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:	CP 085
Project leader:	Dr G M McPherson, STC
Report:	Annual report, November 2013
Previous report:	N/A
Fellowship staff:	Dr Martin McPherson, Science Director, STC (lead Fellowship mentor) Prof. Nigel Paul, Lancaster University (Mentor)
(“Trainee ”)	Dr Phillip Davis, Applied Photobiologist, STC
Location of project:	Stockbridge Technology Centre
Industry Representatives:	Chis Plackett, FEC Russell Woodcock, Bordonhill Nurseries 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): 30 September 2017

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AUTHENTICATION

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

Dr Phillip Davis

Project Manager

Stockbridge Technology Centre

Signature .... Date ....

Prof. Nigel Paul

Lancaster Environment Centre

Lancaster University

Report authorised by:

Dr Martin McPherson

Science Director

Stockbridge Technology Centre

Signature .... Date ....

CONTENTS

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. As noted above (see Research aims), 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 2012	April 2013. This is an on-going exercise as new companies move into the area.	September 2017
Objective T3.	December 2013	Many contacts have been made but this is an on-going exercise that will run throughout the project.	September 2017

Objective T4.	December 2013	This process will continue throughout the fellowship.	September 2017
Objective T5.	December 2013	This process will continue throughout the fellowship.	September 2017
Objective R1.	December 2012	February 2013	-
Objective R2.	January 2013	March 2013	-
Objective R3.	December 2013		- December 2014
Objective R4.	December 2016	-	-
Objective R5.	September 2017	-	-

Summary of Progress

The first year of the Fellowship has gone extremely well and all of the objectives for the first year have been met.

Training objectives

Objective T1.

Through prior experience I possessed considerable relevant knowledge including an understanding and the skills required to design, perform and undertake applied plant science experiments in the area of plant light responses. This knowledge has allowed me to focus on reviewing the existing relevant literature and progressing more rapidly in other areas of the Fellowship programme (e.g. learning how the industry functions and the needs of the industry).

Objective T2.

I have contacts with all the major LED lighting producers (Philips, Fionia, Heliospectra and Valoya) and have had confidential meetings with several other companies considering entering the horticulture lighting market (including plasma lighting and OLED systems). I anticipate this process will continue as more companies move towards creating LED systems for horticulture. In addition to LED lights I have been in contact with a plasma light producer and a polythene cover producer. The work during the first year has been focused on the lighting systems. During the second year I will focus more on spectral filters and cladding materials. Moving forward I will remain open to engage in any lighting companies and will aim to perform trials on an lighting systems/ spectral filters that provide something different to existing products.

Objective T3.

Whilst in the US, prior to starting this position and in agreement with Dr McPherson, I took the opportunity to visit Prof Lopes at Purdue University where I saw their LED trials on tomato and ornamental crops. I have made a number of contacts at Lancaster University in addition to Prof Paul and am a co-supervisor for one of Dr Ian Dodd's PhD students. At Manchester University I have a collaboration with Prof. Bruce Grieve. In Europe I have strong links with Dr Carl-Otto Ottensen (Aarhus University) and Dr Eva Rosenqvist (Copenhagen University) and I travelled to Denmark in December 2013 to perform a short research project in Carl-Otto's Lab. Through Carl-Otto I have attended and presented at a Greengrowing (an EU funded project to develop a realistic vision for the future of the Glasshouse industry in temperate Europe and to examine methods for reducing energy inputs) Workshop held in Belgium where I met scientists from many Northern European Countries. I have attended two international conferences, one in Edinburgh (International Symposium on Plant Photobiology) and one in Korea (Greensys 2013), both provided opportunities to make contacts with scientists from Europe, Asia and North America.

Objective T4.

I have learned a great deal about the potential funding opportunities in the UK and beyond during this first year. With regards to HDC funded research I have attended a number of grower association meetings (BPOA, TGA, BHTA) to observe and discuss with growers how new projects are created and evaluated as well as determining what projects would be favourable to growers. I used this knowledge to help me lead a successful bid (pending AHDB budget approval) for the HDC tender "Manipulation of light spectrum for the benefit of UK horticultural production systems" (the project will be given number CP125).

Beyond HDC funded projects I have attended a number of meetings discussing the government's new AgriTech strategy. I wrote a successful bid for a project funded through the Sainsbury's 20 by 20 funding scheme and a TSB SPARK award.

At STC my involvement in commercial projects has taught me a great deal about the financial budgeting required to design and complete projects on time and to budget. Work on these projects is helping me develop my skills as a project manager especially with regards to managing personnel and budgets.

Objective T5.

