# Grower Summary

## CP 085

## Securing skills and expertise in crop light responses for UK protected horticulture, with specific reference to exploitation of LED technology (EMT/HDC/HTA Fellowship)

Annual Report 2015

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|---|---|
| Project title: | Securing skills and expertise in crop light responses for UK protected horticulture, with specific reference to exploitation of LED technology (EMT/HDC/HTA Fellowship) |
| Project number: | CP85 |
| Project leader: | Dr G M McPherson, STC |
| Report: | Annual report, Year 3, Nov 2015 |
| Previous report: | Annual report, Year 2, Nov 2014 |
| Fellowship staff: | Dr Martin McPherson, Science Director, STC (lead Fellowship mentor)<br>Prof. Nigel Paul, Lancaster University (Mentor) |
| Trainees | Dr Phillip Davis, Applied Photobiologist,<br>Dr Rhydian Beynon-Davies |
| Location of project: | Stockbridge Technology Centre |
| Industry Representatives: | Chis Plackett, FEC<br>Russel Woodcock, Bordonhill<br>James Bean, Crystal Heart Salads<br>Neal Wright, Micropropagation Services<br>Simon Budge, VHB Ltd (Herbs)<br>Colin Frampton, Consultant<br>Steve Carter, Protected and indoor Ornamentals<br>Geoffrey Smith, Mapleton Growers (Protected Edibles - Lettuce) |
| Date project commenced: | 1 October 2012 |
| Date project completed | 30th September 2017 |

(or expected completion date):

DISCLAIMER

## 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.

Dr Phillip Davis
Project Manager
Stockbridge Technology Centre

Signature ............................................................ Date ............................................

Report authorised by:

Dr Martin McPherson
Science Director
Stockbridge Technology Centre

Signature ............................................................ Date ............................................

# Progress Against Objectives

## Objectives

### Training

**Objective T1.** To provide the Fellow with the knowledge, understanding and practical skills to undertake applied plant science in the area of plant light responses, lighting and cladding materials.

**Objective T2.** To establish the Fellow with a network of contacts within the major commercial producers of horticultural LEDs (and cladding plastics).

**Objective T3.** To establish the Fellow with a network of contacts in the science base in fundamental and applied plant photobiology in Europe and beyond.

**Objective T4.** To provide the Fellow with a solid appreciation of the "business basis" for horticultural R&D, including aspects such as staffing, costings and the range of possible funding routes.

**Objective T5.** To establish the Fellow with a network of contacts with experts from the industry, including applied horticultural consultants currently active in supporting UK protected cropping, and through their respective technical groups, representatives of the major protected cropping sectors in the UK.

Research

**Objective R1.** For the fellow to undertake an initial, objective review of current developments and progress in lighting technology with support from the leading manufacturers and including a brief fact-finding tour overseas.

**Objective R2.** To objectively assess the properties of a selection of LEDs currently available or proposed for use in UK horticulture in terms of total irradiance (intensity), spectrum, efficiency and response to dimming.

**Objective R3.** Based on R1 and R2 to identify gaps in current scientific knowledge with respect to crop responses (using existing Arabidopsis light response knowledge) to LEDs relevant to UK production and to undertake pilot-scale experiments into the responses of selected UK protected crops (particularly leafy salads, ornamentals & herbs) to LEDs found to have useful properties in R2. Information obtained under R3 will identify the potential of appropriate lighting systems for specific UK crops. The knowledge gained will be used to design further R&D studies, subject to additional external funding, for future commercial implementation in the UK (See Objective R5).

**Objective R4.** In addition to the Fellowship reports, to produce (i) a technical review of the "state-of-art" of LED lighting in Horticulture, (ii) an article in HDC News summarising the results of the Fellowship and the current status of LED lighting in horticulture and (iii) to participate in a programme of visits, workshops and conferences for growers, including those at the new STC facility.

