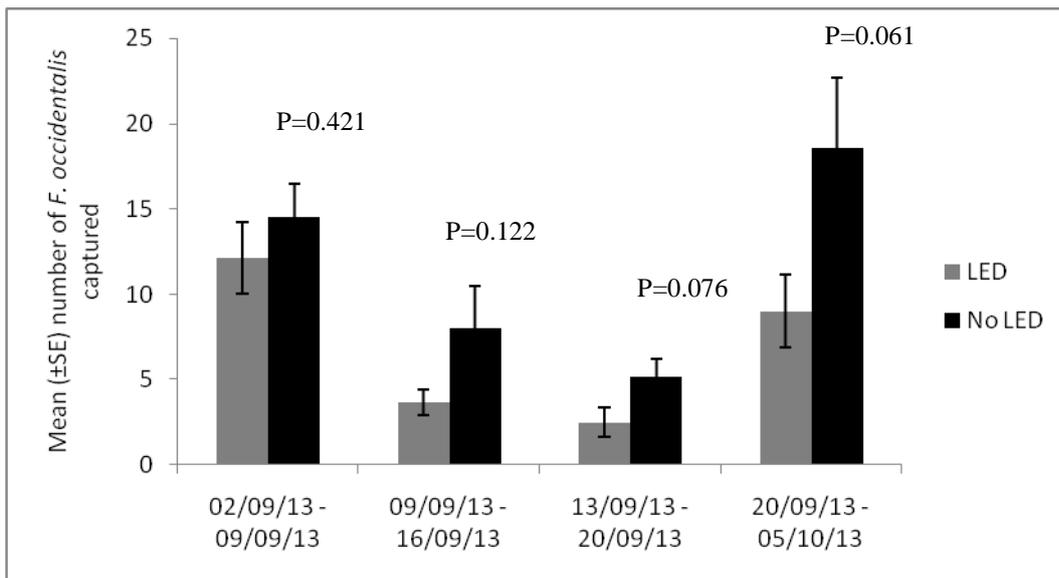
Figure 20. Mean (±SE) number of *F. occidentalis* captured on blue (480 nm) LED and standard yellow sticky traps.

Site 5

Frankliniella occidentalis using **green** (520 nm) LEDs (21/08/13-02/10/13)

There were no significant differences in the capture rate of *F. occidentalis* between the trap types in any of the individual batches (Figure 21). No significant difference was found between the trap types across the entire trapping period (P=0.697) (Figure 22).
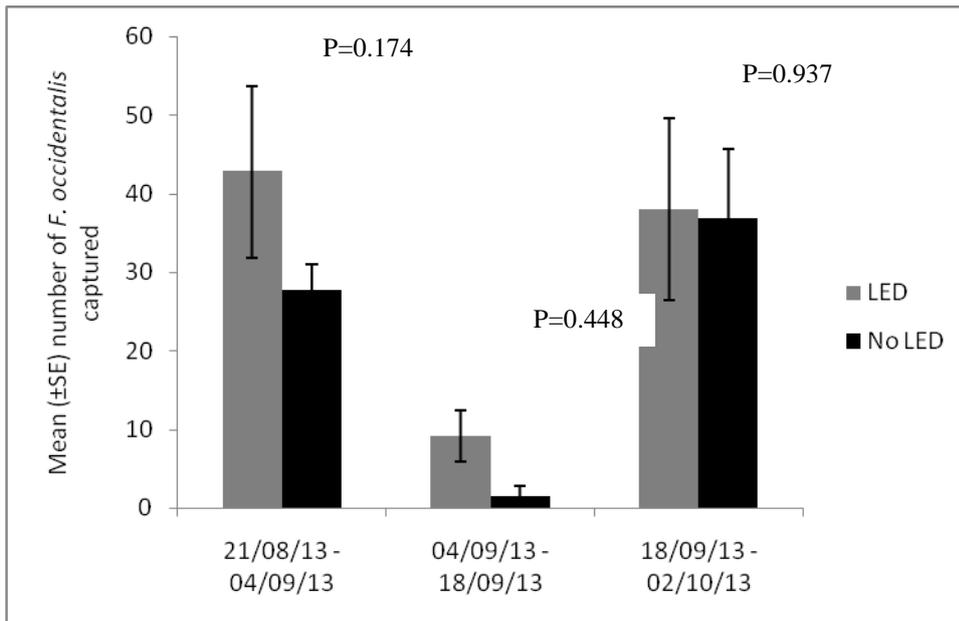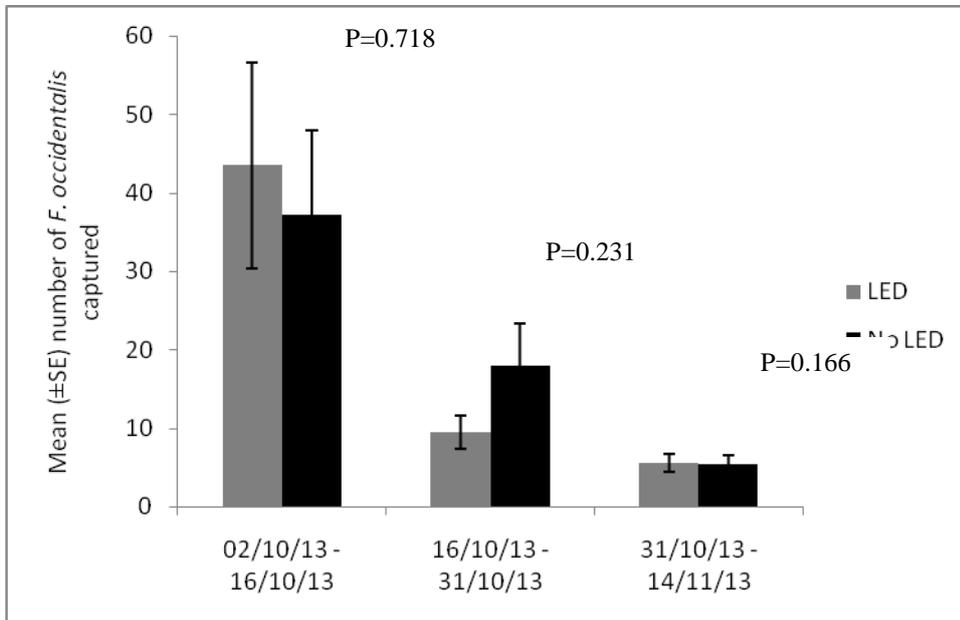
Figure 21. Mean (±SE) number of *F. occidentalis* captured on green (520 nm) LED and standard yellow sticky traps.
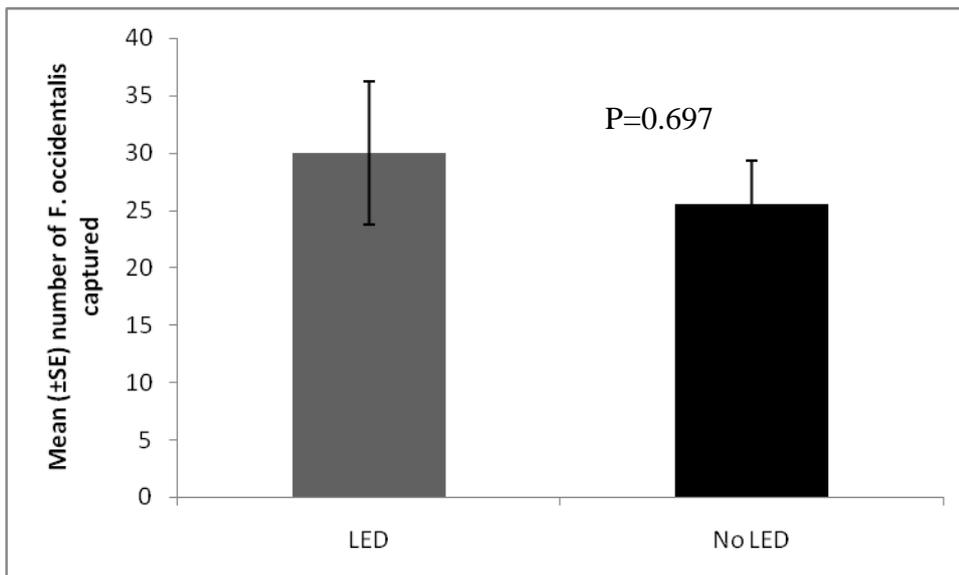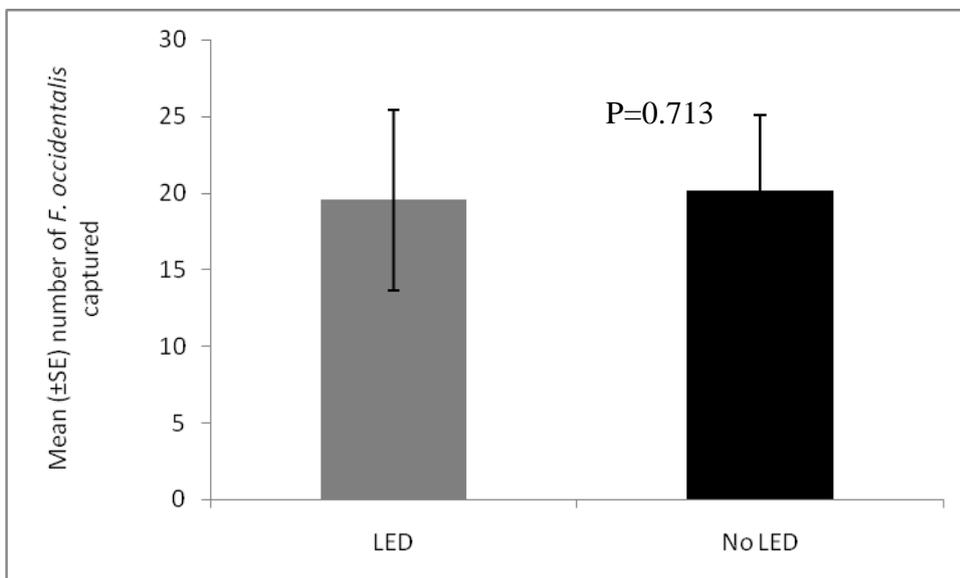

Figure 22. Mean (±SE) number of *F. occidentalis* captured on green (520 nm) LED and standard yellow sticky traps across study period (21/08/13-02/10/13).

Frankliniella occidentalis using **blue** (480 nm) LEDs (02/10/13-14/11/13)

There were no significant differences in the capture rate of *F. occidentalis* between the trap types in any of the individual batches (Figure 23). No significant difference

was found between the trap types across the entire trapping period (P=0.713) (Figure 24).

Figure 23. Mean (±SE) number of *F. occidentalis* captured on blue (480 nm) LED and standard yellow sticky traps.

Figure 24. Mean (±SE) number of *F. occidentalis* captured on blue (480 nm) LED and standard yellow sticky traps across study period (21/08/13-02/10/13).

