Horticultural Fellowship Awards

Interim Report Form

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) Prof. Nigel Paul, Lancaster University (Mentor)
Trainees	Dr Phillip Davis, Applied Photobiologist, Dr Rhydian Beynon-Davies
Location of project:	Stockbridge Technology Centre
Industry Representatives:	Chis Plackett, FEC Russel Woodcock, Bordonhill James Bean, Crystal Heart Salads Neal Wright, Micropropagation Services Simon Budge, VHB Ltd (Herbs) Colin Frampton, Consultant Steve Carter, Protected and indoor Ornamentals Geoffrey Smith, Mapleton Growers (Protected Edibles - Lettuce)
Date project commenced:	1 October 2012
Date project completed (or expected completion date):	30th September 2017

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 ....

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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.
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.

SCIENCE SECTION 1: Spectral Filters

The light transmission spectrum of a range of commercially available spectral filters were examined with the aim of providing a preliminary independent assessment of the optical properties of the different materials.

Introduction

The majority of horticulture relies on natural sunlight for plant growth. Sunlight, however, varies considerably through time and at different times of year there can either be too much or too little light. Plants grown in low light conditions can become etiolated if control measures are not taken to regulate growth and morphology (i.e. plant growth regulator applications or altered temperature settings). In bright light conditions sensitive or weak plants can become scorched. Both problems can result in poor quality plants that are not fit for sale. Cladding materials that alter the spectrum or structure (direct vs diffuse light) of the light entering a crop production facility have the potential to correct some of the issues associated with natural light variation and improve crop consistency and uniformity of plants.

Materials that diffuse sunlight light before it hits the plants have the potential to create a more spatially uniform light environment within the production facility as shadows are largely eliminated. These materials can also result in a more uniform intensity through time as they reduce the light intensity and heat entering structures at midday when the sun in high in the sky but can also help more light enter the production facility early and late in the day when the sun is low in the sky. Diffuse materials, therefore, have the potential to improve plant performance during both summer and winter periods.

Materials that alter the spectrum of light also have the potential to improve different aspects of crop production. UV transmitting and opaque plastics have been investigated for controlling pest populations, altering plant morphology and pigmentation. UV blocking materials tend to reduce the migration of pest species into crop production facilities. However, UV light plays an important role in building plant defences against pests and diseases and plants grown under UV transparent materials are more resistant to pests and diseases than those grown under UV opaque materials. Plants grown in the presence of UV light also tend to have stronger leaf and flower pigmentation as plants produce many pigments as protection against damage caused by UV light. Materials that alter the proportion of blue and green light entering the cropping area also have the potential to alter crop morphology though these types of filter also reduce the total amount of light reaching the plants. These materials may, therefore, have a more beneficial influence during the summer months. The greatest benefits of these materials may be achieved when multiple properties are combined such as in UV transmitting, diffuse plastics.

While much of the work in the fellowship program to date has been associated with spectral manipulation of plants using LED lighting much of the improve understanding of plant light responses will help improve the application of spectral filters. In this report the light transmitting properties of a range of spectral filters that are commercially available have been examined. These measurements were aimed at providing an initial over view of material properties. The filters examined include plastic cladding materials and removable glass coatings. Measurements of light transmission in operational polytunnels have also been performed at the AHDBs pot and bedding plant centre to assess the light quality in commercial polytunnels.

Materials and methods

Transmission spectra of spectral filters

Measurements were performed at Stockbridge Technology Centre under sunny conditions. Transmission spectra were measured outside in direct sunlight using a Jaz spectroradiometer (Ocean optics). The sensor was mounted on a clamp stand and pointed directly at the sun. A measurement of the solar spectrum (I_S) was made before each spectral filter's transmission spectra (I_F) was measured by placing the filter in front of sensor. The filters were placed close to the sensor to minimise unfiltered light entering the sensor. Transmittance (T) was calculated as, $T = I_F / I_S$.

Pot and bedding plant centre measurements

Measurements were made at the AHDBs pot and bedding plant centre at Bagintons Nurseries on the 22nd June 15. Light measurements were made between 11am and 3pm using a hand held portable Jaz spectroradiometer. During the measurement period patchy cloud cover caused large variations in light intensity (Figure 1). To avoid noise in the data measurements were only made under full sun, measurements were stopped even if cloud partially obscured the sun. Several measurements of direct sunlight outside were made before and after measurements were made within each of the trial areas to ensure any changes in light intensity through time were accounted for in the measurements.

Measurements were performed in five trial areas including four polytunnels and one glasshouse. Within the glasshouse measurements were made when the screens were open and when the screens were closed. Two polytunnels were clad with light diffusing plastic one with Lumisol and with Luminance. Two polytunnels were clad with SmartBlue plastic, one was covered in new plastic and one was covered in older plastic.

The spectra presented are the mean of at least 5 measurements. Data were discarded if there was evidence of reduced light levels caused by cloud cover. Transmittance was determined as the mean spectrum within the trial area divided by the mean spectrum measure outside.

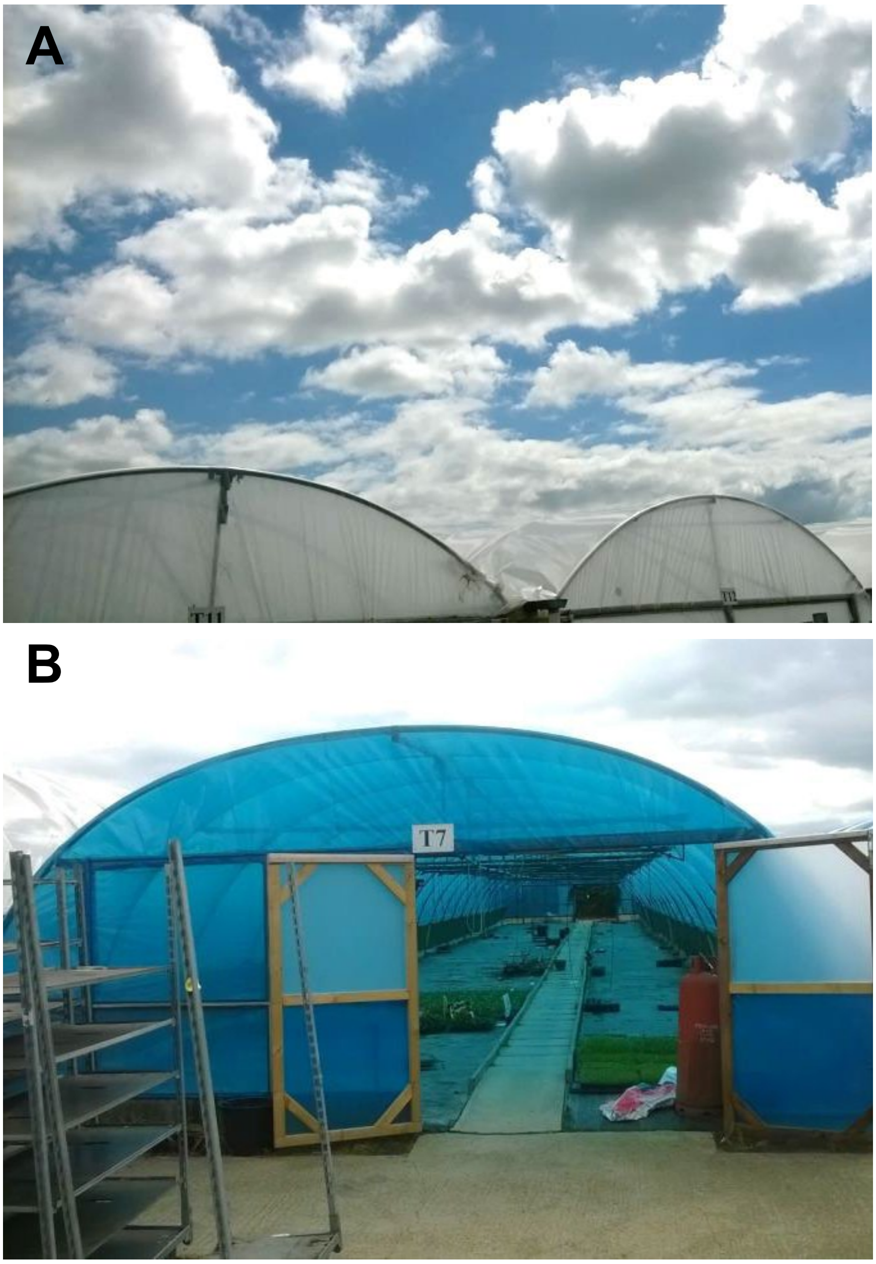

Figure 1. A) Image of the challenging (for light measurement) weather conditions during my visit to the AHDB's pot and bedding plant centre. **B)** Example of one of the polytunnels clad with SmartBlue plastic.