**Objective R5.** This fellowship is intended as being a major element in securing long-term R&D in to LEDs (and other light-based approaches to production) in UK horticulture, but does not in itself deliver a major "stand-alone" research programme. HDC is currently undertaking a major assessment of future priorities for UK-based LED research, and while the outcome of this review remains uncertain, we anticipate that, based on progress during the fellowship and other projects, the Fellow will be taking the lead in preparing applications for funding to extend R&D in LED lighting in the UK, with the Fellow as the lead investigator.

| **Objective** | **Original Completion Date** | **Actual Completion Date** | **Revised Completion Date** |
|---|---|---|---|
| Objective T1. | December 2012 | December 2012 | |
| Objective T2. | December 2013 | This is an on-going exercise as new companies move into the area. | September 2017 and beyond. |
| Objective T3. | December 2013 | Many contacts have been made across the industry and this will be an ongoing exercise. | September 2017 and beyond. |
| Objective T4. | December 2013 | This process will continue throughout the fellowship | September 2017 and beyond. |

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|---|---|---|---|
| Objective T5. | December 2013 | This process will continue throughout the fellowship | September 2017 and beyond. |
| Objective R1 | December 2013 | February 2013 | - |
| Objective R2 | January 2013 | March 2013 | - |
| Objective R3 | December 2013 | - | |
| Objective R4 | December 2016 | August 2015 and ongoing | |
| Objective R5 | September 2017 | - | |

## Summary of Progress

In its third year this Fellowship program has continued to progress well and a substantial amount of knowledge has been gained regarding plant light responses as well as the economic implications that LED lighting systems have on the industry. Building on his knowledge of LED lighting systems and plant light responses Dr Davis has learned more regarding the spectral qualities of plastic cladding materials and removable glass coatings by both surveying the range of materials available in the UK and also by making measurements at the AHDB pot and bedding plant centre in collaboration with Jill England (ADAS).
On-going developments at STC have resulted in the opening on the new LED4CROPS high-wire facility and this has given Dr Davis the opportunity to learn more regarding the engineering aspects of glasshouse design and installation of different lighting systems in glasshouse settings. The new high-wire facility has been used to demonstrate the potential of using LED lighting to produce year round tomato crops and its impact on glasshouse energy budgets. This project has given Dr Davis and Dr Beynon Davies the opportunity to learn about climate management and crop monitoring for commercial tomato crops (thanks to Mr Gerry Andrew and Derek Hargreaves) as well as improving links with the TGA.

## Training objectives

## Objective T1.

Competed year one.

### Objective T2.

During the third year of the Fellowship trainees have remained in contact with the multiple LED manufactures and tracked the changes and advances that have happened in the field. Dr Davis have been involved in the AHDB Hort. Funded project CP 139: Commercial Review of Lighting Systems for UK Horticulture, which was led by Dr Simon Pearson. This project has made some very interesting quantifications of the efficiency of several LED lighting systems and how they compare to standard HPS lighting systems. The project provided a very useful training exercise for me and the results will be very useful for the industry. The trainees knowledge of how plants perform under a range different LED lighting systems has been advanced by the work underway in the AHDB Hort. Funded project CP125. Their knowledge of how LED lighting systems in glasshouses result in electrical energy savings and how that interacts with the reduced radiative heat, in comparison to HPS lighting, and overall glasshouse energy requirements has been greatly advanced via my management of a tomato crop in STC's LED4CROPS high-wire facility.

Trainees have familiarised themselves with the range of spectral filters available, both different plastics and glass coatings both from samples obtained from suppliers and by visiting and performing measurements at ADHB's pot and bedding plant centre.

### Objective T3.

During the third year of the fellowship trainees have remained in contact with the wide range of scientists around the world. Dr Davis hosted a visit of Prof. Carl Otto-Ottosen during which he performed photosynthetic measurements on a Basil and Sage plants grown under a range of red:blue light treatments as part of the AHDB funded CP125project Dr Davis is a co-supervisor for a new PhD student at York University whom will be examining the role of the circadian clock in abiotic stress responses. Dr Beynon-Davies hosted a visit from Mr Richard Boyle during which he made physiological measurements on pelargonium plants grown in the LED4CROPS facility. This experiment was part of his PhD studentship for which Dr Davis is a industry - supervisor.