Trialeurodes vaporariorum

Site 1

Trialeurodes vaporariorum using **blue** (480 nm) LEDs (12/09/13–03/10/13)

There were no significant differences in the capture rate of *T. vaporariorum* between the trap types in batch 1 (P=0.053) (Figure 25), batch 2 (P=0.219) (Figure 26), or batch 3 (P=0.792) (Figure 27). There was a small but significant difference in capture rate across the entire study period ($F_{1, 58}$ = 4.002, P=0.05). LED traps captured a median (Q1, Q3) of 53 (35.25, 89.25), significantly fewer whitefly than standard traps which captured 82.5 (46.5, 104.25), a 55.66% difference (Figure 28).
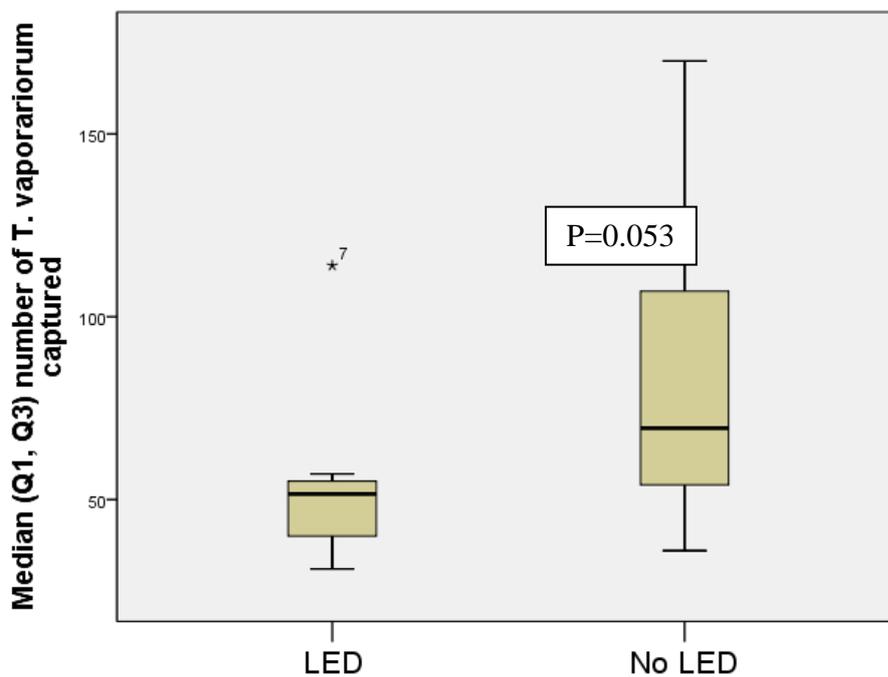
Figure 25. Median, interquartile range, and 95% confidence intervals of *T. vaporariorum* captured on blue (480 nm) LED and standard yellow sticky traps in batch 1 (12/09/13–19/09/13).
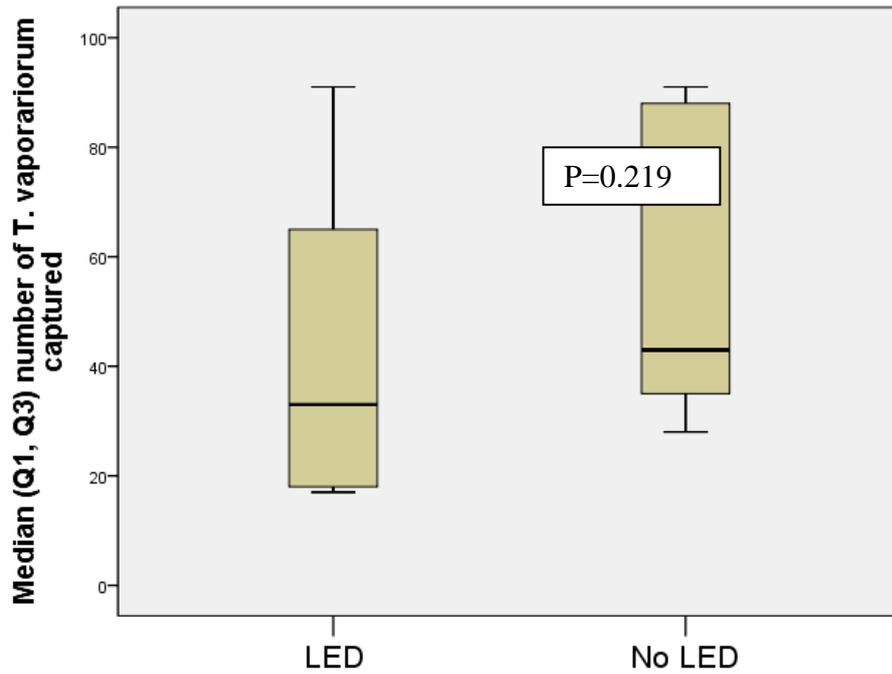
Figure 26. Median, interquartile range, and 95% confidence intervals of *T. vaporariorum* captured on blue (480 nm) LED and standard yellow sticky traps in batch 2 (19/09/13 – 26/09/13).
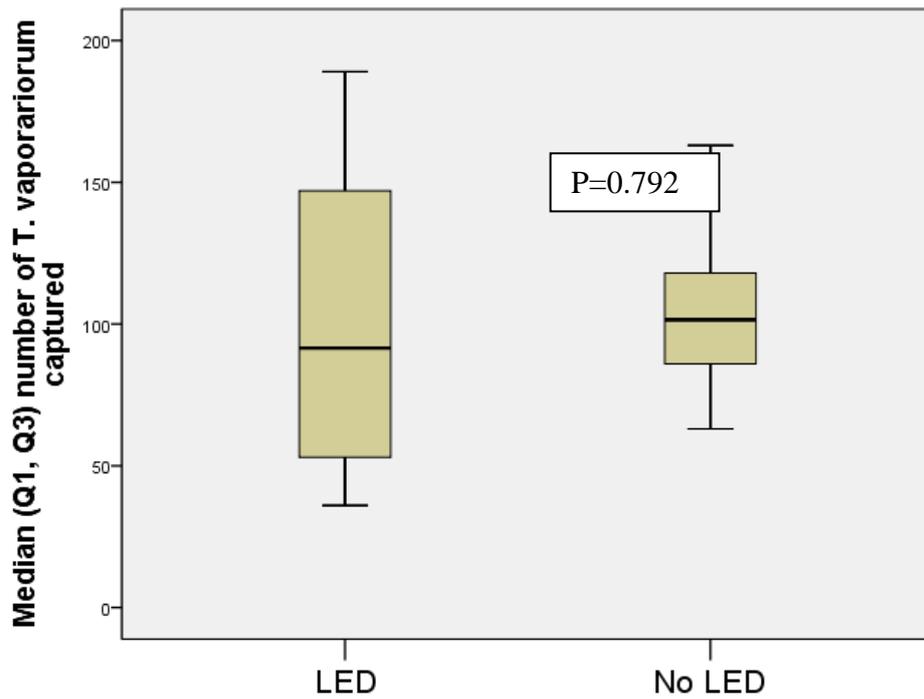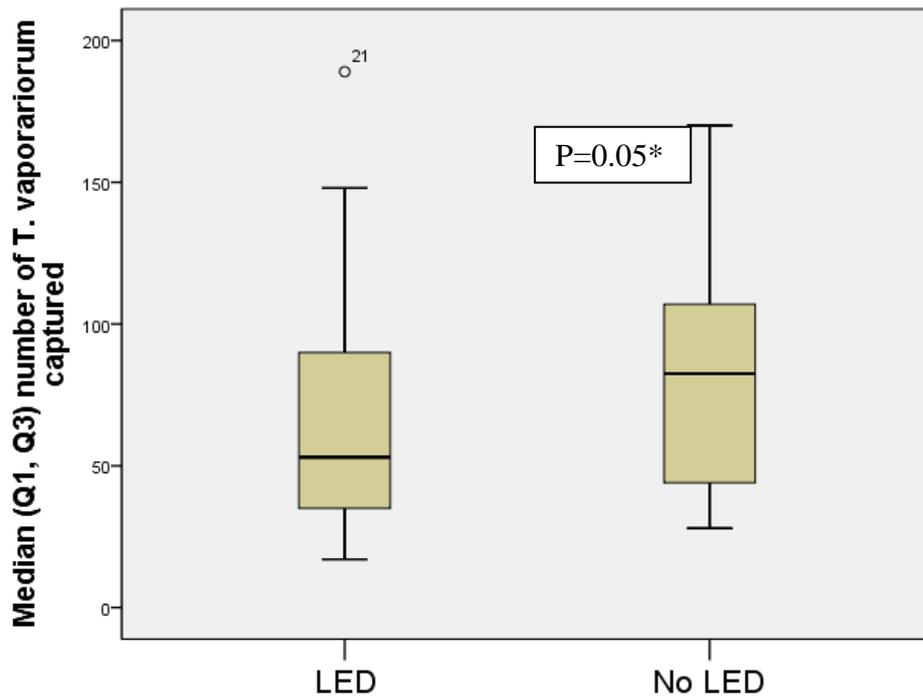
Figure 27. Median, interquartile range, and 95% confidence intervals of *T. vaporariorum* captured on blue (480 nm) LED and standard yellow sticky traps in batch 3 (26/09/13–03/10/13).

Figure 28. Median, interquartile range, and 95% confidence intervals of *T. vaporariorum* captured on blue (480 nm) LED and standard yellow sticky traps across study period (12/09/13–03/10/13). *significant at 0.05.

Site 5

Trialeurodes vaporariorum using **green** (520 nm) LEDs (21/08/13–02/10/13)

There were no significant differences in the capture rate of *T. vaporariorum* between the trap types in any of the individual batches (Figure 29). No significant difference was found between the trap types across the entire trapping period (P=0.518) (Figure 30).
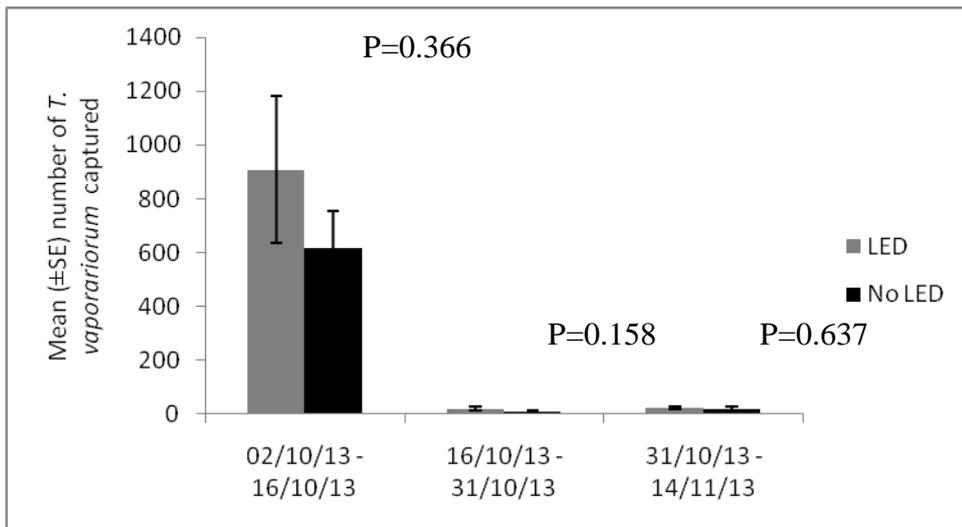
Figure 29. Mean (±SE) number of *T. vaporariorum* captured on green (520 nm) LED and standard yellow sticky traps.
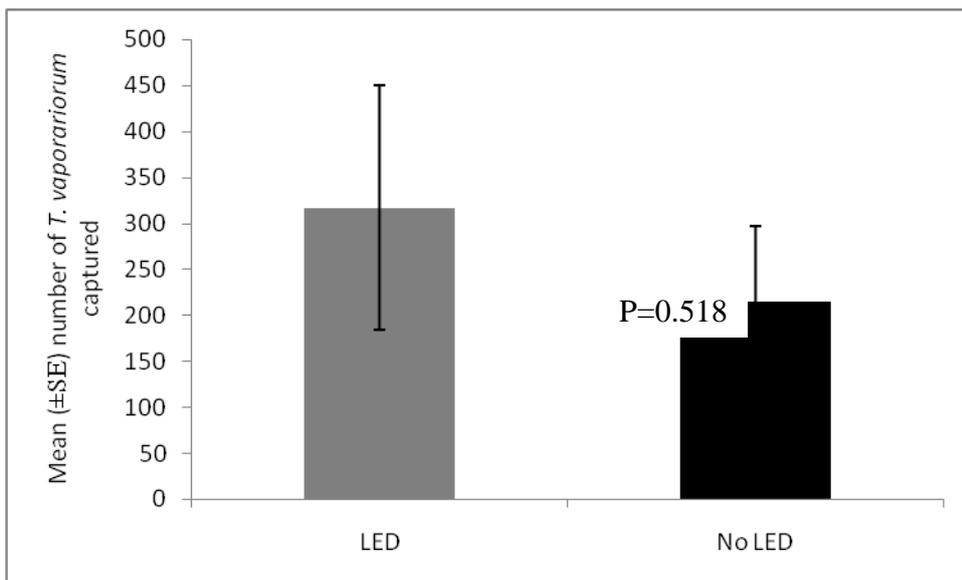

Figure 30. Mean (±SE) number of *T. vaporariorum* captured on green (520 nm) LED and standard yellow sticky traps across study period (21/08/13–02/10/13).