Results

The transmission measurements of the different spectral filters made at STC have been performed once and were made with the aim of providing an overview of optical qualities of the different plastics rather than providing absolute quantitative measurements of the qualities of each product. The measurements are not appropriate for assessing the thermal properties nor the UVB transmitting properties of the materials.

Figure 2 and Table 1 show the measurements performed on samples of horticulture plastics examined. The three clear plastics (SunMater Clear, SunMaster Lite and Lumisol clear) had the highest (88-92%) transmittance values across the PAR spectrum and had very little impact on PAR light quality. Within the UV region of the spectrum more variation was observed with Lumisol clear transmitting the most UV (84%) while SunMaster Lite and SunMaster Clear transmitted slightly less, 77 and 73% respectively.

The diffuse plastics (SunMaster diffuse, Luminance and SunMaster superthermic and SteriLite) transmitted about 10% less radiation than the clear plastics across the PAR (400-700nm) region of the spectrum. This is consistent with the light scattering action of the diffusing agent contained within plastics causing a greater proportion of light reflection. As was the case for clear plastics the greatest variation in transmittance was observed in the UV region of the spectrum. UV transmittance ranged from as low as 6% (SteriLite) up to 65% for Luminance. Comparison of the diffuse and clear SunMaster plastics indicates the diffusing agent has a greater influence of UV transmission than PAR transmission. The Thermaprop plastic is white rather than diffusing and because of this it only transmitted approximately 50% PAR and very little UV (6%) light.

Two coloured plastics were also examined SmartBlue and SmartGreen. The SmartBlue plastic removed about 85% of the red light from the spectrum and about 90% the UV light. The Smart Green plastic transmitted more UV light than the SmartBlue plastic. The SmartGreen transmitted a similar amount of the blue region of the spectrum to the SmartBlue plastic but removed less of the green and red light. The blue plastic had a greater influence of the red:far-red ratio than the green plastic.

The optical properties of six ReduSystems removable glass coatings are shown in (Table 1 and Figure 3). Unlike the plastic filters the absolute transmittance values can be altered by changing how much material is applied to the glass. These coating also differ to the plastics in how their name refers to the effect they have within the plant production area. For example the SmartBlue plastic described above allows blue light to enter the crop production area.

The Reduflex blue coating, however, reflects blue light causing the light entering the glasshouse to contain less blue light and have a yellowish tint.

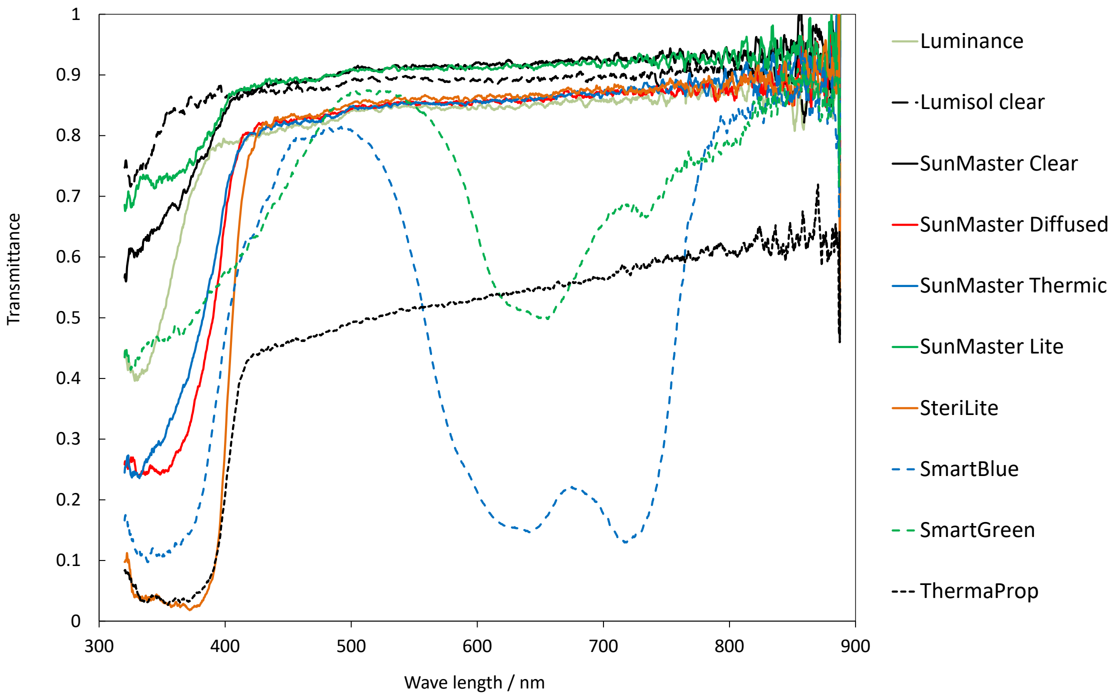

Figure 2. Transmission spectra of several commercially available plastics.

Table 1. Percentage transmission of horticultural plastics and removable glass coatings measured at STC. Transmittance values are provided for different colours of light.

Colour band	PAR 400-700nm	UVA 320-400nm	Blue 400-500nm	Green 500-600nm	Red 600-700nm	Far-red 700-800nm
Clear plastics						
Lumisol clear	89	84	88	89.3	89.4	90.2
SunMaster Lite	91	77	89	91.0	91.5	92.4
SunMaster Clear	91	73	89	91.3	92.0	92.8
Diffusing plastics						
Luminance	84	65	81	85	85.1	86.5
SunMaster Thermic	85	44	82	85.1	86.3	88.0
SunMaster Diffused	85	37	82	85.2	86.1	87.4
SteriLite	85	6	80	85.9	86.9	87.9
ThermaProp	51	6	45	51.4	54.8	59.3
Coloured plastics						
SmartGreen	69	50	75	81.7	55.1	71.9
SmartBlue	44	21	75	53.2	18.2	41.7
Glass coatings						
ReduFuse	105	108.6	105.4	104.6	104.8	104.7
ReduFuseIR	94	83.7	93.5	93.5	94.0	91.9

ReduSol	62	49.9	59.9	61.8	64.6	69.4
ReduHeat	88	46.8	86.3	88.7	88.8	76.6
Reduflex Green	84	51.4	81.4	80.5	88.0	82.2
Reduflex Blue	70	24.9	51.8	70.5	78.9	73.4

The ReduFuse was observed to have a transmission of greater than 100%. This was caused by the ReduFuse coating reducing the reflection occurring from the shiny surface of the plastic used to contain the sample. The reduced reflection allows a greater proportion of the light to be transmitted. The ReduFuse had little impact on the spectral quality of the light though it did allow slightly more UV to pass than PAR. The ReduFuse IR transmitted 94% of PAR, allowed slightly less far–red light through (91%) and even less UV thought (84%). RedSol allowed 62% of the PAR light through but transmitted proportionally more red than blue or UV light. The Redu Heat coating was observed to remove some red, far-red and infra-red light as well as a large proportion of the UV light. Both the Reduflex green and blue coatings removed a large proportion of the UV light. The reduflex blue removed about half the blue light. Reduflex green removed a small proportion of the green light.