### Objective T4.

During the third year of the fellowship Dr Davis has managed two large research projects CP125 and the high-wire tomato project in STC LED4CROPS high-wire facility. These projects have helped Dr Davis further develop his personel and time management skills. He has continued to work with a range of different contacts to examine routes to bring in new collaborative projects and explore different routes for funding projects.

### Objective T5.

Via the high-wire tomato crop project the trainees have made new contacts and developed closer links with the tomato growers association (TGA). During attendance of a meeting of the IPPS Dr Davis made new contacts with a range of plant propagators and visited Whetman Pinks to learn more about their breeding program and Kernock plants to see their ongoing LED trials, during this trip he also visited Suttons Seeds.

## Research Objectives

### Objectives R1 & R2.

While the initial goals of these objectives have been completed further progress has been made in these areas. Dr Davis' involvement in the CP139 project has allowed him access to the light spectra of several LED systems and has continued to keep an eye on the developments across the LED lighting sector. Dr Davis also began to make measurements of the light transmitting properties of a range of spectral filters both on samples in the lab and at AHDB's pot and bedding plant centre. Using the data generated in the CP125 project the trainees have begun to test models to help explain how plants are responding to different colours of light. These models will be useful for predicting how plants will respond to novel combinations of light with the aim a speeding light recipe development.

### Objective R3.

Results from the CP125 project continue to develop my knowledge and understanding of plant light responses. The research is now beginning to move in to the second stage of work that will examine how blue and far-red light responses interact. The aim is to produce compact plants with advanced flowering. The trainees involvement in the tomato crop project at STC has greatly improved their knowledge of tomato crop production and how LEDs can improve crop performance and how this influences the energy management of the glasshouse.

### Objective R4.

A technical review of LED lighting systems has been completed and submitted to AHDB for publication.

Articles will be published in the AHDB grower magazine summarizing some aspects of the LED technical review and the CP125 year on report.
Dr Davis has made several presentations as academic and grower facing events and visited several nurseries (see training and knowledge transfer sections for full details).

## Objective R5.

The funding secured for the CP125 project has created many interesting results and will continue to do so over the coming 18 months. This work package of the fellowship will have two major focuses over the coming year. 1) Building on the findings of CP125 identify areas were further research will improve our ability to efficiently utilise spectral manipulation techniques for improving crop performance. 2) Publish the results from the experiments to increase visibility of this research program in the wider academic world to help encourage collaborative projects with Universities.

## Milestones not being reached

None

## Do remaining milestones look realistic?

Yes, though additional milestones have also been created to extend the scope of the fellowship program and gain a greater benefit for the growers.

## Training undertaken

## Conferences attended

International conference on vertical farming and urban agriculture (VFUA) held Nottingham University in September 2014.

BHTA meeting held at the University of Worcester on 21st October 2014.

Grow save: Update on latest greenhouse energy saving research. STC, November 2014
BPOA Technical Seminar held at The Oxford Belfry Hotel, Milton Common, Thame, Oxfordshire on 21st January 2015.

NCUB, London, March 2015

Association of Applied Biologists, Lancaster University, UK June 2015
Tomato Growers Annual Meeting, Coventry, September 2015.
South West growers conference / IPPS meeting, Exeter, October 2015.

## Grower Visits

Kernock Park Plants, Ornamentals, February and October 2015.
Suttons Seeds, October 2015.
Whetman Pinks, Ornamentals, October 2015.
AHDB's pot and bedding plant centre, Bagintons Nurseries, Ornamentals, June 2015.

## Expertise gained by trainees

Both Dr Davis and Dr Beynon-Davies have continued to improve their understanding of plant light responses through their ongoing trials. Much of the advances in their knowledge of plant light responses have come from their research for the AHDB funded CP125 project while a greater understanding of the agronomic and economic benefits of LEDs have come from industry funded projects.