Trialeurodes vaporariorum using **blue** (480 nm) LEDs (02/10/13–14/11/13)

There were no significant differences in the capture rate of *T. vaporariorum* between the trap types in any of the individual batches (Figure 31). No significant difference

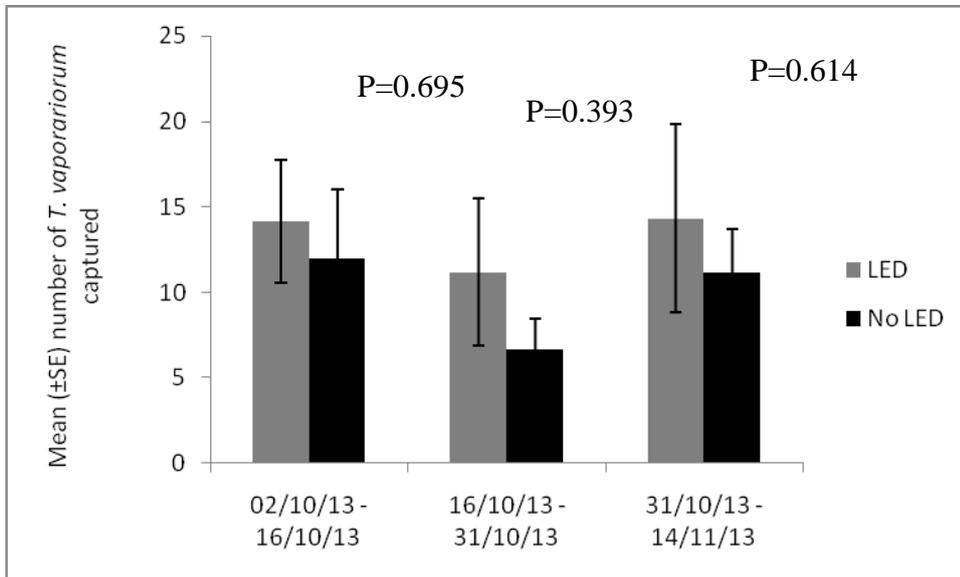was found between the trap types across the entire trapping period (P=0.604) (Figure 32).

Figure 31. Mean (±SE) number of *T. vaporariorum* captured on blue (480 nm) LED and standard yellow sticky traps.
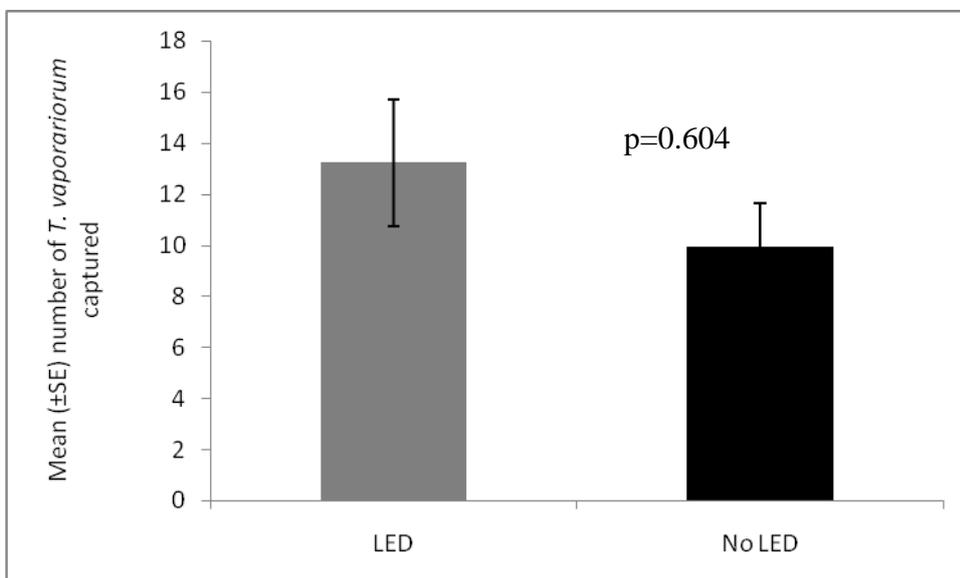

 Figure 32. Mean (±SE) number of *T. vaporariorum* captured on blue (480 nm) LED and standard yellow sticky traps across study period (21/08/13–02/10/13).

Site 7

Trialeurodes vaporariorum **green** (540 nm) LEDs (10/04/13–27/04/13)

There were no significant differences in the capture rate of *T. vaporariorum* between the trap types (P=0.177) (Figure 33).
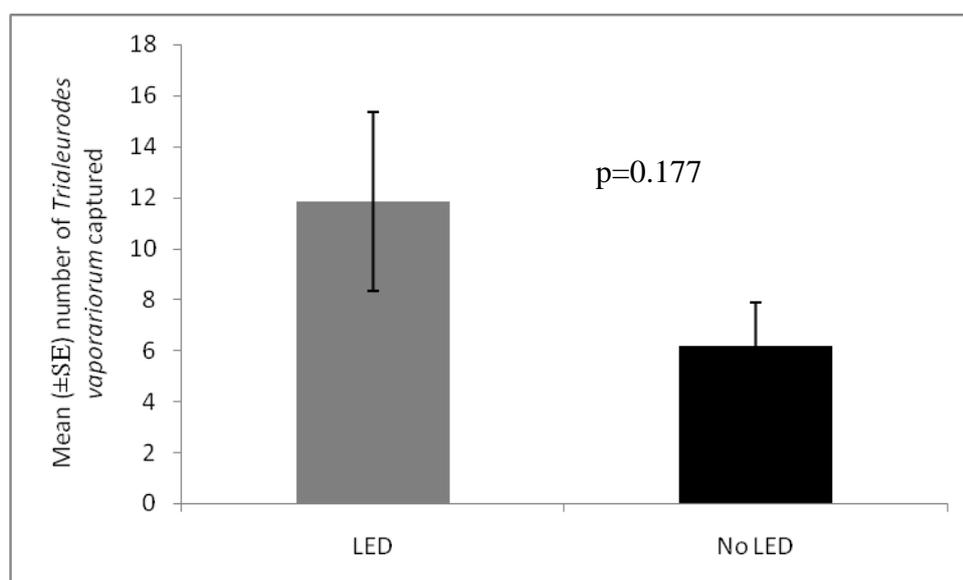

Figure 33. Mean (±SE) number of *T. vaporariorum* captured on green (540 nm) LED and standard yellow sticky traps across study period (10/04/2013–27/04/2013).

Plutella xylostella

Site 3

Plutella xylostella using **green** (540 nm) LEDs (11/10/12–22/11/12)

Significantly more *P. xylostella* were captured by LED traps in batches 1 (U = 12.5, Z = -3.362, P=0.001) and 2 (U = 33.5, Z = -2.230, P=0.007). In batch 1 LED traps captured a median (Q1, Q2) of 2 (0, 3.5) and standard traps captured 0 (0, 0) (Figure 34). In batch two LED traps captured 1 (0, 1.75) and standard traps captured 0 (0, 0) (Figure 35). A significant difference was found across the study period (U = 83, Z = -4.341, P=<0.001), with LED traps capturing 0.5 (0, 0.5) and standard yellow sticky traps capturing 0 (0, 0) (Figure 36).
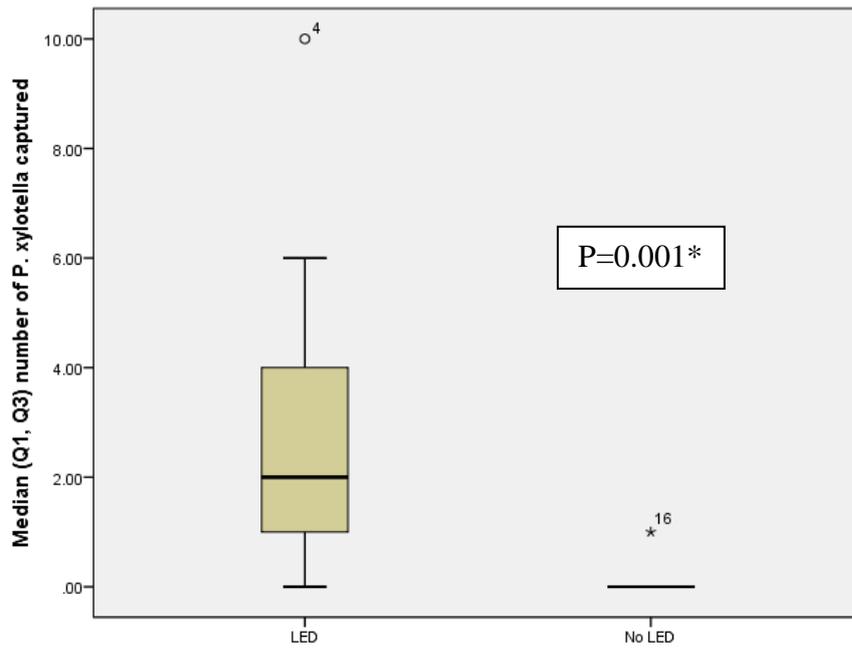
Figure 34. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on green (540 nm) LED and standard yellow sticky traps in batch 1 (11/10/12-08/11/12). *significant at 0.05.