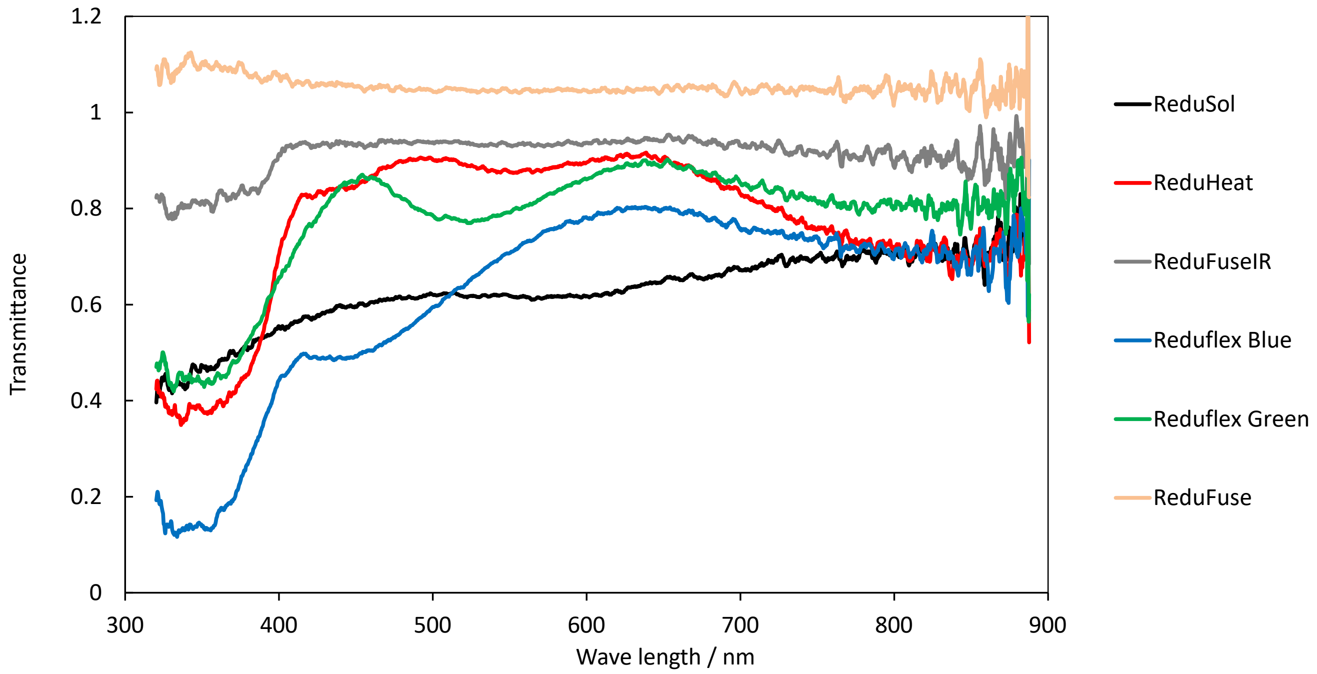

Figure 3. Transmission spectra of several ReduSystems glass coatings.

AHDB's pot and bedding plant centre measurements

Glasshouse

The spectrum of sunlight is shown in Figure 4 (black line). The mean PAR intensity of full sun during the measurement periods was 2224 µmol m^{-2} s^{-1} this is consistent with the maximum solar radiation expected at this location in sunny conditions. Inside the glasshouse the PAR light intensity was reduced by 21% and the UVA light intensity is reduced by 38%. The spectrum within the glasshouse (Figure 4, green line) is similar in shape to that of full sun but when the light transmittance of the glasshouse is determined (Figure 5) it is clear that UV light with wavelengths less than 350nm are absorbed by the glass. Within the PAR region of the spectrum slightly more green light (81%) was transmitted than red (80%) or blue (76%) light (Table 2 and Figure 5). With the screens in the glasshouse closed the total light inside the glasshouse was greatly reduced with only 15% of the available sunlight reaching the plants (Table 2). The screen did not influence the spectrum of the light.

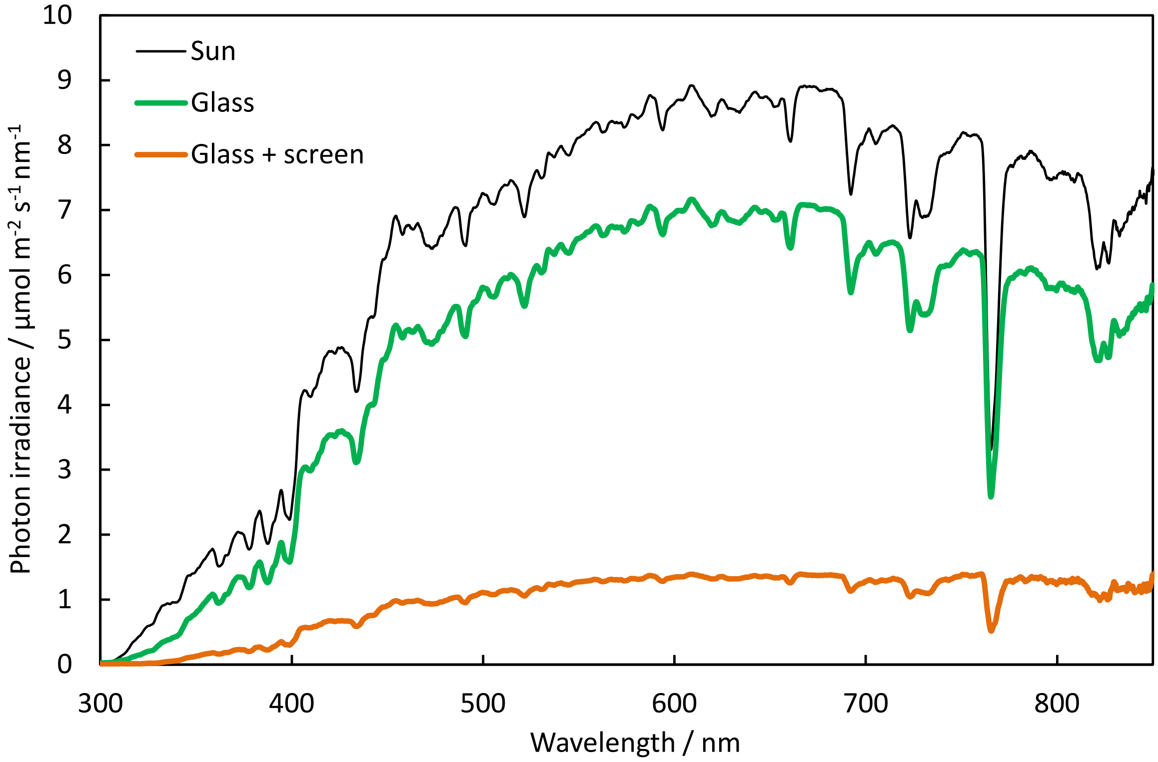

Figure 4. Light spectra measured outside in full sun (Sun) inside the glasshouse when the screens were open (Glass) and when the screens were closed (Glass + Screens).

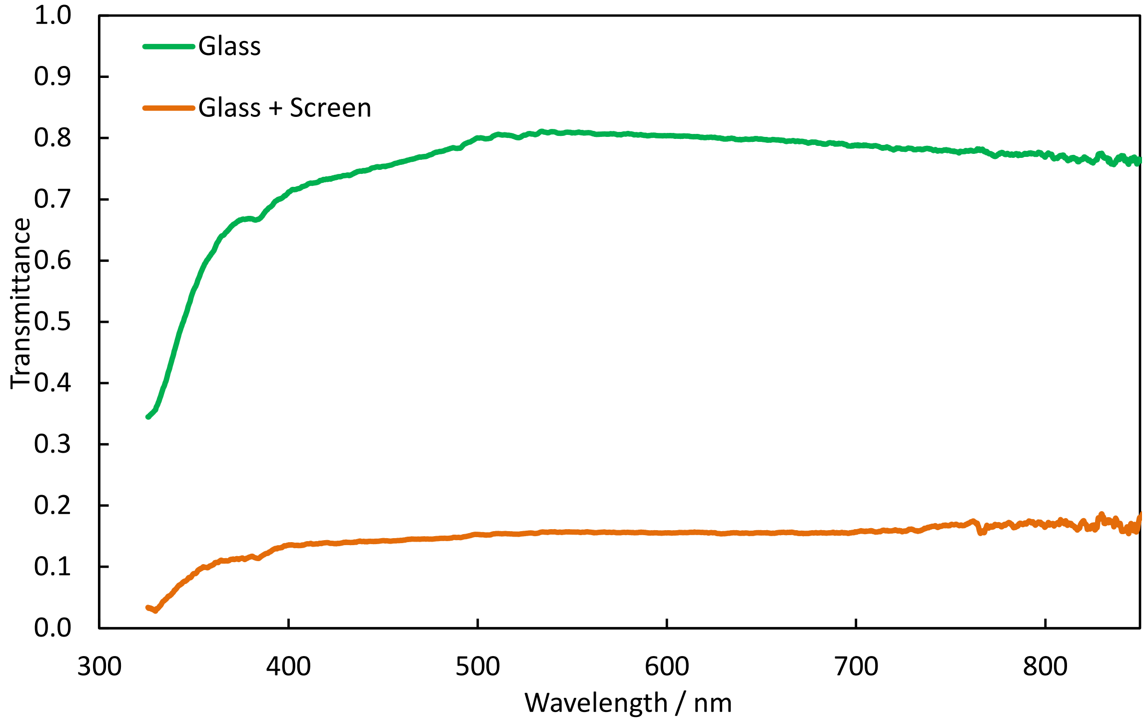

Figure 5. Transmittance spectra of the glasshouse with the screens open (glass) and the closed (glass + screens).