I have made contacts (see appendix I) with a large number of growers, grower organisations, seed producers, agchem, biocontrol, distribution and marketing companies as well as a number of major retailers and other large multinational companies. From discussions I have had with the numerous growers I have met at STC and during nursery visits I have increased my knowledge of commercial crop production in the UK considerably. In particular discussions with the Fellowship steering group have been very helpful in identifying what growers expect from the research performed through the Fellowship programme. I am already getting a good understanding what information growers in the different crop sectors require with regards to crop lighting solutions and how I will be able to provide this information. During the second year a greater emphasis will be placed on meeting more growers from the ornamental and hardy nursery stock sectors.

Research Objectives

Objective R1 & R2.

I have had access to a wide range of lighting products (LEDs from Philips, Valoya, Fionia, SolidLIte, Illumitex, Heliospectra, and two Chinese manufacturers) from manufacturers based in Europe, USA and Asia and have made preliminary assessments of their spectral output and intensity. I am also regularly assessing new products as they become available. I attended a brief fact finding trip of LED manufacturers (Valoya, Heliospectra and Fionia) in Europe and produced an article for HDC news about this trip.

Objective R3.

I have grown a wide range of commercially important crops in the LED4CROPs facility. These crops have included leafy greens, herbs and ornamental crops. I have used dwarf bean as a model crop to explore the influence of red, blue and far red light on plant responses. The bean crop was selected as it is easy to grow, its responses to light are large (they make a good tool for demonstration purposes) and they can be grown from seed to harvest in approximately 7 weeks. Plans are in place for a wider range of lights produced by different manufacturers (Valoya [2 X AP67 and 2 X NS2 fixtures], Fionia [2 X FL300 fixtures], Heliospectra [2 X L4A-S10 fixture], SolidLite) to be installed in a different growth facility at STC so plant performance under the different lights can be assessed. A number of photosynthetic measurements were performed to assess photosynthetic performance under the different light spectra produced by the different manufacturers' lights.

Objective R4.

A technical review of lighting in horticulture has been produced, this will be updated in early 2014 before it is finalised. An article for HDC news is currently in preparation. I have attended and presented at a wide range (see training and knowledge transfer sections for a full list) of grower and scientific conferences and workshops.

Objective R5.

Objective R5 was timed to occur towards the end of the Fellowship (years 4 & 5), however, due to fast pace at which interest in LED lighting has grown and my advanced prior knowledge in scientific research these objectives have been brought forward. During this year I prepared a bid in response to the 'Manipulation of light spectrum for the benefit if UK horticultural production systems' tender. This bid was successful (CP125) and will form a beneficial companion project for the work being undertaken in Fellowship programme.

Milestones not being reached

None

Do remaining milestones look realistic?

Yes

Training undertaken

Conferences attended

Hortifair October 2012.

HDC focus on light spectrum, STC, December 2012 – Speaker.

International Symposium on Plant Photobiology, Edinburgh, June 2013.

Tomato Growers Annual Meeting, Coventry, September 2013– Speaker.

HDC Studentship Conference, Pershore College, September 2013 – Speaker.

Greensys 2013, Jeju, Korea, October 2013.

GreenGrowing Workshop, Lokeren, Belgium, October 2013 – Speaker.

Grower visits

Purdue University, Indiana, USA. Prof. R Lopez. Supplemental LED lighting for bedding plant plug production, August 2012.

Jepco, Norfolk House Farm, Spalding. Pea shoot and protected lettuce production, October 2012.

Crystal Heart Salads, Lettuce propagator and hydroponic lettuce producer, 2012.

Bordonhill Nurseries, Warwickshire. Protected Ornamentals. November 2012.

Winchester Growers Bulbs and cut flowers, January 2013

EM Coles Farms Bulbs and Stocks, January 2013.

Lambs Nursery, Bulbs and Stocks, January 2013.

Swedeponics, Sweden, February 2013.

Gartneriet PKM, Denmark, February 2013.

Farm Energy Centre, Chris Placket March 2013

Lincolnshire Herbs, Lincolnshire, Herb grower, March 2013.

Bentleys, Snaith and Gomersal sites. Cress and microherb producer. April 2013.

Hornsfield Nurseries, Worcestershire, Tomato grower, September 2013.

Wallings Nursery, Protected strawberries, February 2013.

Premier plant propagators, Strawberry propagator, May 2013.

Other

Grant writing course

Expertise gained by trainees

I have gained a good knowledge of the available LED lighting systems and the different advantages each provides.

I have gained a good understanding of the workings of the industry and how spectral manipulation could benefit the different crop sectors.