Dr Davis visited the lighting industry association (the LIA) to gain a better understanding of the process required to measure the energy efficiency and efficacy of LED lighting systems. January 2015.

Through involvement in the projects running in the LED4CROPS High-wire facility Dr Davis and Dr Beynan-Davies have gained a great deal of information regarding climate control and lighting systems for use tomato crops.

Trainees have gained knowledge of the spectral effects of commercially available spectral filters.

Trainees have gained further insights to the process of gaining funding from AHDB panels which will be highly valuable for gaining future projects.

Trainees have gained insights into the methods used for converting between measurement units of different type of light measurement.

## Other achievements in the last year not originally in the objectives

The David Piccaver Sicence award at the Grower of the year awards 2015.
Dr Davis has performed research paper reviews for several academic journals as part of the peer review process.

# Changes to Project

## Are the current objectives still appropriate for the Fellowship?

Progress with the original objectives of the fellowship has been good but as the program has developed it has become clear there is the opportunity to add additional objectives to expand the scope of the fellowship and to improve the benefits provided to the industry.

**Objective T6.** A main focus of the fellowship program is securing the skills and expertise for performing and understanding plant light response research programs. The training aspects of this fellowship will be extended to encompass the training of additional members of the research team at STC by Dr P Davis. This will not only develop the skills of Dr Davis but will expand the personnel available to the industry as a whole thus improving access to skills in lighting research. Much of this training will be provided to Dr Rhydian Beynon-Davies whom has recently completed an AHDB funded PhD at Lancaster University, but will also be expanded to members of the Entomology and Pathology teams during crossover projects. The training provided to Rhydian will largely follow the direction of the main fellowship program and will focus of developing Rhydian's skills and increasing his understanding of the role of lighting in the industry and as well as improving his knowledge and contacts within the industry. ***This will be ongoing for the remainder of the fellowship.***

**Objective R6.** In the current research environment there is a growing need to increase collaboration between organisations like STC, Universities and industry. In order to develop links with Universities it is necessary to further develop my scientific credentials through publication of my research in academic journals. This will both boost awareness of our research in academic circles but also demonstrate our scientific expertise in a manner that can be quantified. ***This will form a major focus of the fellowship during year 4.***

**Objective R7.** The skills necessary to acquire project funding and run lighting projects are currently in development under objective R5 and through management of CP125. However, this program will be expanded to encompass development of collaborative projects with Universities and companies both with in the UK and as part of EU projects. Developing collaborative projects will require increases interactions with the network of contacts developed in training objectives T2-T5. ***This will be a major focus of the fellowship during years 4 and 5.***

# GROWER SUMMARY 1: Spectral Filters

## Headline

Spectral filters, both plastic polytunnel cladding materials and removable glass coatings, can potentially be used to improve crop performance and quality if the correct spectral qualities can be achieved. A survey of the light transmitting properties of these materials has been performed.

## Background

With the use of LED lighting systems plant morphology, pigmentation and flowering time can all be manipulated to improve crop production systems. Experiments underway in the CP125 project examining plant responses to LED lighting have greatly improved our understanding of how to manipulate plants and much of this information is relevant to how plants respond to sunlight and spectral filters.

Within the UK there is a large area of crop grown under some form of protection (polytunnels and glasshouses). Several types of plastic cladding materials are available that alter the quality of light and removable glass coatings for glasshouses that provide shading and spectral manipulation are also now available. Each material has properties that have the potential to improve some aspect of crop performance under certain conditions. Selecting the best material for a given crop and location is a challenge as there is limited independent information regarding the light spectrum achieved under each material. Here we report assessments of the light transmission spectrum of a range of spectral filters that are commercially available. We also report on measurements of the light environment in the different treatments in use at AHDB's pot and bedding plant centre. These measurements will aid the interpretation of the crop responses observed.