Table 2. The mean light intensity measured outside and within each trial area under conditions of full sun.

Colour	PAR	UVA	Blue	Green	Red	Far red
Wave band / nm	400-700	320-400	400-500	500-600	600-700	700-800
	Mean photon irradiance / µmol m^{-2} s^{-1}					
Sun	2224	123	572	795	858	752
Glass	1760	76	433	641	685	583
Glass + Screen	339	13	82	124	134	123
Lumisol	1556	71	376	562	618	568
Luminance	1632	82	402	588	643	574
New SunSmart blue	956	26	372	406	178	298
Old SunSmart blue	982	28	355	417	210	292
	% transmission					
Glass	79	62	76	81	80	78
Glass + Screen	15	10	14	16	16	16
Lumisol	70	57	66	71	72	76
Luminance	73	66	70	74	75	76
New SunSmart blue	43	21	65	51	21	40
Old SunSmart blue	44	22	62	52	25	39

Diffusing plastics

Light spectra were assessed in two polytunnels with light diffusing plastic. One was clad with Lumisol and one was clad with luminance. The light spectrum under the two plastics was similar though some differences especially at shorter wavelengths were observed. In the far-red region of the spectrum both plastics transmitted a similar amount of light (76%, Figure 6 and Table 2). As wavelength decreased both absolute transmittance and the differences in transmittance between the two plastics increased (Figure 6). In the red and green regions of the spectrum Luminance transmitted 3 % more light than Lumisol. In the blue region of the spectrum Luminance transmitted 6 % more light than Lumisol and in the UVA region of the spectrum Luminance transmitted 9 % more light than Lumisol.

SmartBlue plastic

Light measurements were aslo performed in two polytunnels clad with SunSmart Blue plastic. One tunnel was clad with new plastic and one was clad with older plastic. These plastics transmitted approximately 40% of the available PAR light. The light spectra within the two tunnels was largely similar (Figure 7) with proportionally greater transmission in blue (~65%) than green (51%), red (21%) or UVA (43%) region of the spectrum (Table 2). The older blue plastic transmitted slightly more red and UVA light than the new plastic which is consistent with slight sun damage of the plastic and/or pigments within the plastic.

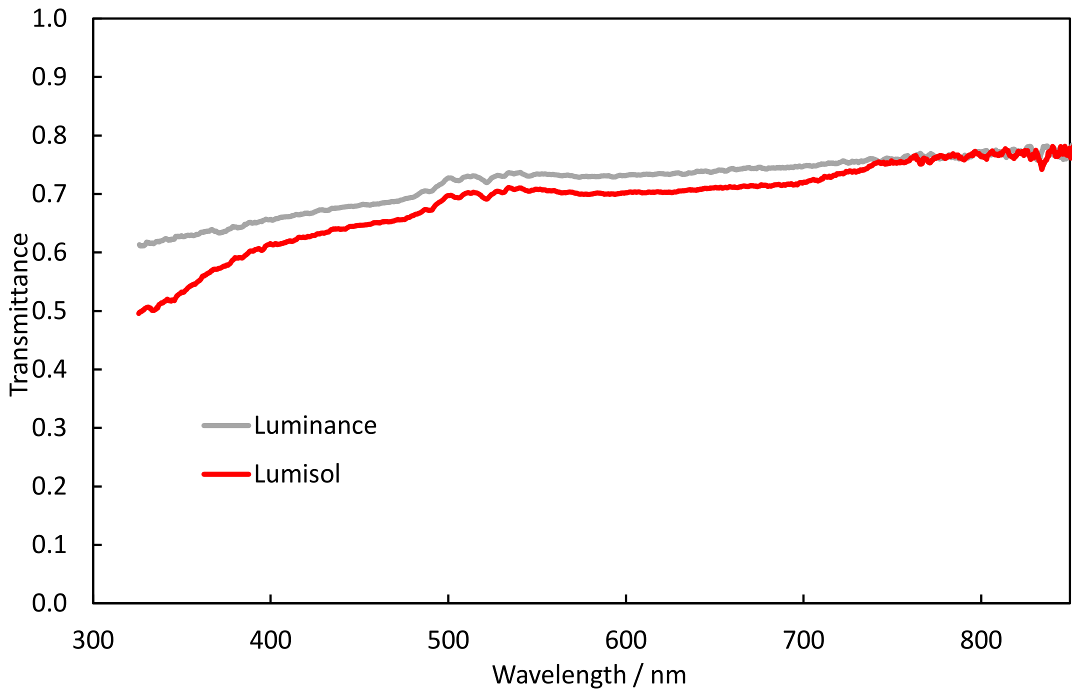

Figure 6. Transmittance spectra of Luminance and Lumisol clad polytunnels.

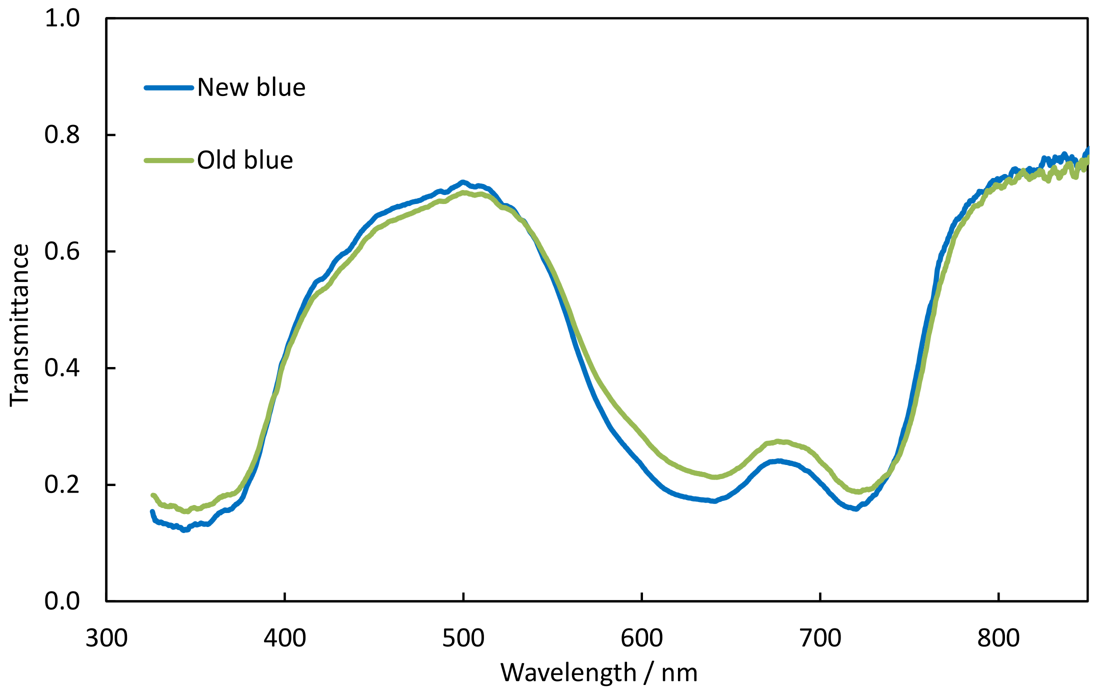

Figure 7. Transmittance spectra of new and old SunSmart Blue clad polytunnels.