Figure 35. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on green (540 nm) LED and standard yellow sticky traps in batch 2 (08/11/12-22/11/12). *significant at 0.05.
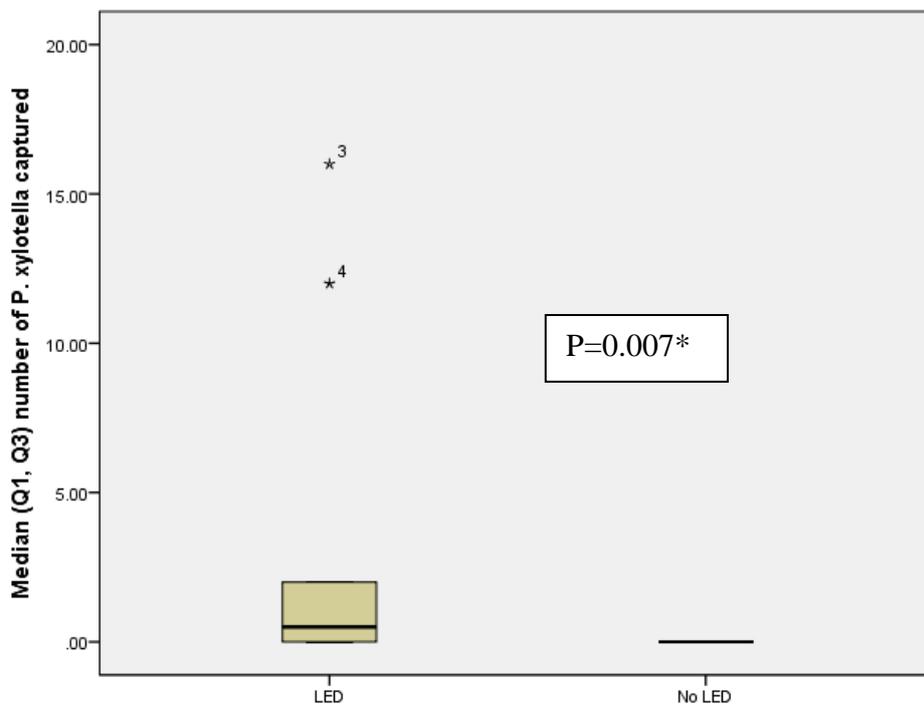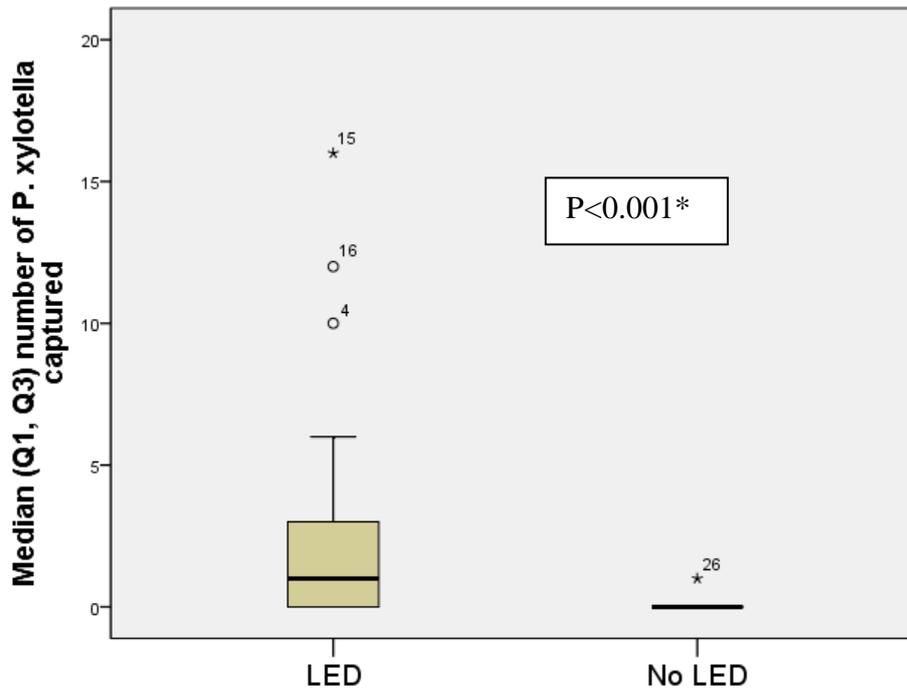

Figure 36. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on blue (480 nm) LED and standard yellow sticky traps across the study period (11/10/12–22/11/12). *significant at 0.05.

Plutella xylostella using **blue** (480 nm) LEDs (02/09/13–20/09/13)

No significant differences were found in batches 1 (P=0.130) (Figure 37) or 2 (P=0.132) (Figure 38). Significantly more *P. xylostella* were captured by LED traps in batch 3 (U = 1, Z = -2.823, p=0.004), with a median (Q1, Q3) of 5.5 (3.5, 6.875) captured by LED traps and 0 (0, 0.25) captured by standard yellow sticky traps (Figure 39). A significant difference in capture rate was found over the study period (U = 75.5, Z = -3.515, p<0.001), with 6.5 (1, 14.24) captured by LED traps and 0 (0, 1) by standard yellow sticky traps (Figure 40).

Figure 37. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on blue (480 nm) LED and standard yellow sticky traps in batch 1 (02/09/13–09/09/13).

Figure 38. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on blue (480 nm) LED and standard yellow sticky traps in batch 2 (09/09/13-16/09/13).

Figure 39. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on blue (480 nm) LED and standard yellow sticky traps in batch 3 (13/09/13-20/09/13). *significant at 0.05.
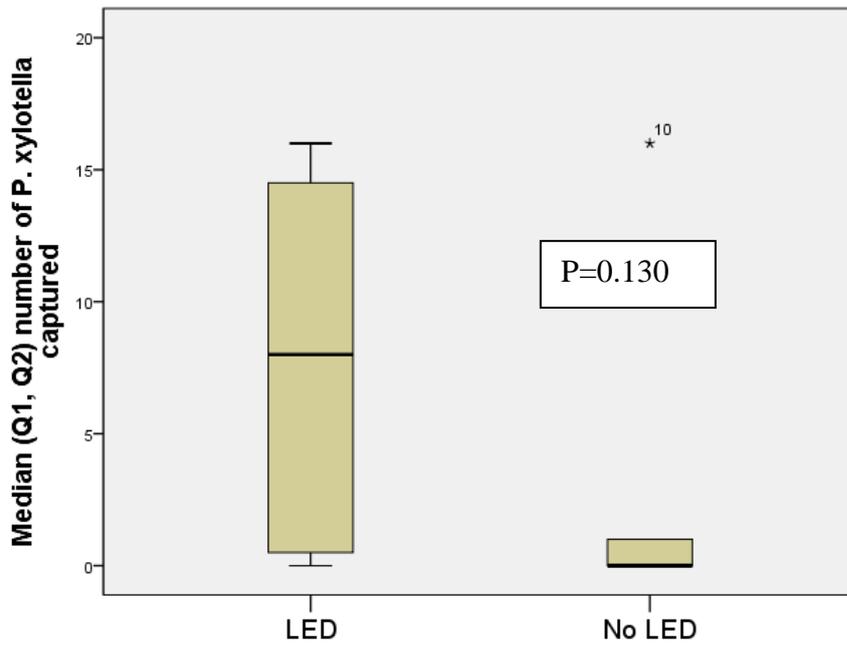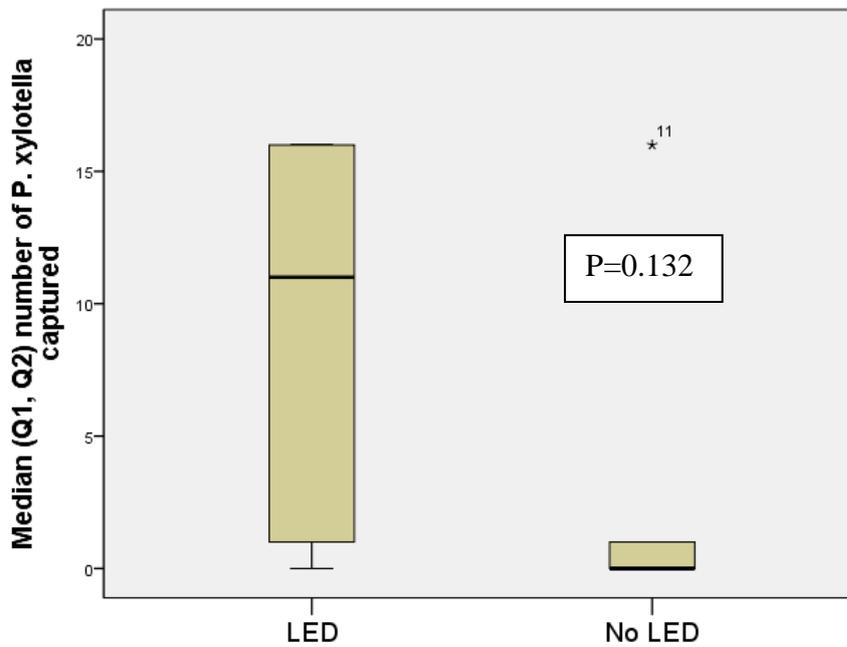
Figure 40. Median, interquartile range, and 95% confidence intervals of *P. xylostella* captured on blue (480 nm) LED and standard yellow sticky traps across the study period (02/09/13–20/09/13). *significant at 0.05.

Encarsia formosa

Site 1

Encarsia formosa using **green** (540 nm) LEDs (09/08/12–23/08/12)

There were no significant differences in the capture rate in batches 1 (P=0.203). Significantly fewer *E. formosa* were captured in batch 2 (U=135.5, Z=-2.149, P=0.032) with a median (Q1, Q3) of 6 (3, 7) captured by LED traps and 3 (1, 5) by standard yellow sticky traps (Figure 41, Figure 42). There was no significant difference in capture rate across the entire study period (P=0.079) (Figure 43).
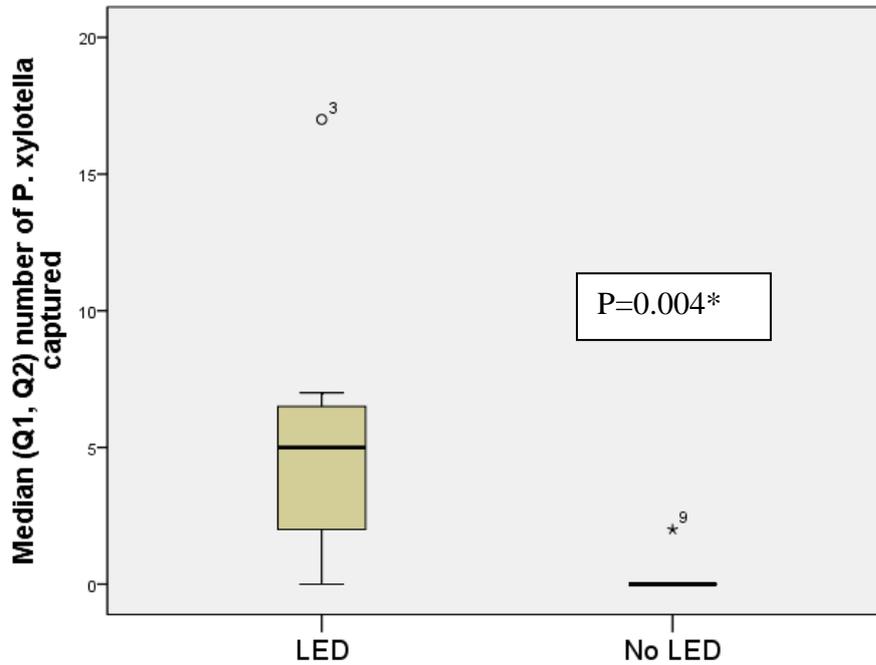
Figure 41. Median, interquartile range, and 95% confidence intervals of *E. formosa* captured on green (540 nm) LED and standard yellow sticky traps in batch 1 (09/08/12–16/08/12).

Figure 42. Median, interquartile range, and 95% confidence intervals of *E. formosa* captured on green (540 nm) LED and standard yellow sticky traps in batch 2 (16/08/12–23/08/12). *significant at 0.05.
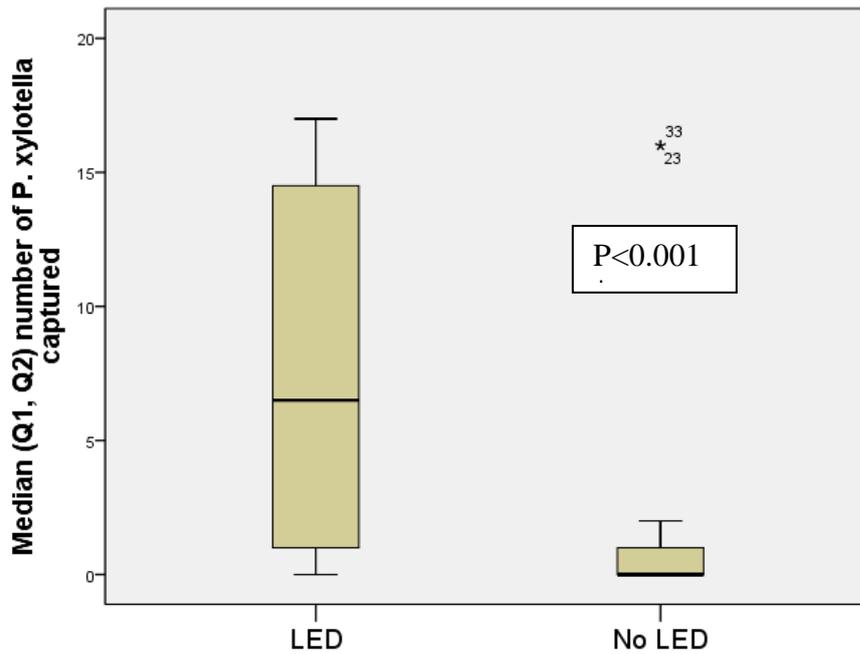

Figure 43. Median, interquartile range, and 95% confidence intervals of *E. formosa* captured on green (540 nm) LED and standard yellow sticky traps across study period (09/08/12–23/08/12).