## Summary

The transmission spectra of a range of spectral filters (both plastics and glass coatings) were measured at Stockbridge Technology Centre under full sun conditions. Clear plastics (Sunmaster Clear and Lumisol Clear) were found to transmit approximately 90% of the direct photosynthetically active radiation (PAR). For diffuse plastics (SunMaster diffused and Luminance) PAR transmission was decreased to approximately 85%. While the diffuse plastics slightly reduced total light transmission due to increased reflectance they are expected to produce a more uniform light environment and to increase plant uniformity. Plants are also able to use diffuse light more efficiently than direct light so may even grow faster under diffuse plastic. While the clear, diffuse and white plastics differed in the amount of PAR light they transmitted they all transmitted evenly across the spectrum so had little influence of the PAR light quality. Transmittance in the UV region of the spectrum was more variable. Clear and UV transparent films (SunMaster Clear, SunMaster Lite, Lumisol Clear) transmitted the largest proportion of UV light (between 72 and 84%). The diffuse materials (SunMaster diffuse and Luminance) were observed to reduce UV transmission to a greater extent than PAR light with UV transmission as low as 40%. The thermaprop and sterilite plastics blocked UV transmission with as little as 6% UV passing through. Increased UV transmittance has been shown to improve plant pigmentation and resistance to pest and pathogen attacks so can both improve plant quality and reduce the need for pesticide applications. The two coloured plastics (SmartBlue and Smart Green) examined greatly altered the colour and, therefore, the quality of the light entering the cropping area. The Smart blue transmitted only 44% of PAR light but 75% of the blue light. This is expected to reduced growth rate compared to uncoloured plastics but may help maintain plant compactness because the blue proportion of light increased from 20% to 40% of PAR. The Smart Blue plastic was also observed to reduce UV transmission, allowing only 20% through. The SmartGreen plastic is also expected to reduced growth rates but to a lesser extent than the SmartBlue plastic, as 70% of PAR was transmitted. The SmartGreen transmitted a similar amount of blue light to the SmartBlue plastic but allows a greater amount of red and green light through. Interestingly the Smart Green plastic also transmitted a greater proportion of UV light (51%) than the SmartBlue plastic.

The light transmitting qualities of several removable glass coatings were also examined. These materials can be applied at different concentrations to alter the total amount of light entering a glasshouse so for the measurements presented here it is the relative amounts of the different colours of light rather than the absolute transmission values that are of interest. The ReduFuse coating was observed to increase transmittance by reducing the reflection of the surface on the plastic to which the coating was applied. The ReduFuse and ReduFuseIR had little impact on the spectral quality of the measured light and transmitted evenly across the measure spectral range measured. The ReduSol was observed to transmit slightly less blue and UV light than red or green light. The ReduHeat was found to transmit less UV than PAR light and less far-red and infrared light. The ReduFlex Blue and ReduFlex Green materials act differently to the blue and green plastics described above. The ReduFlex material reduces the amount of blue or green light entering the growth area by preferentially reflecting these colours of light. ReduFlex Blue coating transmitted only 24% of the UV light and only 50% of blue light compared to 79% of the red light. The ReduFlex green coating transmitted less UV than PAR. There was a slight decrease in the transmittance in the green region of the spectrum but this is expected to have little effect on plant performance.

The measurements made at STC provide information on how the different filters affect light quality and quantity of light but do not necessarily correlate directly with how well the materials perform when installed on polytunnels or glasshouses. This is due to several factors including the ever changing angle of the sun through the days and seasons and the different shapes of the relevant structures. Measurements of the light spectrum in several polytunnels and a glasshouse at the AHDB pot and bedding plant centre were made to test how a selection of different plastics perform *in situ*. The light measurements will also be useful for describing the responses of the plants grown under the different materials. Comparison on the measurements made at STC and the pot and bedding plant centre demonstrate that the overall influence on the light spectra was similar in the two systems but the magnitude of changes in the transmission spectrum differed. In the polytunnels maximum transmittance values were smaller and minimum transmission values were larger. This resulted in less extreme changes in the measure spectra in polytunnels. These data indicated that while spectra on the light transmitting qualities of plastics is useful more real world measurements are required to fully understand how the light environment changes in different structures and through the seasons.