Discussion

Plastic cladding materials

UV light can provide many benefits for commercial horticulture including, increased leaf and flower pigmentation, increased leaf toughness and plant compactness as well as increased pest and disease resistance. Several modern plastics transmit UV light. The clear UV transmitting plastics examined were found to allow approximately 90% of the PAR light and between 70 and 90% of the UVA light to pass. Too little UVB light was incident to be accurately detected by the Jaz spectroradiometer used in this experiment but large differences in UVB transmittance between the different plastics are expected. Diffuse plastics were observed to transmit approximately 10% less PAR light than clear plastics under the conditions measured in these experiments. This is consistent with the light scattering properties of these materials which cause increased reflection of the light hitting the materials. While this would initially suggest diffuse material would cause reduced plant growth as less light is entering the cropping area this is not the case. There are several reasons why diffuse light can improve crop performance:

A) Plants are able to capture diffuse light more effectively than direct light and can therefore potentially use more of the light entering the crop production area for photosynthesis and growth.

B) Under diffusing materials there are fewer shadows and the light is more uniform over the growing surface. This results in a more uniform crop.

C) The diffusing materials can damp out the changes in light intensity through time that occur in natural light conditions (as clouds pass across the Sun) and this helps plants acclimate to the light environment, can reduce stress and increase photosynthetic performance of certain crops.

D) The diffuse materials can also reduce leaf temperature, though this can have a positive or negative impact on photosynthetic performance depending on temperature, it will lower water use more consistent.

Comparison of the SunMaster Clear and SunMaster Diffuse plastics showed that diffusing the light had a greater impact on UV light transmittance than PAR light. This has two potential causes 1) the substance scattering the light within the polythene scatters UV light more strongly than the other colours of light. This could result in greater UV reflection or the measurement method observing a lower proportion of the scattered UV light. 2) The plastic absorbs in the UV region of the spectrum and scattering occurring within the material increases the amount of UV light absorbed by the material. The SteriLite plastic and the Thermaprop were found to transmit very little UV light. These plastics may be useful for preventing the migration of insects into a crop production facility but would reduce plant tolerance to any pests that do enter the facility. They would also be useful for plant material that is sensitive to higher light levels as UV light can be highly damaging.

Coloured filters

The benefits of specific colours of light on crop performance are being highlighted through the LED projects associated with this fellowship and with the AHDB funded CP125 project. The improved understanding of plant light responses will potentially help interpret the responses of plants grown under coloured plastics and potentially help focus research in to developing plastics with specific properties. The SmartBlue plastic is designed with aim of boasting the blue proportion of the light spectrum. This is because higher percentages of blue light have been shown to help plants remain compact. However, the large amount of red and green light that was removed by this plastic may result in slower growth and potentially weaker plants especially during the winter months. During the summer months this plastic may protect sensitive plants from scorching while also promoting compactness. The smart blue plastic removed over 80% of the UV light measured and so would not promote the benefits provided by UV light. The SmartGreen plastic is also expected to reduce plant growth rates slightly compared with non-coloured plastics as it removed some of the red light but will have a lesser effect than the SmartBlue plastic. Unlike the SmartBlue plastic the

SmartGreen allowed almost half the UV light to pass and may help promote plant disease resistance.

Removable glass coatings

Removable glass coatings provide a level of flexibility to the optical properties of glasshouses and polytunnels as they can added or removed at different times of year to alter light diffusion, light intensity and solar heating to match the conditions or meet the needs of different crops. The creation of coatings that alter the colour of the light increases the range of tools available to help manipulate crop responses. The magnitude of the effect of these materials can be altered by changing how much is applied to the glass. With this in mind the absolute values presented here are less relevant than the relative changes across the spectrum (effect on colour). The two diffusing coatings (ReduFuse and ReduFuse IR) had relatively uniform transmission across the spectrum measured. These coatings would be expected to influence plants by altering the structure and intensity of the light rather than larges changes in spectral quality. The ReduFuse coating in this work was observed to increase light transmission probably by reducing the reflectance of the shiny surface of the plastic base layer. The ReduFlex blue reflected proportionally more blue and UV light than other colours of light. This means less UV and blue light enters the glasshouse giving the light yellowish tint. This material is designed to reduce the light levels and stress plants receive in high light environments while retaining a relatively larger proportion of the red light that powers plant growth most effectively. The lower blue light intensities may also help reduce stomatal conductance to minimise water usage. Under bright light conditions reducing the blue proportion of the light is unlikely to result in plant stretching.

Pot and Bedding Plant Centre

The measurements made under controlled conditions at STC provide information about the spectral properties of the different plastics but not how they perform when installed on a tunnel. The measurements made at the pot and bedding plant centre were performed to assess how the plastics performed *in situ* and to aid interpretation of the plant measurements made in the different production zones. These measurements partially account for different angles of incidence caused by the shape of the polytunnel but not those caused by the changing solar angle. The transmittance measurements of the SmartBlue plastic made at STC (44% PAR, 21% UV) and at the pot and bedding plant centre were similar (43% PAR, 21% UV), thought the maximum transmissions were slightly lower and the minimum transmissions slight higher for the pot at bedding plant centre measurements. The luminance diffuse plastic also performed similarly at the two locations though PAR transmission was 14% lower at the pot and bedding plant centre (73% PAR, 66% UV) compared to STC (84% PAR, 65% UV). These measurements demonstrate that simple spectral assessments of materials can provide guidance to the effect they will have on the light spectrum but also that for an assessment of absolute light environment within a polytunnel or glasshouse changes in measurement geometry (solar angle and structure shape) need to be accounted for by measurement or modelling exercises.

Measurements made on the different ages of SmartBlue plastic indicated that the pigments included in this plastic were stable when exposed to sunlight and spectral quality is retained thought time. Some older generation materials have suffered from degradation of pigments added to materials to alter the spectrum and this greatly reduces their usable life time.

Conclusions

There are a growing range of spectral filters available for use in polytunnels and glasshouses. The life span of modern plastics can be up to 10 years so it is important to ensure the best plastic for a given crop or range of crops is purchased to gain the best return for the investment. While the glass coatings can be removed relatively easily if they are having negative impacts on crop performance it is still important to select the best coating for a given purpose to avoid the extra labour costs and potential loss of sales. The information provided in this report takes the first steps at providing independent verification of spectral qualities of the different materials. Comparison of the measurements made at STC and the AHDB pot and bedding plant centre indicate additional assessments will be required to determine how the absolute quantity and quality of the light entering polytunnels and glasshouses treated with spectral filters changes at different times of year. It will be important for spectral measurements to be backed up with crop performance data (some which will be available from the ongoing work at the AHDB pot and bedding plant centre).

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:

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

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 150m^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 150m^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 $E = \frac{\mathrm{n \times W \times e}}{\mathrm{A}} = \frac{48 \times 190 \times 2.4}{150} = 146\ \mu\mathrm{mol\ [PAR]\ m^{-2}\ s^{-1}}$.

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 $E = \frac{\mathrm{n \times W \times e}}{\mathrm{A}} = \frac{64 \times 105 \times 2.1}{135} = 104\ \mu\mathrm{mol\ [PAR]\ m^{-2}\ s^{-1}}$.

SCIENCE SECTION 2: Understanding light in glasshouses

Introduction

Glasshouse crop production relies on the sun to drive plant growth. Seasonal changes in sunlight, however, result in changing plant quality and growth rates through the seasons. In winter few crops can be grown to the same quality as they can in the summer months without the use of some form of supplemental lighting and short day lengths can cause some crops to become dormant. The use of artificial lighting combined with heating can maintain active growth during the winter months but the high running costs can make the economics of winter growing challenging and in many cases glasshouses largely stop active production.

The introduction of LED lighting systems for use in horticultural settings has gained considerable interest in the industry, in a large part due to the potential energy savings compared to HPS lighting. If the energy savings are sufficient the economics of winter crop production may alter favourably and increase the profit potential for UK growers. As new technology the design of LEDs is diverse between manufacturers and energy efficiencies differ (some are even less efficient than HPS light for more information see CP139). For the maximum benefit of any lighting to be achieved it is important to ensure that the amount of light provided is sufficient. However, determining how much light will be produced by different light sources can be challenging as different units are used to report light output from different lamp types. The output of HPS lights are often reported in units of Lumens and light intensities in growth facilities are reported in Lux. Lux sensors are inappropriate for measuring LED lighting sources (especially those with only red and blue LEDs). LEDs are often reported in $\mu mol\ m^{-2}\ s^{-1}$ which provides a count of the number of photons hitting a surface. To further confuse matters sunlight is often recorded in Wm^{-2}, a measure of the energy contained within the light hitting a surface. Conversion factors can be created to switch between the different units of measurement but the values are specific to each light source and the type of sensors being used to measure the light.