Other achievements in the last year not originally in the objectives

I have conducted several commercially funded projects, in the LED4CROPS facility and have learned a great deal about differences in plant light responses. The information provided to the industry, through these commercial trials, will help guide their future business plans but is also providing me with a great understanding of needs of the industry.

The understanding I have gained through these trials will help me deliver other commercial and publicly funded projects.

Using a Jaz spetroradiometer I have performed measurements of the supplemental lighting at a range (tomato propagator, three herb producers) of commercial glasshouses.

Changes to Project

Are the current objectives still appropriate for the Fellowship?

Yes

GROWER SUMMARY

Using LEDs to control plant morphology and reduce the need for PGRs.

Headline

Increasing the percentage of blue light reduced plant height, while addition of far-red light increased crop height. With careful selection of the light recipe plant height can be controlled reducing or potentially removing the need for plant growth regulators. In some crops far-red light will be beneficial and may increase harvestable yield.

Background

The use of plant growth regulators (PGRs) are required to keep commercially grown crops within the strict retailer set specifications. Growers are under increasing pressure to decrease the use of chemical inputs to reduce chemical residues and environmental impacts. If PGRs are banded it will be difficult to grow many plants to sufficient quality. In addition PGRs cannot be used on all crops (e.g. most food crops) and alternative methods must be used if crop morphology is to be controlled. A number of non-chemical approaches for controlling crop heights have been developed, including reduced watering strategies, increased EC values and temperature manipulations (negative DIF or DROPS and JUMPS: see HDC research project PC 41). While these approaches can be effective for some crops they are often used to counteract plant stretching that has been caused by poor light quality during growth. Spectral manipulation via LED lighting or spectral filters will improve crop quality and reduce the need for PGR applications.

To extend the growth season or increase productivity crops are often lit with high pressure sodium lighting. While HPS light is good for driving photosynthesis and crop growth the spectrum of the light often results in plants becoming stretched. This is because HPS light is deficient in the blue light that helps keep plants compact. The introduction of LED lighting for horticulture has provided the opportunity to design light mixtures or recipes that have the correct spectral mix to both drive efficient photosynthesis and control plant height. In this initial study we have examined the influence of the red:blue and the red:far-red ratios on the height of a range of crops with the aim of improving our understanding of how crops respond to LED lighting.

Summary

A series of small pilot scale trials were performed in the LED4CROPS growth facility at STC to examine the influence of light spectrum on plant height and yield in a range of crops species in the absence of background sunlight. The influence of three colours of light were tested: blue (430 nm); red (660 nm); and far-red (735 nm).

Controlling plant height

Tomato, Sweet Pepper and a several microherbs (Basil, Red Amaranth, Coriander, Watercress, Red Veined Sorrel, Red Perilla and Parsley) were grown as young vegetative plants under four different red and blue light recipes (no far-red was included). In each treatment the light intensity was kept constant at 200 µmol m^{-2} s^{-1}. As the proportion of blue light was increased plants became more compact and had a smaller leaf area. The most desirable plants (plants with shorter internodes) tended to be those where there was a higher incidence of blue light relative to red light.

Harvestable Yield

Dwarf bean plants demonstrate large responses to different light recipes and therefore are a good crop to demonstrate the effect of changing the light recipes.

Bean plants were grown under four different red and blue light recipes (no far-red was included). In each treatment the light intensity was kept at 150 µmol m s^{-1} but the blue proportion was changed.

As found with the other crops investigated bean stems were shorter resulting in more compact plants when blue light formed a higher proportion of the total light intensity. However, the more compact plants had a lower bean yield so plants grown under a low proportion of blue light were more desirable. A second experiment was performed on bean plants to examine the influence of far-red light on plant height and yield. In each treatment plants were provided with 186 µmol m^{-2} s^{-1} of photosynthetically active radiation (16% blue) and four different far-red intensities (0, 9, 24, 48 µmol m^{-2} s^{-1}). Increasing the far-red light resulted in taller plants with a larger leaf area and larger bean yield. The largest plants were those produced with the highest far red light (48 µmol m^{-2} s^{-1}) but this treatment also had the highest electrical inputs.

Conclusions

These experiments demonstrate that light can be used to control plant morphology in crops that can't be treated with plant growth regulators. The consistency of the responses between the different species examined suggested that the results will be applicable to all species and that spectral manipulation will be a useful tool for the reduction of plant growth regulators in the ornamental sectors. The data also indicate that the best light regime will differ between crops depending on the qualities desired from the crop and what part of the crop is harvestable/saleable. It is also possible that the lighting regime may need to be changed during different crop stages e.g. vegetative and reproductive stages.