## Financial Benefits

Selection of the correct spectral filters can improve crop performance and ensure the maximum return from investment. It is especially important to select an appropriate polytunnel cover as these may be expected to last for 10 years. The correct filters could improve crop quality and reduce the need to control morphology with plant growth regulators. If an inappropriate plastic is selected it could have a long term negative impact on crop performance or result in the need for a costly replacement. Using the example of tomato, 1% light loss equates to 1% yield loss, the long term implications of selecting poor spectral filters is clear to see. From this perspective removable coatings provide a flexible solution as they can added and removed in response to variable weather conditions ensuring the light environment can be adjusted to meet the needs of the crop.

This work provides growers with independent information regarding the spectral quality of different materials to help them select the correct plastic or removable coating. However, additional information regarding plant light responses to the different light environments is required for maximum benefits to be achieved. The ongoing trials at the AHDB pot and bedding plant centre will provide some of that information.

## Action Points

Understanding the light environment within crop production facilities is important for correct management of the crop. By making measurements both inside and outside a crop production structure it is possible to determine actual light transmission of that structure. It is important to ensure the light environment does not change between measurements. For horticultural purposes measurements should ideally be made using good quality PAR sensors. If LUX metres are available they can be used for materials that do not greatly affect to colour of the light. However, for any material that alters the colour of the spectrum for example SmartBlue plastic or ReduFlex Blue LUX metres should be avoided as they will give incorrect estimates. For a complete understanding of how a structure is influencing the light environment measurements should be made at different times of day and at different times of year. Measurements of light intensity within a crop production facility combined with the spectral information provided in this report can be used improve understanding of crop appearance and quality as well as aid management decisions for crops that are not performing optimally.

## GROWER SUMMARY 2: Understanding light in glasshouses.

### Headline

The majority of light within a glasshouse is provided by sunlight but more and more growers are exploring the options for supplemental lighting systems. Understanding how to compare different sources of light is important to ensure plants receive sufficient light for healthy growth. Here we use measurements of different sources of light (sun, HPS and LED) in the LED4CROPS hire-wire glasshouse facility as an example of how to make these comparisons.

### Background

Much of the work performed as part this fellowship and the parallel CP125 projects has been focused on plant responses to LED lighting in closed facilities with no sunlight. This work is important for understanding how light can influence plant growth and development. However, the majority of crop production systems will remain in glasshouse situations where the sun has a large influence over plants. LEDs are expected to have many applications in glasshouse settings but understanding how to use LED requires a better understanding of how this light compares to sunlight. The work reported here is aimed at learning more about how LEDs perform in glasshouse settings and to provide examples of how to correctly compare light measurements made using different types of commonly used light sensor (Lux, Watts, Joules and PAR sensors) on different sources of light (sun, HPS and LED lights).

Traditionally high pressure sodium (HPS) lights have been used to light crops during the winter months to maintain crop vigour and growth. Until the release of LED lighting systems HPS lights were the most energy efficient type of light but even so their energy consumption means achieving economic winter production can be challenging. The introduction of LED lighting systems for horticultural use holds the potential to alter that economic balance as they are more energy efficient and therefore, have lower running costs. The reduced running costs must be weighed in comparison to the ‘current’ higher installation costs of LEDs compared to HPS but also with the potential benefits (increased yield, and crop quality) that may be achieved by using LED light sources.

This year STC invested in an upgrade to one of their glasshouses. The height of the glasshouse was increased to allow high-wire crop production techniques and three different supplemental lighting systems were installed, 1) conventional HPS top lights, 2) a hybrid system containing HPS top lights and LED interlighting and 3) an all LED system with LED top lights and LED interlights. Each of the three sources of light (sun, HPS and LED) are generally measured and reported in different units (joules, lux and µmol $m^{-2}$ $s^{-1}$). In order to make comparisons of the different light sources conversions between the different measurement systems are required.