Here we report on light measurements made in the LED4CROPS High-wire facility and use the measurements to demonstrate how to compare light measurements made using different sensors and measurement units.

Materials and methods

Light measurements and supplemental light treatments.

External sunlight was measured as ‘irradiance’ using a global radiometer attached to the PRVIA computer at STC. Irradiance measurements have units of watts per metre squared (Wm^{-2}). Measurements were recorded every five minutes and were summed to determine the daily light integral (DLI) which was recorded with units of joules per squared centimetre per day ($J\ cm^{-2}\ d^{-1}$).

Within the LED4CROPS High-wire glasshouse three different supplemental light treatments have been installed.

1) Conventional HPS top lights.

2) A hybrid system with HPS top-light and LED interlights.

3) An all LED system with LED top-lights and LED interlights.

The light intensity of the supplemental top lighting was measured at ~1m below the top-lights. Measurements were made in a grid pattern over a $35m^{-2}$ area at the centre of each compartment using a hand held PAR meter (Skye Instruments). This light measurement area was smaller than the lit area. Measurements were performed in the centre of the compartments to avoid the drop off in intensity that occurs towards the edges of the compartments. This provides a better estimate of the intensity that would be achieved in a larger production facility if the lamps were installed at the same spacing.

Results and Discussion

The expected light intensity with in a crop production area can be calculated based on the manufactures (or data from independent measurement see CP139) reported lamp efficacy data (see Box 1 for details). These calculations help during the light installation design process to ensure that a sufficient number of lamps are installed to achieve the desired light levels. They are also useful for comparison with measured light data to ensure that the lights and/or reflectors have been correctly installed and are achieving the design specification. The light intensities for the HPS top light installations were calculated to be 268 µmol [PAR] $m^{-2}\ s^{-1}$ for the conventional HPS treatment and 134 µmol [PAR] $m^{-2}\ s^{-1}$ for the hybrid treatment. The calculated intensity for the LED top lights was 146 µmol [PAR] $m^{-2}\ s^{-1}$. For the LED interlighting the calculated light intensity was 104 µmol [PAR] $m^{-2}\ s^{-1}$.

The mean measured light intensities measured 1m below the top-lights over an area of $35m^2$ at the centre of each compartments were 259 µmol [PAR] m^{-2} s^{-1} for the conventional HPS only treatment,133 µmol [PAR] m^{-2} s^{-1} for the hybrid treatment and 144 µmol [PAR] m^{-2} s^{-1} for the LED top lights. These values were close to the predicted light intensities demonstrating the accuracy of the calculations. The light from the LED interlights shines sideways, this makes it difficult to accurately measure their light output in a glasshouse setting. However, the accuracy of the calculated values from the top lights gives confidence that these values are of use for calculating the total supplemental light intensity received in each compartment. Total supplemental light intensities were calculated to be 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 total amount of light is important for achieving fast growth the distribution of the light is also important for achieving crop uniformity. Figure 8 shows the measured light distribution under the three different top light installations. The light was most uniform under the LED top lights were the standard deviation of the measurements was equal to 19% of the mean irradiance. In the HPS treatments the standard deviation of the measurements was between 35 and 37% of the mean light intensity. Part of the higher light uniformity associated with the LED treatment is caused by the larger number of lights required to achieve the light intensity. The reflectors used on HPS lamps differ considerably and have a large impact on light uniformity. Other designs of reflector may lead to better uniformity.

Measurements were also made below the canopy to examine how much of the supplemental light passed through the canopy. In all treatments between 8 and 10% of the total light input hit the floor. However, only 4% of the light from the interlights was lost from the bottom of the canopy. This suggests that less of the HPS light, than the LED top lights passed through the canopy. No measurements of the light lost from the top of the canopy (due to reflection) were made so it is not possible to determine the total light absorbance from these data. Vertical light distribution is also important if the canopy as a whole is to achieve maximum photosynthesis. The images in Figure 9 demonstrate the region of the canopy were the interlights delivered their light. The light provided by the interlights illuminated the leaves low in the canopy more than if the same amount of light had been provided from the top of the canopy (as in the conventional HPS light treatment). This is expected to increase the total light use efficiency of the canopy.

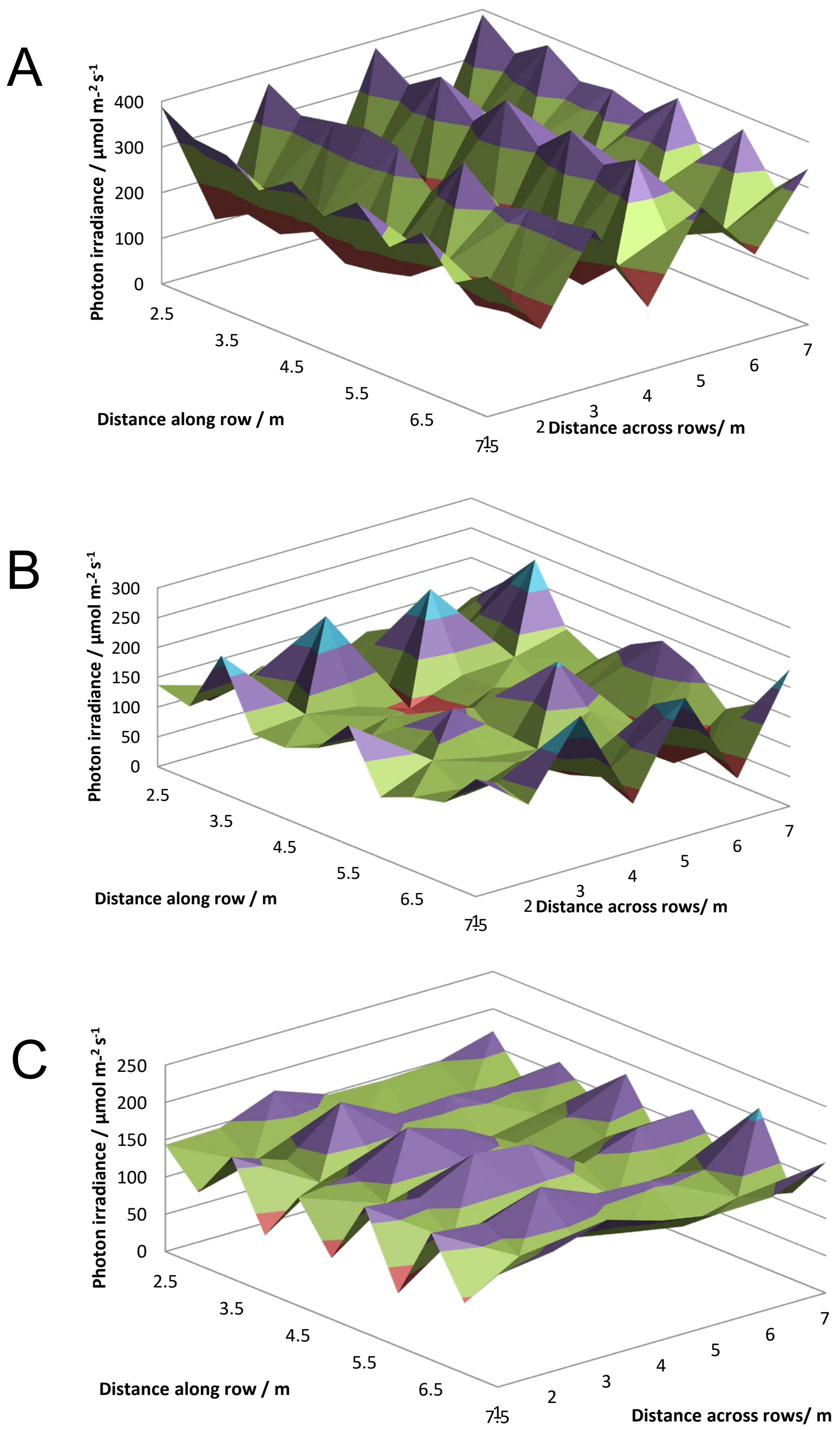

Figure 8. Spatial patterns of light intensity 1 m below the top lights in the **A)** conventional HPS treatment, **B)** the hybrid treatment (HPS top light) and **C)** LED treatment. Measurements were made over an area of $35m^2$ at the centre of each compartment.