Financial Benefits

It is currently too early in the project to assess the financial implications of the research, or to make recommendations as to the best practice for LED lighting systems. The current high initial investment cost associated with the LED systems is perceived as inhibitory. The prices of LEDs are anticipated to decrease in the coming years and improve the economic case. As energy prices continue to rise this will bring the increased efficiency of LED light relative to HPS/HID lights into more focus. Understanding the plant light responses will be key to making the best of LED lighting and help define when the economics merit investment.

Action Points

It is too early in the project to make suggestions as to the best use of LED lighting systems.

SCIENCE SECTION

The influence of light quality on crop height and yield was investigated with the aim of developing light recipes that will reduce the need for plant growth regulators.

Introduction

Plants use light to power the process of photosynthesis which fixes the carbohydrate needed for growth. The intensity of the light affects how rapidly photosynthesis can proceed but the colour of the light has a profound effect on how the plant uses its carbohydrate for growth. Plants possess several light sensitive compounds called photoreceptors that are used to measure the intensity and colour / quality of the incident light. Plants use this information to modulate their growth to match the surrounding environment. In shaded conditions plants grow tall in an attempt to reach the light. In high-light conditions plants remain compact and produce a range of secondary metabolites such as anthocyanin to protect against the potentially damaging high-light exposure.

The photoreceptors can be grouped roughly into three groups based on what colour of light they are responsive to, red:far-red, blue and UVB photoreceptors. The ratio of red to far-red light is sensed by a family of photoreceptors called phytochromes (Quail 1991). This information is relevant to plants as shade conditions (e.g. below a forest canopy) are often associated with a low red : far-red ratio. This is because the leaf canopy acts as a spectral filter, preferentially removing red light and allowing far-red light to penetrate deep into the understory. Blue and UVA light are sensed by a number of different types of photoreceptors including the cryptochromes (Cashmore et al 1999) and phototropins (Briggs and Christie 2002). These receptors control, phototropism, stomatal opening, synthesis of many secondary metabolites such as anthocyanin and also reduce stem elongation helping to keep plants compact. UVB light is sensed by a compound called UVR8 (Rizzini et al 2011). UVB light is highly damaging to biological molecules and so exposure to even small amounts can cause scorching of plant tissues. UVR8 functions to increase the production of secondary metabolites that screen the plant tissues from potentially damaging UVB in the same way natural melatonin and sunscreen protects our skin.

While a considerable amount is known about the biological mechanisms and biochemical pathways associated with plant light responses there is relatively little information regarding the practical implementation of this information. During the first year of this Fellowship we have performed a number of small-scale assessments of the influence of red, blue and far-red light on plant responses. This work has taken the first steps towards the development of solutions to range a problems facing growers. These experiments examined the potential to use light quality to control plant height with the aim of reducing the need for plant growth regulator applications.

Materials and methods

All the experiments were performed in the LED4CROPS facility at STC. The temperature in the building was maintained at 21°C. Plants were irrigated once per day (twice per day for mature bean plants) with an automated ebb and flood irrigation system. Plants were irrigated with a dilute nutrient solution (EC = 2mS, pH = 5.5; see table 1). Within the facility two types of LED systems were used a) Philips research modules (Deep red (660nm), blue (450nm) and far-red (735nm) Philips Greenpower research modules) and b) Philips Greenpower production modules (Philips Greenpower production module deep red/blue). The research modules allow different light recipes to be designed as the intensity of the red, blue and far-red LEDs can be independently controlled. The production modules have a fixed red:blue ratio and intensity. The production modules were used in combination with far-red research modules which allowed the investigation of a range of red:far-red ratios.

Table 1. Desired concentrations of the different nutrients included in the irrigation system.

Nutrient	Concentration / mg l^{-1}
Nitrate	147
Phosphours	40
Potassium	299
Magnesium	48
Calcium	168
Sulphur	70
Sodium	20
Chloride	60
Iron	2.18
Manganese	0.64
Boron	0.34
Copper	0.22
Zinc	0.51
Molybdenum	0.06
Bicarbonate	139

Tomato (Elegance), pepper (variety unknown) and bean (Prodigon) plants were grown in rockwool (Grodan BV) blocks. Tomato and pepper plants acquired from a professional grower and were brought in as young plants. Tomato and pepper plants were grown for 12 days before measurements were made.

The bean plants were germinated in moist vermiculite and transferred, after 3-4 days, to the rockwool blocks and covered with vermiculite. Plants were grown for 7 weeks before harvesting. The tomato plants were supplied by a commercial plant producer and were approximately 3 weeks old. The tomato plants were grown for a further 2 weeks under the different light treatments.