## Summary

Based on the number of lights installed and the lamp efficacy data (a measure of how efficiently lights convert electricity to light) we calculated the expected light intensity in the glasshouse compartments. When compared to measurements made 1m below the lamps these calculations were found to be accurate. These calculations (See Box1) can be useful for determining how many lights will be needed to achieve a desired light intensity which provides some of the initial information required to determine the costs associated with an LED installations. The measured light intensity below the top lights in the conventional HPS treatment was 259 µmol [PAR] $m^{-2}$ $s^{-1}$, below the HPS lamps in the hybrid system it was 133 µmol [PAR] $m^{-2}$ $s^{-1}$ and below the LED top lights it was 144 µmol [PAR] $m^{-2}$ $s^{-1}$. Due to the orientation of the LED interlights it is difficult to measure the light they produce in a glasshouse setting, however, their calculated light output was 104 µmol [PAR] $m^{-2}$ $s^{-1}$. Total supplemental light intensities were 259 µmol [PAR] $m^{-2}$ $s^{-1}$, 237 µmol [PAR] $m^{-2}$ $s^{-1}$, 248 µmol [PAR] $m^{-2}$ $s^{-1}$ in the conventional HPS, hybrid and LED only compartments respectively. While the light intensities were similar in the three lighting systems the distribution of light within the growth areas differed. The LED top lights were found to have a more uniform light distribution over the measured area than the HPS lamps. The LED interlights also improved the vertical distribution of light in a tomato crop by providing light to the shaded region of the canopy.

Sunlight measurements at STC were made using a global radiation sensor connected to the PRIVA computer. This sensor measures all wavelengths of sunlight and records the data in units of W $cm^{-2}$ (DLI values have units of J $cm^{-2}$ $d^{-1}$). The measurements of the supplemental lighting systems were made using a PAR sensor. This type of sensor measures light with wavelengths between 400 and 700 nm (the light that can be used for photosynthesis) with units of µmol [PAR photons] $m^{-2}$ $s^{-1}$ (DLI values have units of mol [PAR photons] $m^{-2}$ $d^{-1}$). HPS lamp light is often measured using Lux meters. When measurements are made in different units it is difficult to compare the measurements. If the measurements are all converted to have the same units it is possible to make direct comparisons between light sources. This allows more informed decision making as when in the year lights should be turned on and for how long.

The seven year average global radiation DLI measured for the 1st April at STC was 1087 J $cm^{-2}$. Assuming a glasshouse light transmission of 70% this was the equivalent of 14.8 mol [PAR] $m^{-2}$ $d^{-1}$. If supplemental lighting with an intensity of 259 μmol [PAR] $m^{-2}$ $s^{-1}$ was turned on for 16 hours this would provide a crop with a DLI of 15.4 mol [PAR] $m^{-2}$ $d^{-1}$, similar to the sunlight received inside a glasshouse in April at STC. For HPS lighting, an intensity of 259 μmol [PAR] $m^{-2}$ $s^{-1}$ is equivalent to 19,350 Lux.

## Financial Benefits

For growers considering investing in lighting systems it is useful to be able to determine the numbers of lights that would be needed to achieve a specific light intensity. This can be used to help determine the investment costs required. With light costing £400,000 per hectare (or more depending on the lighting system) it is important to ensure the crop will receive enough light to achieve the desired goals.

A good understanding of the expected light outputs from any lighting system is important to ensure light installations provide enough light to drive good plant growth. Much of our experience of using supplemental lighting systems come from the use HPS installations. However, the light output of HPS systems has historically been described in terms of Lux. The light output of the majority of LED lighting systems, especially those using predominantly red and blue light, are reported in units of μmol $m^{-2}$ $s^{-1}$. Where LEDs are being considered for replacing HPS lamps it is necessary to ensure the LEDs produce the equivalent amount of light. Getting the amount of light incorrect would lead to poor plant performance and potentially expensive mistakes.