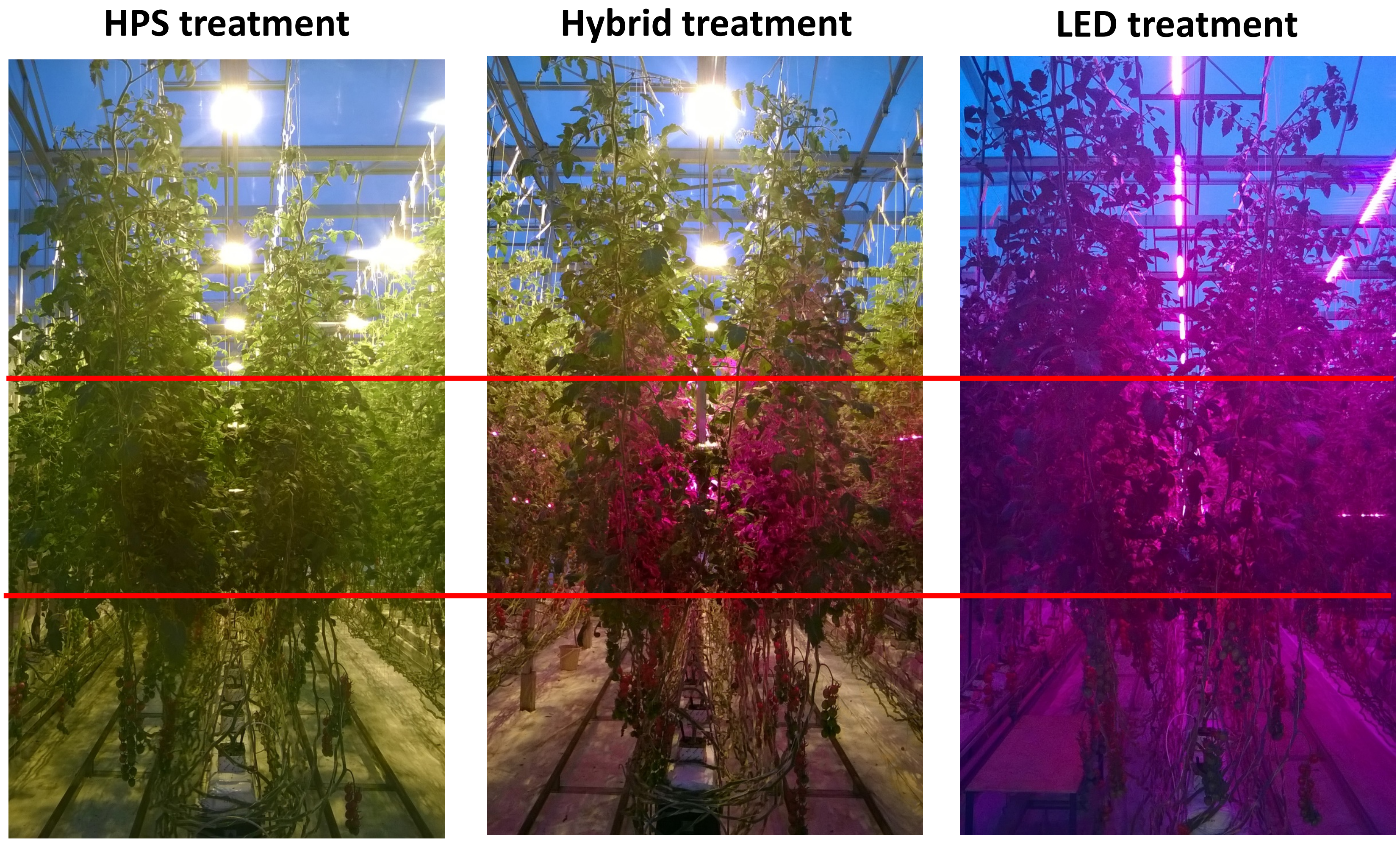

Figure 9. Images of the crop illuminated with the three different lighting systems, conventional HPS, the hybrid treatment illuminated by HPS top lights and LED interlights and the LED top and LED interlight treatment. The red lines highlight the lower portion of the leaf canopy where the LED interlights provide light to leaves that would normally experience shade.

Comparing light measurements from different light sources

The measurements of supplemental light reported here have been measured as photon irradiance with units of μmol [PAR] m^{-2} s^{-1}. These measurements are the most appropriate for understanding plant growth and light responses. However, many historical measurements have been made in different units for example the long term light records at STC are made in units or W cm^{-2}. Also HPS light intensity is often reported with units of Lux. In order to understand how the different sources of light influence plant growth and responses it is necessary to convert all the values to have the same units. Each type of measurement defines a different quality of the light. Photon irradiance is a count of the number of photons incident of a surface. Irradiance is a measure of the energy contained in the light hitting a surface. Lux measurements represent how bright a light appears to the human eye. Converting between the different units requires knowledge of the spectrum of each light source and the spectral range over which the measurement has been made. Photon irradiance was measured with a PAR meter that detects light with wavelengths between 400 and 700nm (the band of light that can be used for photosynthesis). The sunlight was measured using a global radiation senor that detects all wavelengths of sunlight (200-4000nm). Lux meters measure over a similar spectral range as PAR meters but they are more sensitive to green light than red or blue light. Due to these constraints conversion factors are specific to each light source and each type of light sensor. Here we will demonstrate the stages required to convert between the different measurement types.

Conversion factors are provided for the three light sources used in this experiment (Table 3). The conversion factors work for both instantaneous light measurements and daily light integrals (DLI). All the conversion factors provided are for use with measurements made over the PAR light range and so cannot be used directly with global radiation measurements made in W m^{-2} over the full spectrum (200-4000nm). These measurements must first be to converted to W m^{-2} over the PAR range (W[PAR] m^{-2}). This can be done by multiplying the measured global radiation value by 0.42, the proportion of the energy from the solar spectrum contained within the PAR range, before using the conversion factors.

For example, the seven year average global radiation DLI measured for the 1st April at STC was 1087 J cm^{-2}. First this measurement must be converted to units of MJ m^{-2}. This is done by dividing by 100, which in this case gives a value of 10.87 MJ m^{-2}. Next the value is multiplied by 0.42 to change the value from global radiation to PAR radiation, resulting in a value of 4.57 MJ[PAR] m^{-2}. Next we look in the conversion table for the relevant conversion factor (Table 3). We wish to convert solar radiation in MJ [PAR] m^{-2} to mol [PAR] m^{-2} so the correct conversion factor is 4.62. Using this conversion factor we get a corrected DLI of 21.1 mol [PAR] m^{-2}. As these global radiation measurements were made outside of the glasshouse we must also correct for the light transmission of the glasshouse structure if we are to make an accurate comparison with the amount of light provided by supplemental lights. For example, assuming the light transmission is 70%, then the transmission corrected value is 14.8 mol [PAR] m^{-2} d^{-1}. To gain a more accurate estimate of glasshouse light transmittance continuous measurements are required inside and outside the glasshouse. Average transmittance can then calculated as the ratio of the DLI inside and the DLI from outside the glasshouse. Transmittance values change with the angle of the sun and so it is influenced by time of day and time of year.

In order to compare the DLI of sunlight to the amount of light provided by the supplemental lighting we need to calculate the DLI from the supplemental light treatments. For a constant intensity light source the DLI (in units of mol [PAR] m^{-2} d^{-1}) can be calculated by multiplying the measured photon irradiance (with units of μmol [PAR] m^{-2} s^{-1}) by duration of the light period (measured in seconds) and dividing by 1,000,000. Assuming the supplemental lighting was on for 16 hours then the DLIs were 15.4 mol [PAR] m^{-2} d^{-1}, 13.7 mol [PAR] m^{-2} d^{-1} and 14.9 mol [PAR] m^{-2} d^{-1} for the conventional HPS treatment, the hybrid and the LED only treatments respectively. Comparison of the DLIs shows that 16 hours of the supplemental light treatments used in these trials is similar to the amount of sun light received with the glasshouse on the 1st April.