Site 5

Encarsia formosa using green (520 nm) LEDs (21/08/13-04/09/13)

There were no significant differences in the capture rate in batches 1 (P=0.804) or 2 (P=0.604) (Figure 44, Figure 45). There was no significant difference in capture rate across the entire study period (P=0.718) (Figure 46).

Figure 44. Median, interquartile range, and 95% confidence intervals of *E. formosa* captured on green (520 nm) LED and standard yellow sticky traps in batch 1 (21/08/13-04/09/13).

Figure 45. Median, interquartile range, and 95% confidence intervals of *E. formosa* captured on green (520 nm) LED and standard yellow sticky traps in batch 2 (04/09/13-18/09/13).
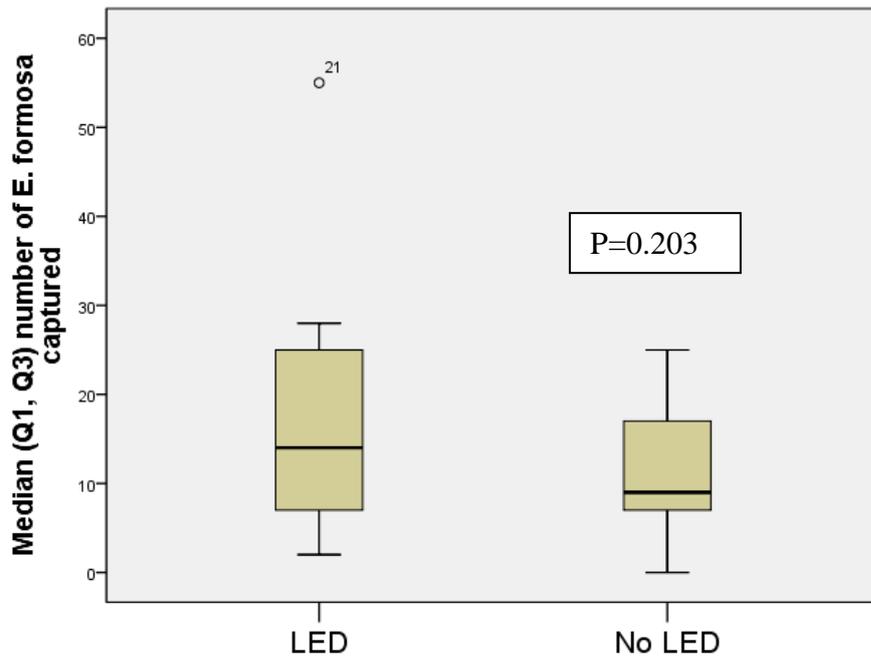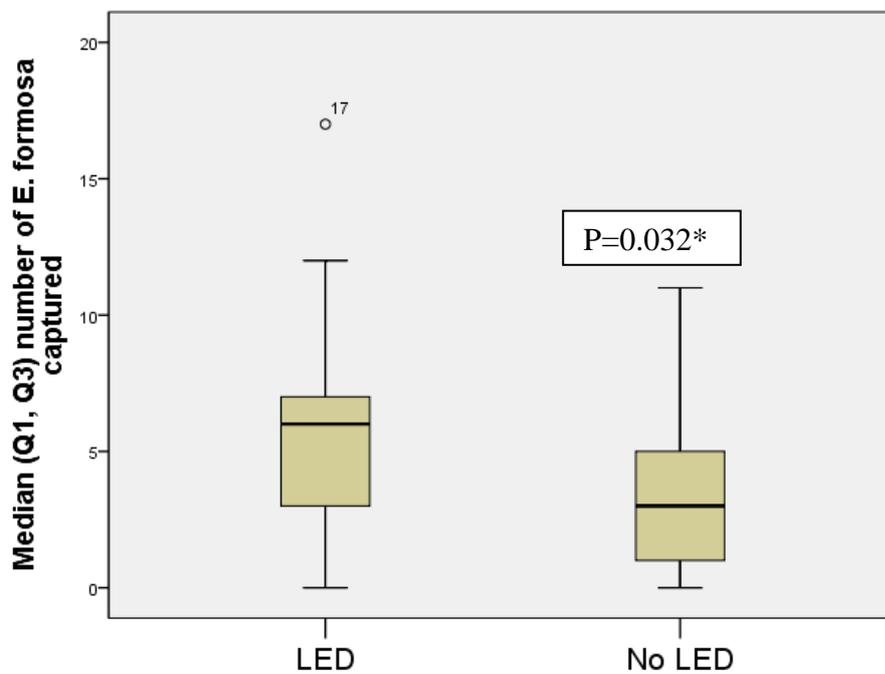
Figure 46. Median, interquartile range, and 95% confidence intervals of *E. formosa* captured on green (540 nm) LED and standard yellow sticky traps across study period (21/08/13-18/09/13).

Site 7

Encarsia formosa using green (540 nm) LEDs (10/04/2013–27/04/2013)

No significant differences were found between in the capture rate of *E. formosa* between LED and standard traps (P=0.320) (Figure 47).
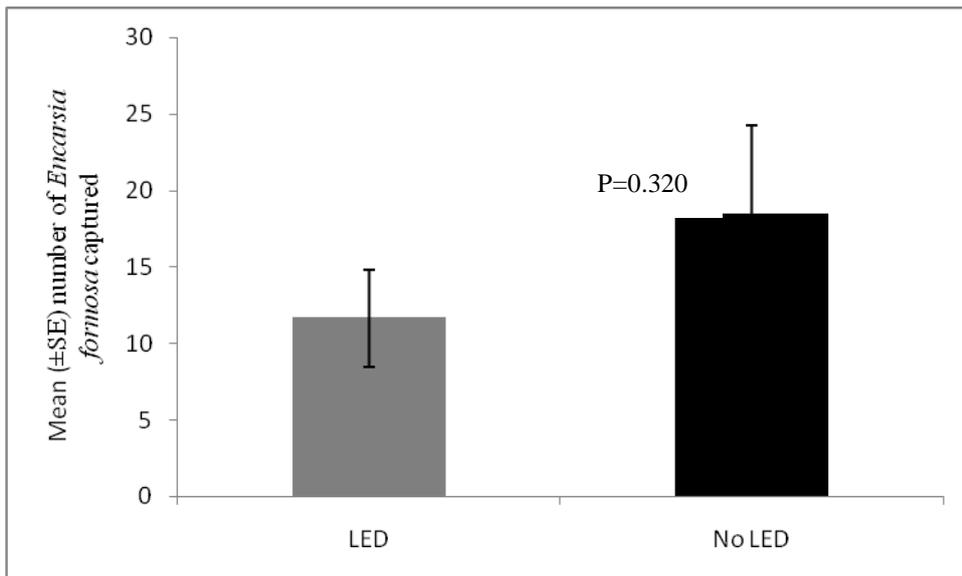
Figure 47. Mean (±SE) number of *E. formosa* captured on green (540 nm) LED and standard yellow sticky traps across study period (10/04/2013–27/04/2013).

Kleidotoma psiloides

Site 1

Kleidotoma psiloides using **green** (540 nm) LEDs (09/08/12–23/08/12)