The calculations provided in BOX 1 can be used to calculate how many lamps are required to light a glasshouse with a given type of lamp (using manufacturer data of lamp wattage and efficacy). With this information it is possible to approximate installation and operational costs.

## Action Points

For growers considering switching from HPS light to LEDs the methods presented here can be used help determine how many LEDs would be required to achieve the same levels of light. This can be used to determine the installation costs as well as the running costs and potential electricity savings.

For growers considering installing LED lighting systems they should consider purchasing a PAR meter, Lux meters should not be used.

Historical light measurements made using different sensors and measurement units can be converted to have the same units. This will help growers understand how much plant-usable light is present in a glasshouse at different times of year. When combined with knowledge of plant light requirements this information will help direct management strategies aiding growers to decide when lighting systems should be used.

## BOX 1: Calculating the expected light intensity of lamp installations.

The expected light intensity ($E$ = μmol [PAR] $m^{-2}$ $s^{-1}$) with in a crop production area can be calculated based on the manufactures (or data from independent measurements see CP139) reported lamp efficacy data using the formula:

$$E = \frac{n \times W \times e}{A} \qquad \text{(Equation 1)}$$

Where $n$ = number of lamps, $W$ is the wattage of the lamps, $e$ is the lamp efficacy (μmol $J^{-1}$) and $A$ is the area ($m^2$) being lit. Some manufactures report lamp output in as photon flux ($F$ = μmol $s^{-1}$). Photon flux values can be converted to efficacy values by dividing the photo flux value by the wattage of the lamp. Alternatively photon flux values can be used to calculate the expected light intensity directly using the simplified equation:

$$E = \frac{\mathrm{n} \times F}{\mathrm{A}} \qquad \text{(Equation 2)}$$

The lamp installations in the LED4CROPS high-wire facility are used as examples bellow.
Calculated intensity of conventional HPS treatment.

The conventional HPS installation contained 32, 600W HPS lamps covering an area of 150$m^2$. The efficacy of 600W HPS lamps was 2.1 μmol $J^{-1}$. So using equation 1 we can calculate the expected light intensity to be $E = \frac{\mathrm{n \times W \times e}}{\mathrm{A}} = \frac{32 \times 600 \times 2.1}{150} = 268\ \mu\mathrm{mol\ [PAR]}\ m^{-2}\ s^{-1}$.
Calculated intensity of HPS light from hybrid treatment

The hybrid treatment contained 16, 600W HPS lamps covering an area of 150$m^2$. The efficacy of 600W HPS lamps was 2.1 μmol $J^{-1}$. So using equation 1 we can calculate the expected light intensity to be $E = \frac{\mathrm{n \times W \times e}}{\mathrm{A}} = \frac{16 \times 600 \times 2.1}{150} = 134\ \mu\mathrm{mol\ [PAR]}\ m^{-2}\ s^{-1}$.
Calculated intensity of LED top lights

The LED top light installation contained 48, 190W Philips LED modules covering an area of $150m^2$. The efficacy of these LEDs was 2.4 µmol $J^{-1}$. So using equation 1 we can calculate the expected light intensity to be $E = \frac{\mathrm{n}\times\mathrm{W}\times\mathrm{e}}{\mathrm{A}} = \frac{48\times190\times2.4}{150} = 146\ \mu\mathrm{mol\ [PAR]\ m^{-2}\ s^{-1}}$.

Calculated intensity of LED interlights

For the interlight installations 64, 105W Philips LED interlight modules were used to light an area of $135m^2$. The efficacy of theses LEDs was 2.1 µmol $J^{-1}$. So using equation 1 we can calculate the expected light intensity to be $E = \frac{\mathrm{n}\times\mathrm{W}\times\mathrm{e}}{\mathrm{A}} = \frac{64\times105\times2.1}{135} = 104\ \mu\mathrm{mol\ [PAR]\ m^{-2}\ s^{-1}}$.