Table 3. Conversion factors for switching between measurement units for different light sources. ALL VALUES IN THIS TABLE ARE CALCULATED FOR PAR WAVELENGTHS (400-700nm). Multiply the measured value by the relevant conversation factor for the light source of interest.

INSTANTANEOUS MEASUREMENTS			
Measured units ->	W [PAR] m^{-2}	μmol [PAR] m^{-2} s^{-1}	μmol [PAR] m^{-2} s^{-1}
Desired units ->	μmol [PAR] m^{-2} s^{-1}	W [PAR] m^{-2}	Lux
DAILY LIGHT INTEGRALS			
Measured units ->	MJ [PAR] m^{-2} d^{-1}	mol [PAR] m^{-2} d^{-1}	-
Desired units ->	mol [PAR] m^{-2} d^{-1}	MJ[PAR]m^{-2} d^{-1}	-
Solar radiation	4.62	0.22	56.3
HPS	4.99	0.20	72.2
Philips top-light	5.36	0.19	10.2

To compare the measurements made here with historical measurements of HPS light intensity made as Lux we have outlined the steps required to convert between the two units. Lux measurements are not normally used to calculate DLI values so here we use the instantaneous measurements under the HPS lamps. The mean light intensity 1m below the HPS lamps was 268 µmol [PAR] m^{-2} s^{-1}. For the HPS lamps the conversion factor is 72.2 (Table 3) resulting in a light intensity of 19,350 Lux. To convert Lux measurements to photon irradiance values simply divide the Lux value by the conversion factor. So 18,000 Lux is equal to 249 µmol [PAR] m^{-2} s^{-1} and 21,000 Lux is equal to 291 µmol [PAR] m^{-2} s^{-1}.

Conclusions

When lighting systems are being considered for use in a crop production area it is possible to make simple but accurate calculations of the expected light intensity based on the numbers of lamps, the growing area and the reported lamp efficacy data (provided by manufactures or from independent lamp testing). These data can be used to determine investment costs required to achieve specific light intensities. Once installed in a glasshouse LEDs can provide supplemental lighting of an equivalent light intensity to HPS lighting systems while also providing a more uniform distribution of light over the crop. LED interlighting provides light to the normally shaded regions of a tomato canopy improving the vertical distribution of light which is expected to help plants use the light more efficiently. While the different sources of light (Sun, HPS and LEDs) are often measured using different types of sensor and using different measurement units it is possible to convert between units to allow direct comparison between measurements. Conversion factors are specific for each light source but can be generated for any system.

Knowledge and Technology Transfer

Publications

- Colour reactions. December 2014/January 2015 issue pages 16-17.
- CP125 Annual report - Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs.
- CP 139 Final report. Commercial review of lighting systems for UK horticulture.

Presentations and outreach events

The numbers of visitor to the LED4CROPS facilities at STC increased this year due to the opening of new LED4CROPS high-wire facility. Visitors have spanned all areas of the industry from individual growers (from both UK and overseas) through to large seed companies and retailers. During the opening of the high-wire facility we had over 50 delegates. The BPOA held a meeting at STC and were given tours of the facilities. The post conference tour for the AHDB studentship conference visited STC to see the LED4CROPS facilities. We have also presented our work at many conferences and made TV appearances to translate our work to the wider public.

- International conference on vertical farming and urban agriculture (VFUA) held Nottingham University in September 2014. Dr Phillip Davis. Title: The challenges of producing plants in vertical farms.
- BHTA meeting held at the University of Worcester on 21st October 2014 Dr Phillip Davis. Title: Herb responses to LED light.
- Growsave event held at STC on the 6th November 2014. Dr Phillip Davis. Title: LED update.
- IPPS/ HDC/ Fargo/GroSouth/WSNSDG Study Day - Innovation in Plant Production held on 11th November 2014. Dr Phillip Davis. Title: The influence of light and the future of LEDs.
- HDC PO panel meeting held at STC ion 18th November 2014 at STC. Dr Philip Davis. Title: HDC project CP125 - Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs.
- BPOA Technical Seminar held at The Oxford Belfry Hotel, Milton Common, Thame, Oxfordshire on 21st January 2015. Dr Phillip Davis & Dr Dave George. Title: Understanding crop and pest responses to LED lighting (CP 125).
- AAB/FES Conference: Knowledge exchange: from research to the food supply chain held at Lancaster University in June 2015. Dr Phillip Davis. Title: Exploiting photobiology in protected cropping.

- Dr Phillip Davis and Dr Rhydian Beynon-Davies manned a stand at the great Yorkshire show. The stand (Figure 10) had a display of LED inter-lighting for tomato crops (right hand side) and multi-tiered LED lighting systems (left hand side) July 2015.

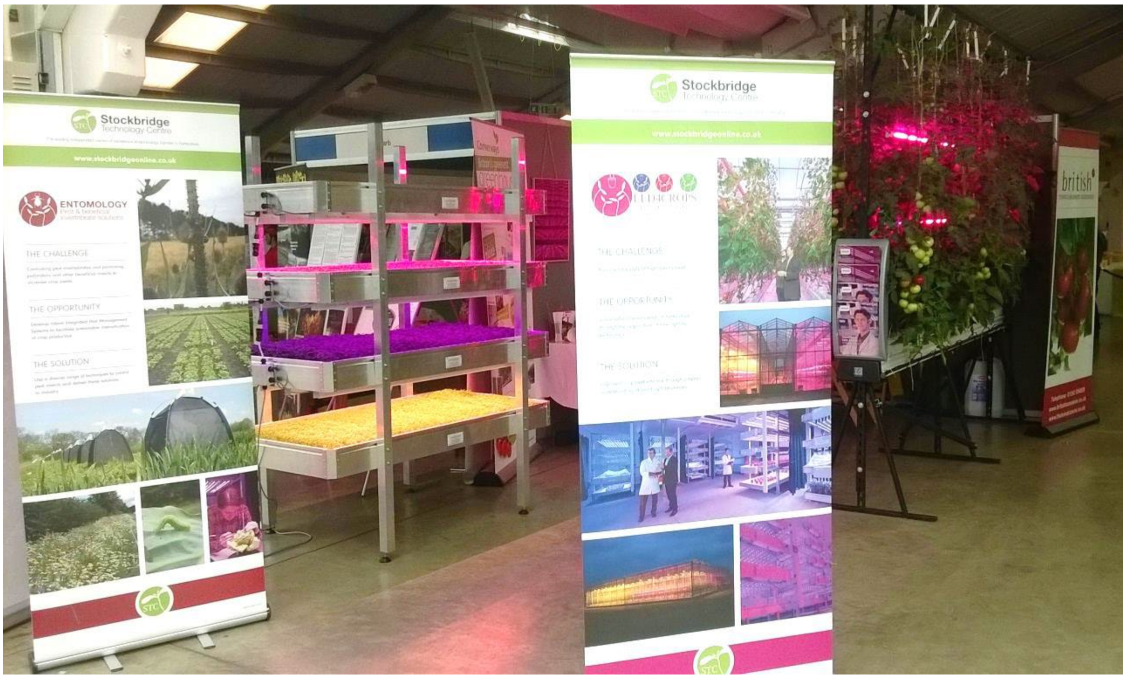

Figure 10. Photograph of the STC stand at the Great Yorkshire Show demonstrating the use of LED lighting for tomato crops and urban farm growing systems.

- Dr McPherson was filmed in the LED4CROPS facility for the BBC's One Show, July 2015.

Glossary

DLI — Daily light integral. A measure of the amount of light received over a 24 hour period.

Efficacy — A measure of how efficient a lamp is at converting electrical energy into light.

This value is reported in units of $\mu mol\ J^{-1}$.

Global radiation — This refers to all wavelengths of light that are received from the sun and has wavelengths between 200 and 4000nm.

HPS — High pressure sodium lamp.

Irradiance — A measurement of the amount of light energy received at a surface and has units of Wm^{-2}.

LED — Light emitting diode

LUE — Light use efficiency. A measure of how effectively plants convert light energy to harvested fruit yield.

PAR — Photosynthetically active radiation. The region of the electromagnetic spectrum that plants can use for photosynthesis. Wavelengths between 400 and 700nm.

Photon-irradiance — A measurement of the number of photons hitting a surface every second and has units of $\mu mol\ m^{-2}\ s^{-1}$.