There were no significant differences in the capture rate in batches 1 (P=0.09) or 2 (p=0.544) (Figure 48, Figure 49). LED traps captured significantly fewer *K. psiloides* across the study period ($F_{1,81}$ = 24.649, P<0.001), with LED traps capturing 61.5 (26, 108.75) and standard traps capturing 103.5 (45.25, 153.25), a 68.29% difference (Figure 50).
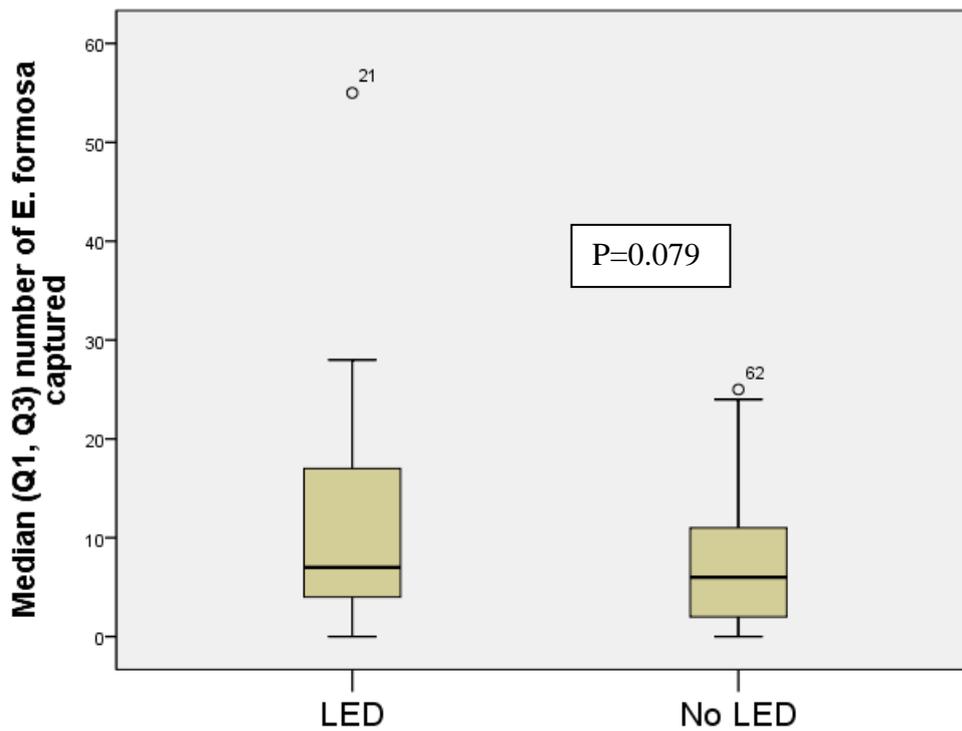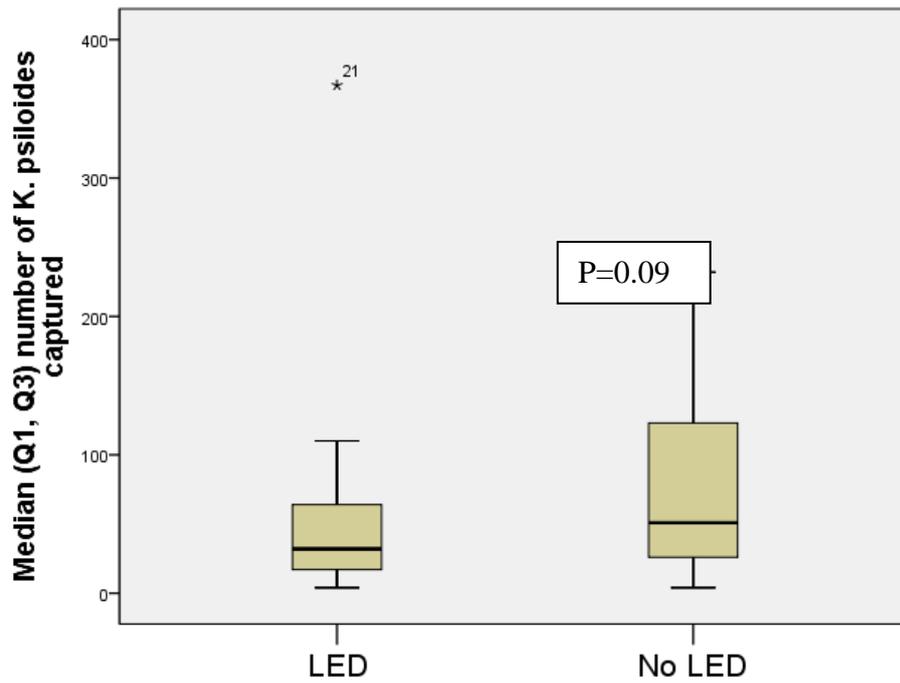
Figure 48. Median, interquartile range, and 95% confidence intervals of *K. psiloides* captured on green (540 nm) LED and standard yellow sticky traps in batch 1 (09/08/12–16/08/12).
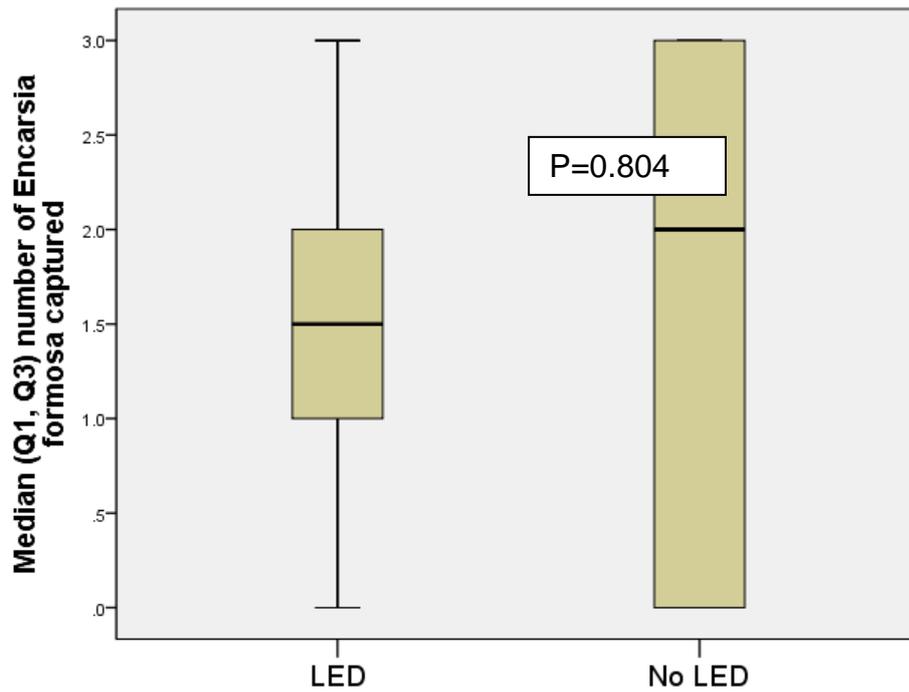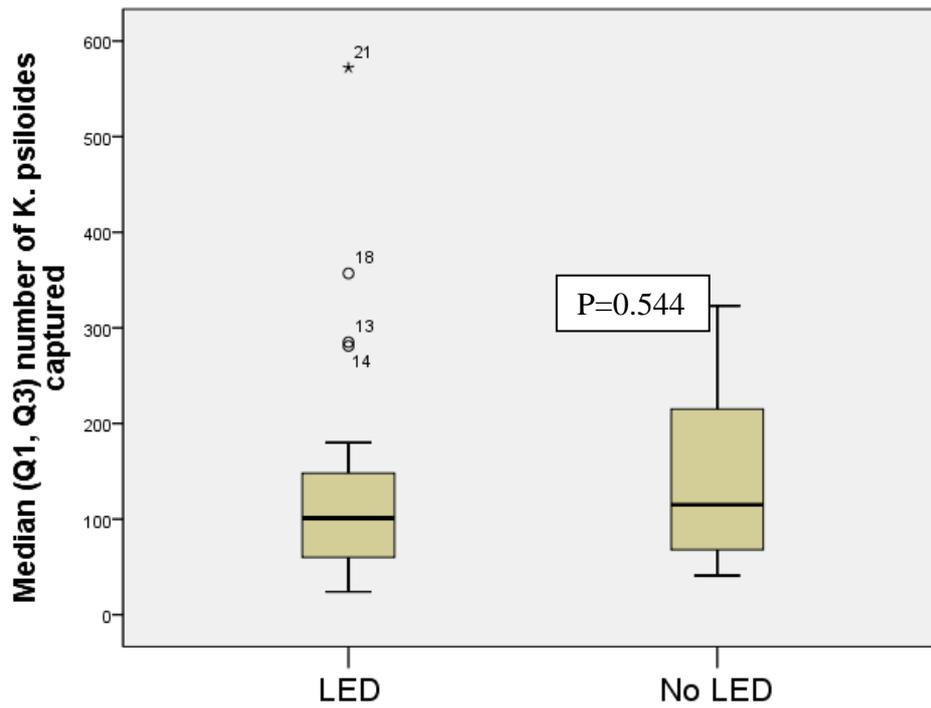
Figure 49. Median, interquartile range, and 95% confidence intervals of *K. psiloides* captured on green (540 nm) LED and standard yellow sticky traps in batch 2 (16/08/12–23/08/12).
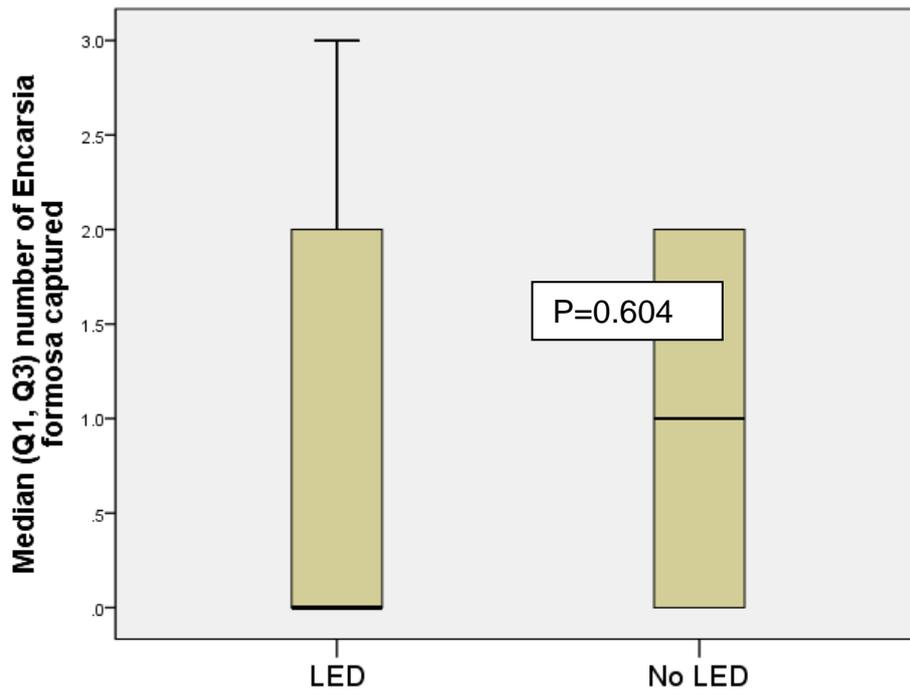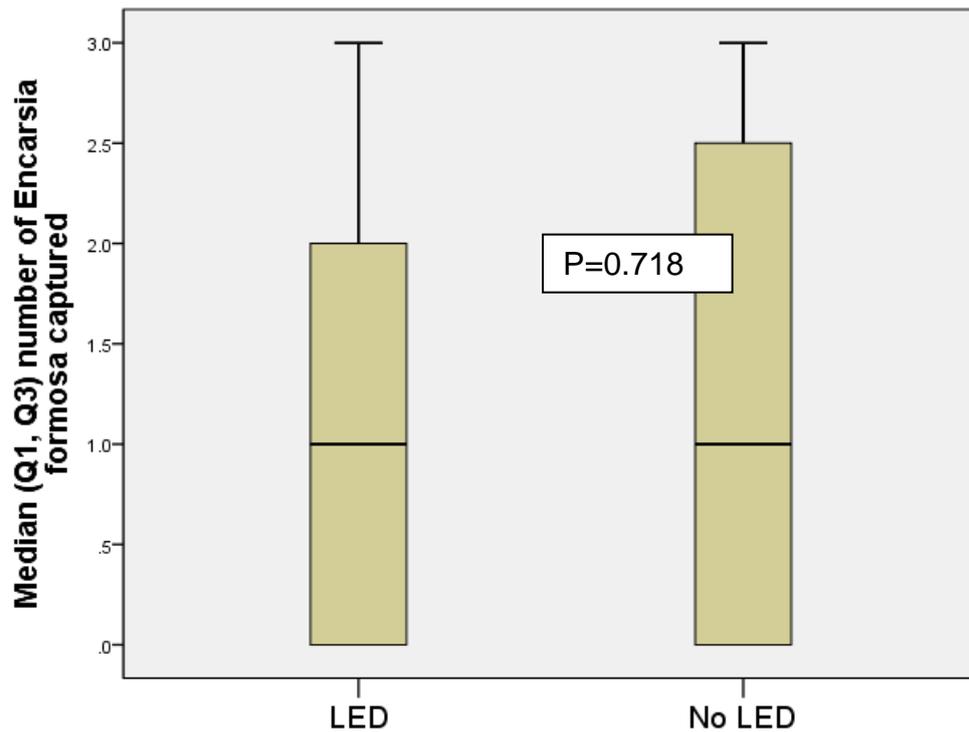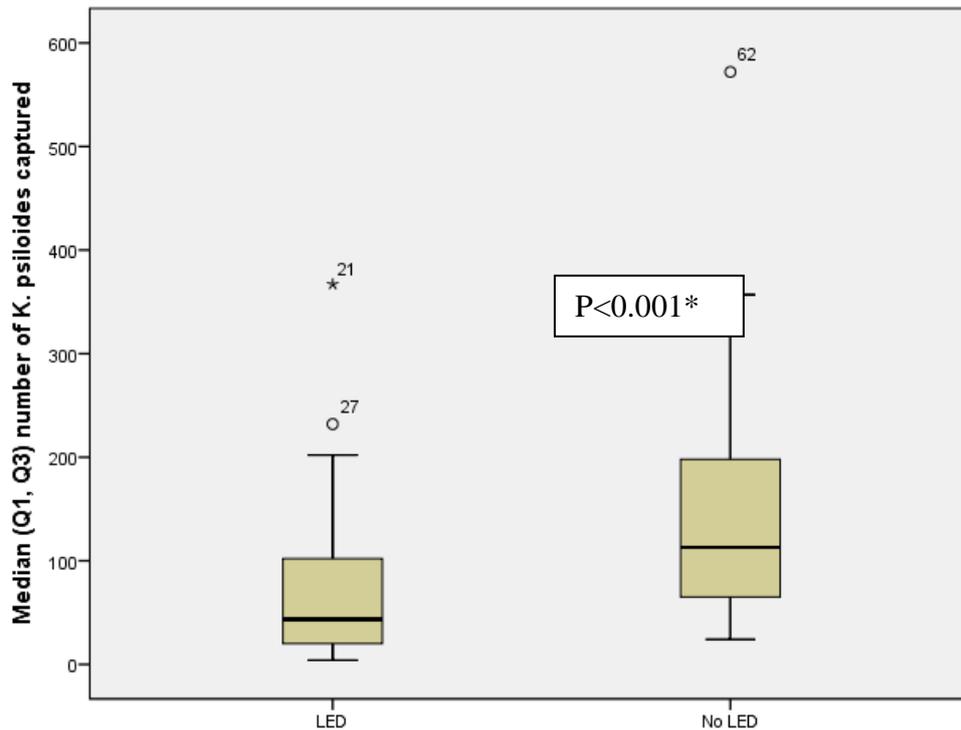
Figure 50. Median, interquartile range, and 95% confidence intervals of *K. psiloides* captured on green (540 nm) LED and standard yellow sticky traps across study period (09/08/12–23/08/12). Significant at 0.05*.

Relative spectral preference

Frankliniella occidentalis

There were significant differences found between the control wavelength and 360 nm (P=0.0019), 380 nm (P=0.039), 420 nm (P=0.0214), 480 nm (P=0.039), and 500 nm (P=0.039) (Table 16). A visual representation based on these data (Figure 51) shows peaks of relative attractiveness at 360 nm, 420 nm, and 480 nm.

Table 16. P values showing differences between control, and test, wavelengths for *F. occidentalis.* The number of decisions equals the numbers of time the subjects chose a wavelength (i.e. moves from the central area), and was a maximum of 10. *Significant at 0.05, ** Significant at 0.005.

Wavelength (nm)	P value	Number of decisions	Wavelength (nm)	P value	Number of decisions
340	0.0703	8	500	0.039*	9
360	0.0019**	10	520	0.0625	5
380	0.039*	9	540 (Control)	N/A	N/A
400	1	9	560	1	8
420	0.0214*	10	580	0.4531	7
440	0.125	7	600	1.3125	6
460	0.1796	9	620	0.625	4
480	0.039*	9	N/A	N/A	N/A
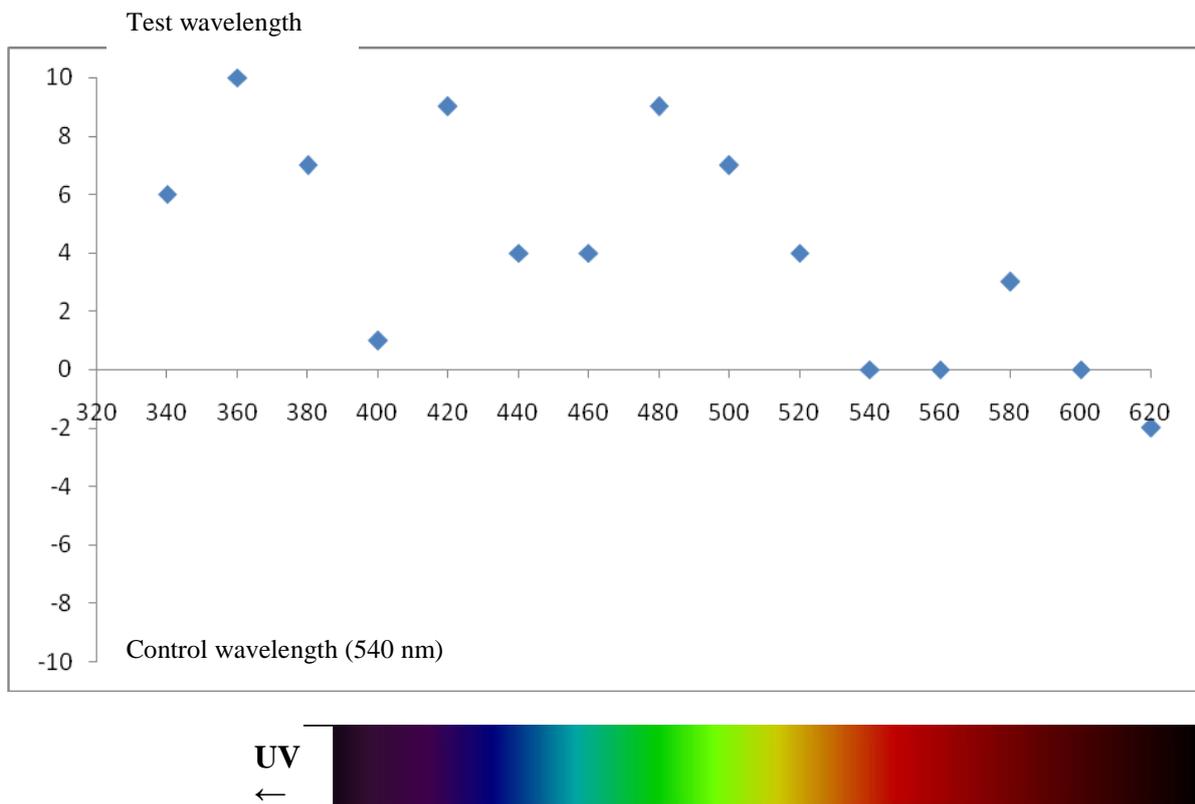
Figure 51. Visual representation of relative spectral preference of the control wavelength versus the test wavelengths for *F. occidentalis*. Ten runs were completed for each wavelength comparison, choices were allocated +1 for test wavelength, -1 for control, and 0 for remaining the in the central area. The higher the value the stronger the preference for that wavelength.

Trialeurodes vaporariorum

There were significant differences found between the control wavelength and 320 nm (p=0.0156), 340 nm (p=0.0156), 380 nm (p=0.703), 440 nm (p=0.039), 600 nm (p=0.0625), and 620 nm (p=0. 0.0625) (Table 17) A visual representation based on these data (Figure 52) shows a high degree of relative attractiveness between 320-400 nm, with an additional peak at 480 nm.

Table 17. P values showing differences between control, and test, wavelengths for *T. vaporariorum*. The number of decisions equals the numbers of time the subjects chose a wavelength (i.e. moves from the central area), and was a maximum of 10. *Significant at 0.05.

| Wavelength (nm)	P value	Number of decisions	Wavelength (nm)	P value	Number of decisions
320	0.0156*	7	480	0.5078	6
340	0.0156*	7	500	1.3125	5
360	0.1796	9	520 (Control)	N/A	N/A
380	0.0703	8	540	1	5
400	0.5078	9	560	0.375	5
420	1	8	580	0.375	5
440	0.039*	9	600	0.0625	5
460	0.7265	8	620	0.0625	5
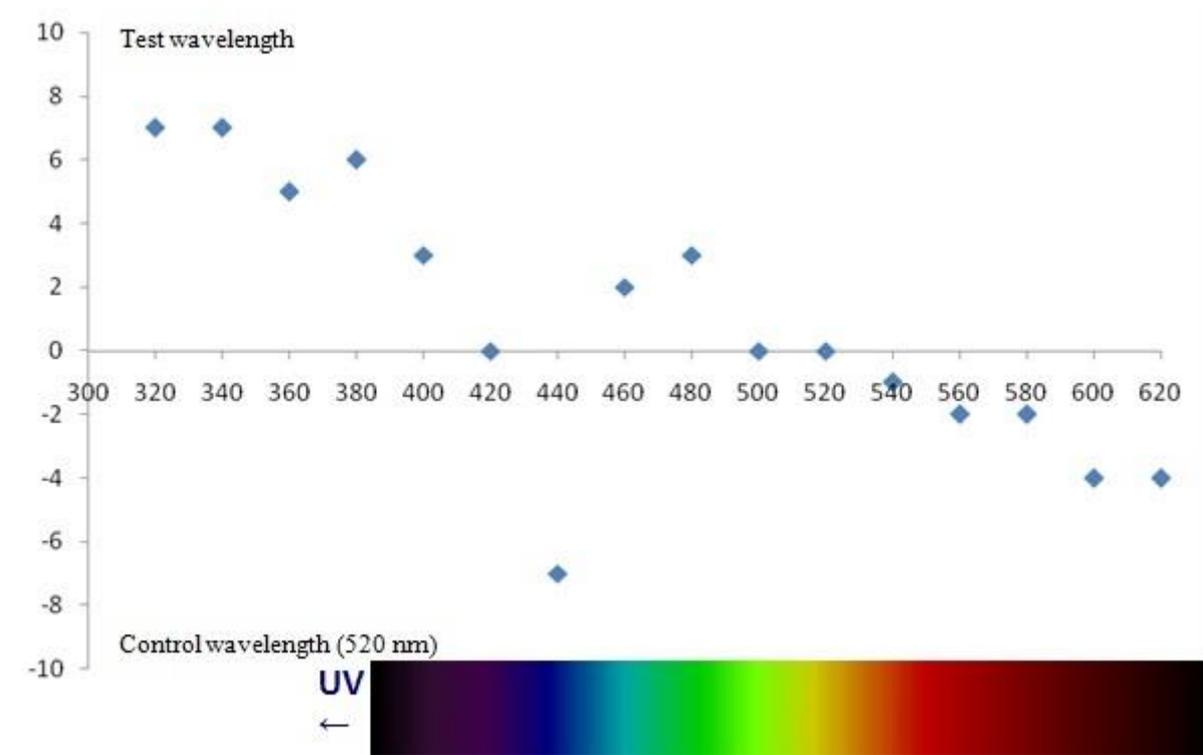
Figure 52. Visual representation of relative spectral preference of the control wavelength versus the test wavelengths for *T. vaporariorum*. Ten runs were completed for each wavelength comparison, choices were allocated +1 for test wavelength, -1 for control, and 0 for remaining the in the central area. The higher the + value the stronger the preference for that wavelength. The higher the – value the stronger the non-preference for that wavelength.

Results Summary

- *B. difformis* showed an increased attraction to green (540 nm) LED equipped yellow sticky traps at all three sites.

- *B. difformis* showed a slight increase in attraction to blue (480 nm) LED equipped yellow sticky traps.

- *F. occidentalis* showed peak relative attraction at 360, 420, and 480 nm wavelengths when compared against 540 nm.

- *F. occidentalis* showed no significant increase in attraction to yellow sticky traps equipped with green (540 nm) or blue (480 nm) LEDs.

- *T. vaporariorum* showed peak relative attraction at 320, 340, 380, and 480 nm wavelengths when compared against 520 nm.

- *T. vaporariorum* showed a small increase in attraction to yellow sticky traps equipped with green (540 nm) LEDs, and no increase in attraction to those equipped with blue (480 nm) LEDs.

- *P. xylostella* showed a strong significant increase in attraction to yellow sticky traps equipped with green (540 nm) or blue (480 nm) LEDs.

- *E. formosa* showed no overall change in attraction. Although one batch of green (540 nm) equipped yellow sticky traps at site 1 showed a significant increase in attraction, results from sites 5 and 7 using green 5 (520 nm) and green (540 nm) showed a slight decrease in attraction.

- *K. psiloides* showed a significant decrease in attraction to yellow sticky traps equipped with green (540 nm) LEDs over the study period.

Discussion

Bradysia difformis

The main findings of this trap comparison were an increase in the capture rate of *B. difformis* using both 540 nm and 480 nm LEDs. The difference in the number captured differed at the different sites.

The findings of this study are similar to those of Chen *et al.* (2004), where the capture of a related species, *Bradysia coprophila,* was increased by 431% attaching a green (530 nm) LED to standard yellow sticky traps. It is worth noting that Chen *et al.* (2004) found a greater difference in attraction during the summer months, skewing the overall increase in capture and indicating seasonality may be a factor in the attraction of *B. coprophila* to these traps. Unfortunately, due to the short growing season within the UK, it was not possible to confirm this.

There were notable differences in the increase in *B. difformis* captured at the different study sites, with an increase of 25.4% at site 1, 47% at site 2, and 349% at site 3 when using the green (540 nm) LEDS. There are a number of reasons which

could account for this, but it seems likely these differences are due to the growing methods used at the sites, and the population sizes of *B. difformis.*

Sites 1 and 2 grow their crops on benches, while site 3 grows their crops on the ground, using capillary matting covered in perforated plastic sheets. This results in a humid environment where high populations of *B. difformis* are common, and the plastic covering prevents the flies from making contact with the growing medium over the majority of its surface. Female *B. difformis* lay eggs under the debris on the surface of soil, so it is likely that an increase in the difficulty of finding a viable landing site for egg laying increases their flight time or frequency, resulting in a greater number captured on traps.

The high population of *B. difformis* at site 3 may also result in more active individuals. As competition for resources will be greater than at sites 1 and 2, it is reasonable to suggest a greater level of activity that would be associated with a greater difficulty in finding food, as well as dispersal around the glasshouse seeking areas with less competition for resources.

Blue (480 nm) LED traps were less successful, and no overall significant difference was observed. However, there was a pattern of LED traps capturing more than standard traps, with significant differences in batches 4 and 5.

Although *B. difformis* feed on organic matter within the soil, it is plausible that they exhibit an attraction to green as the presence of plants indicates organic matter is likely to be present. Although blue has been previously found to be effective in attracting a related species, *Bradysia paupera* (Ishitani *et al.,* 1997), the lamp used also produced output in the blue spectrum, making it difficult to identify the wavelength/s responsible for the attraction.

In summary it was shown that the addition of both green (540 nm) and blue (480 nm) LEDs to standard yellow sticky traps can increase their attractiveness to *B. difformis,* with green (540 nm) having the greater effect. Further research is

required to determine the factors contributing to the success of green (540 nm) LED traps at site 3.

Frankliniella occidentalis

The main findings of this study were peak attractions at 360, 420, and 480 nm, suggesting these wavelengths may be effective for increasing the attractiveness of traps to *F. occidentalis*. No significant differences were observed when comparing sticky traps equipped with either green (540 nm) or blue (480 nm) LEDs to standard yellow sticky traps.

The comparison between standard yellow sticky traps to those equipped with green (540 nm) LEDs produced similar results to those of Chen *et al.* (2004), where no significant differences were found when comparing green (530 nm) and standard yellow sticky traps.

This is unsurprising as in the behavioural experiments *F. occidentalis* showed a spectral preference for every other wavelength tested with the exceptions of 560, and 620 nm. *F. occidentalis* is known to show a preference for blue sticky traps (Chen *et al.,* 2004), although a preference for white has been observed in field crop experiments (Hoddle *et al.,* 2002). This preference for blue may be a result of their attraction to flowering plants, which may reflect within the blue region of the light spectrum, although this is typically not the case for flowers grown by commercial growers (FReD, 2014).

There were no significant differences found when comparing standard yellow sticky traps to blue (480 nm) LED equipped traps. This is in contrast to results found by Chu *et al.* (2005) where a greater number of *F. occidentalis* were captured by blue sticky traps equipped with blue (460 nm) LEDs. These results may be explained by the use of yellow sticky traps here, and the distance dependent responses to light demonstrated by *F. occidentalis* (Chu *et al.,* 2005).

Chu *et al.* (2005) compared the attraction of *F. occidentalis* to a range of wavelengths by releasing *F. occidentalis* into a dark room, and found that a much greater number of *F. occidentalis* were captured by UV traps when compared to other traps when the light sources were placed closer to the release point of the release. This indicates that the response of *F. occidentalis* to light occurs over short distances. These distant dependant responses to light, coupled with the results

found here, suggest that the yellow sticky traps and blue (480 nm) combination were ineffective as the relatively large reflectance area of the blue sticky trap may be required in order to lure *F. occidentalis* close enough for the blue LED light to create a difference in capture rate. Using a brighter blue LED may solve this issue, although there are safety concerns with using bright blue lights at eye level which prohibit this experiment in a glasshouse frequented by workers (Barker *et al.,* 2011; Kernt *et al.,* 2012).

In summary it was shown that equipping yellow sticky traps with green (540 nm) or blue (480 nm) LEDs does not increase their attractiveness to *F. occidentalis.* The high relative attraction of *F. occidentalis* to 360 nm is promising, and this may be an effective wavelength for increasing trap attraction to *F. occidentalis* in future when the cost of UV LEDs decreases, and light output increases.

Trialeurodes vaporariorum

The main findings of this study were peak attractions at 320, 340, 380, and 480 nm, suggesting these wavelengths may be effective for increasing the attractiveness of traps to *T. vaporariorum*. No significant differences were observed when comparing sticky traps equipped with either green (540 nm) or blue (480 nm) LEDs to standard yellow sticky traps.

A small increase in capture rate was found in sites 5 and 7 for traps equipped with green (540 nm) LEDs, this is consistent with an experiment by Chu *et al.* (2004), where a 31% increase was found using green (530 nm) LEDs. There were no significant differences found at sites 1 or 5 when comparing standard yellow sticky traps to those equipped with blue LEDs.

The combination of the field work and behaviour experiment suggests that either green (540 nm) or blue (480 nm) are effective at increasing the attractiveness of sticky traps to *T. vaporariorum*. Although a peak in relative spectral preference was seen at 480 nm, it should be noted that this is in comparison with 520 nm, a wavelength to which *T. vaporariorum* does not appear to exhibit a strong preference for despite showing a strong spectral sensitivity to this wavelength.

In summary it was shown that equipping yellow sticky traps with green (540 nm) or blue (480 nm) LEDs does not increase their attractiveness to *T. vaporariorum.* The high relative attraction of *T. vaporariorum* to 320, 340, and 380 nm is promising, and

these may be effective wavelengths for increasing trap attraction to *F. occidentalis* in future when the cost of UV LEDs decreases, and light output increases.

Plutella xylostella

The main findings of this study are a significant increase in the capture of *P. xylostella* for yellow sticky traps equipped with green (540 nm) or blue (480 nm) LEDs.

The attraction of *P. xylostella* to LED lights has been previously documented (Cho & Lee, 2012), where a preference for green (520 nm) was demonstrated, supporting the assertion by Sivapragasam & Saito (1986) that the high spectral reflectance of yellow sticky traps within the green region of the light spectrum is explanatory of their preference for yellow sticky traps when compared against blue, red, and clear. Despite this attraction it is unusual for *P. xylostella* to be captured by the standard yellow sticky trap, as they typically fly below the crop canopy, rarely straying to the height sticky traps are typically placed.

The addition of LEDs to sticky traps at site 3, greatly increased the number of *P. xylostella* captured, although there was a high degree of variation between traps and overall, a low number of *P. xylostella* were captured. The low number captured is to be expected, as the traps were placed at a commercial facility which does not grow plants of the Crucifer family, which are the only group *P. xylostella* feed on, and the presence of *P. xylostella* in this facility is likely due to nearby facilities growing members of this plant family.

The attraction to the green (540 nm) LED equipped traps is likely to be a result of *P. xylostella's* food sources primarily being coloured, at least in part green. While this is inconsistent with the greater success of the blue (480 nm) LED traps found here, it is important to note that these experiments were conducted in 2012, and 2013 respectively, and a greater population of *P. xylostella* may have been present during the 2013 season.

In summary it was shown that equipping yellow sticky traps with green (540 nm) or blue (480 nm) LEDs increases their attractiveness to *P. xylostella,* although this may be due to the disruption of flight navigation cues rather than an increase in attraction. This finding is of particular interest as the standard sticky traps were ineffective for monitoring *P. xylostella* at the study site, typically capturing no

individuals. Further research is required to gain further understanding of this effect, in particular a direct comparison between green and blue LED equipped sticky traps, as well as traps with light angled downwards towards the crop.

Encarsia formosa

The main findings of this study were that there was a slight increase in attraction to yellow sticky traps equipped with green (540 nm) LEDs at site one. No differences in the attraction of *E. formosa* to yellow sticky traps equipped with green (540 nm) at site 7 or (540 nm) LEDs at site 5.

Although one batch of green (540 nm) equipped yellow sticky traps at site 1 showed a significant increase in attraction, results from sites 5 and 7 using green (520 nm) and green (540 nm) LEDs showed a slight decrease in attraction. Suggesting this increase in attraction is either a site specific effect, or a chance effect.

The findings of this study confirm that the addition of green (520 or 540 nm) LEDs to yellow sticky traps are unlikely have a direct negative effect on the use of *E. formosa* for use as a biological control agent. This is consistent with what is known about how *E. formosa* locates its hosts. *E. formosa* appears to search randomly throughout the crop for whitefly signs, for example the presence of larvae, pupae, or adult whitefly (van Lenteren *et al.,* 1996). They appear to be unable to detect infested plants from a distance, which suggests they locate potential host sites based on other stimuli, for example visual or chemical cues related to whitefly host plants. This search behaviour may result in an increase in *E. formosa* on sticky traps which capture a greater number of whitefly.

Unfortunately, due to the lack of success in increasing the attraction of sticky traps to *T. vaporariorum* in these experiments, it is not possible to determine this at this time. Future studies should seek to determine whether there is a correlation between the number of *T. vaporariorum* and *E. formosa* captured on sticky traps.

Kleidotoma psiloides

The main finding of this study was that *K. psiloides* showed a significant decrease in attraction to yellow sticky traps equipped with green (540 nm) LEDs over the study period.

Very little is known about this naturally occurring parasitic wasp of shore flies (family: Ephydridae). The results from this study along with anecdotal evidence gained from a grower in England suggest that *K. psiloides* are attracted to the colour yellow. This would imply that at a site with a high population of *K. psiloides*, yellow sticky traps may be detrimental to their use as a control for shore fly. The addition of a green (540 nm) LED to these traps may go towards counteracting this.

Conclusions

Bradysia difformis

Equipping yellow sticky traps with green (540 nm) LEDs increases their attraction to *B. difformis*, potentially improving the monitoring of this species. The increase in attractiveness differed between sites and was most effective at a site growing poinsettia on capillary matting covered by perforated plastic sheet.

Although blue (480 nm) increased the catch rate, this increase was not great enough to recommend blue (480 nm) for this species.

Frankliniella occidentalis

The wavelengths 360, 420, and 480 nm were identified as potentially effective for attracting *F. occidentalis.* In comparisons between LED equipped yellow sticky traps and standard yellow sticky traps, both green (540 nm) and blue (480) were ineffective. The ineffectiveness of the blue (480 nm) LEDs may be due to the use of the yellow sticky trap, pairing this LED with a blue sticky trap may prove to be more effective.

Trialeurodes vaporariorum

The wavelengths 320, 340, 380, and 480 nm were identified as potentially effective for attracting *F. occidentalis.* Yellow sticky traps equipped with green (540 nm) LEDs attracted slightly more *F. occidentalis* than those without. Blue (480 nm) LEDs were ineffective for increasing attraction.

Plutella xylostella

Yellow sticky traps equipped with green (540 nm) or blue (480 nm) LEDs captured significantly more *P. xylostella* than standard yellow sticky traps.

Encarsia formosa

A slight increase in attraction was found for yellow sticky traps equipped with green (540 nm) LEDs at one site; however, at the other site using green (540 nm) a decrease in attraction was found, although this was not significant. A similar decrease in attraction was seen when using green (520 nm) LEDs.

Kleidotoma psiloides

Yellow sticky traps equipped with green (540 nm) LEDs attracted significantly less *K. psiloides* over the study period.

Knowledge and Technology Transfer

Event description	Date
SAC Postgraduate Conference (Presentation)	21-22/03/2012
Presentation to crop growers (to obtain volunteers for field work)	26/03/2012
HDC Studentship Conference 2012 (poster presentation)	04-05/06/2012
Koppert Entomology Course 2012	05-07/07/2012
HDC Focus on Light Spectrum for Horticulture	04/12/2012
SRUC Studentship Conference 2013	20-21/04/2013
HDC Studentship Conference	09-10/09/2013

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