Herb seeds were germinated and grown on inseroMat hydroponic matting. Seedlings were grown for 10 days before plant heights were measured.

Plant heights were measured as the distance between the surface of the growing medium and the tip of the apical meristem. Leaf areas were determined by detaching leaves from the plant and passing them through a Li-3100 Li-COR leaf area meter (Li-COR, Lincoln, Nebraska, USA).

Light Treatments

To assess the influence of red and blue light on plant height several different crops were grown under four different red and blue light recipes (no far-red was included). In each experiment the light intensity was kept constant, at either 150 or 200 µmol [PAR] m^{-2} s^{-1}. The percentage of blue light was varied between 16 and 75%.

To assess the influence of far-red light on plant height bean plants were grown under red and blue light provided by Philips Greenpower production modules. The percentage of blue light was 16% and the total PAR was 186 µmol m^{-2} s^{-1}. Far-red light was provided by Philips Greenpower research far-red lamps. Four different far-red light treatments were used in addition to the PAR light provided by the Philips production modules, 0 (control), 9, 24 and 48 µmol m^{-2} s^{-1}.

Results

The influence of red and blue light on plant height.

Plant heights were strongly influenced by the light spectrum. Tomato plants grown under the higher proportions of blue light had stems 37% shorter than those grown under the low percentages of blue light, see figure 1 and table 2. Leaf area was also found to correlate with stem length, taller plants had larger leaf areas, see table 2. For tomato propagation smaller plants may be desirable as they are more easily transported, however, changes in leaf area will impact the growth rate post sale as larger leaves are able to capture more light. In these experiments there was no obvious differences in leaf numbers between the treatments. However, differences in photosynthetic rates resulting from different leaf areas would be expected to lead to differences in plants exposed to these treatments for a longer period of time. Similar results were observed in sweet pepper plants grown at the same time, see table 1.

To investigate the influence of red and blue light on a broader range of crop species seven different microherb crops were tested (Basil, Red Amaranth, Coriander, Watercress, Red Veined Sorrel, Red Perilla and Parsley). The influence of % blue light was measured after 7 days growth. There was considerable variation in the length of the hypocotyl of the different species. Red Amaranth, Coriander and Watercress produced tall seedlings between 1 and 4 cm in height. The light spectrum had a strong influence on height in these tall seedlings with the seedlings grown in 16% blue light being 3 to 4 times taller than those grown in 75% blue light, see figure 2A. Basil and Parsley seedlings were less than 1 cm in height but also showed a strong response to % blue light, see figure 2B. Red veined sorrel and Red Perilla produced very short seedlings and showed only a weak response to different light recipes, see figure 2B.

In addition to plant height, red:blue ratio also has an influence on other aspects of plant morphology. Bean seedlings grown under 100% red light were compared with seedlings grown under a red : blue mixture, see figure 3, to demonstrate the influence of blue light on leaf angle. In the absence of blue light the bean leaves drooped down so the leaf blade was hanging almost vertically. In the presence of blue light the leaf blade is held flat, parallel to the floor. The leaf angle has an important role in controlling how much light a leaf can intercept and will therefore influence the photosynthetic and growth rates of the plant.

Figure 1. The influence of red:blue ratio on the height of tomato plants. The total light intensity in each treatment was maintained at 200µmol m^{-2} s^{-1} and the percentage of blue increased (left to right).

Table 2. Mean height and leaf area of tomato and sweet pepper plants grown under four different red-blue light mixtures. Bracketed values indicate the standard deviation. The total light intensity in each treatment was maintained at 200 µmol m^{-2} s^{-1} and the percentage of blue varied. Plant height was measured at the start (3/7/2013) and the end of the experiment (15/7/2013) while leaf area was only measured at the end of the experiment.

	% Blue	Height / cm		Leaf area / cm2
		03/07/2013	15/07/2013	15/07/2013
Tomato	25	8.0 (1.7)	30.4 (6.5)	858 (205)
	40	7.3 (1.5)	22.7 (1.6)	719 (125)
	60	8.2 (1.4)	20.1 (2.2)	700 (57)
	75	8.2 (1.3)	19.2 (1.8)	660 (108)
Pepper	25	3.0 (0.27)	12.2 (0.5)	432 (81)
	40	2.9 (0.22)	10.8 (0.9)	417 (46)
	60	2.9 (0.31)	8.3 (0.7)	278 (95)
	75	2.9 (0.18)	6.7 (1.0)	181 (68)

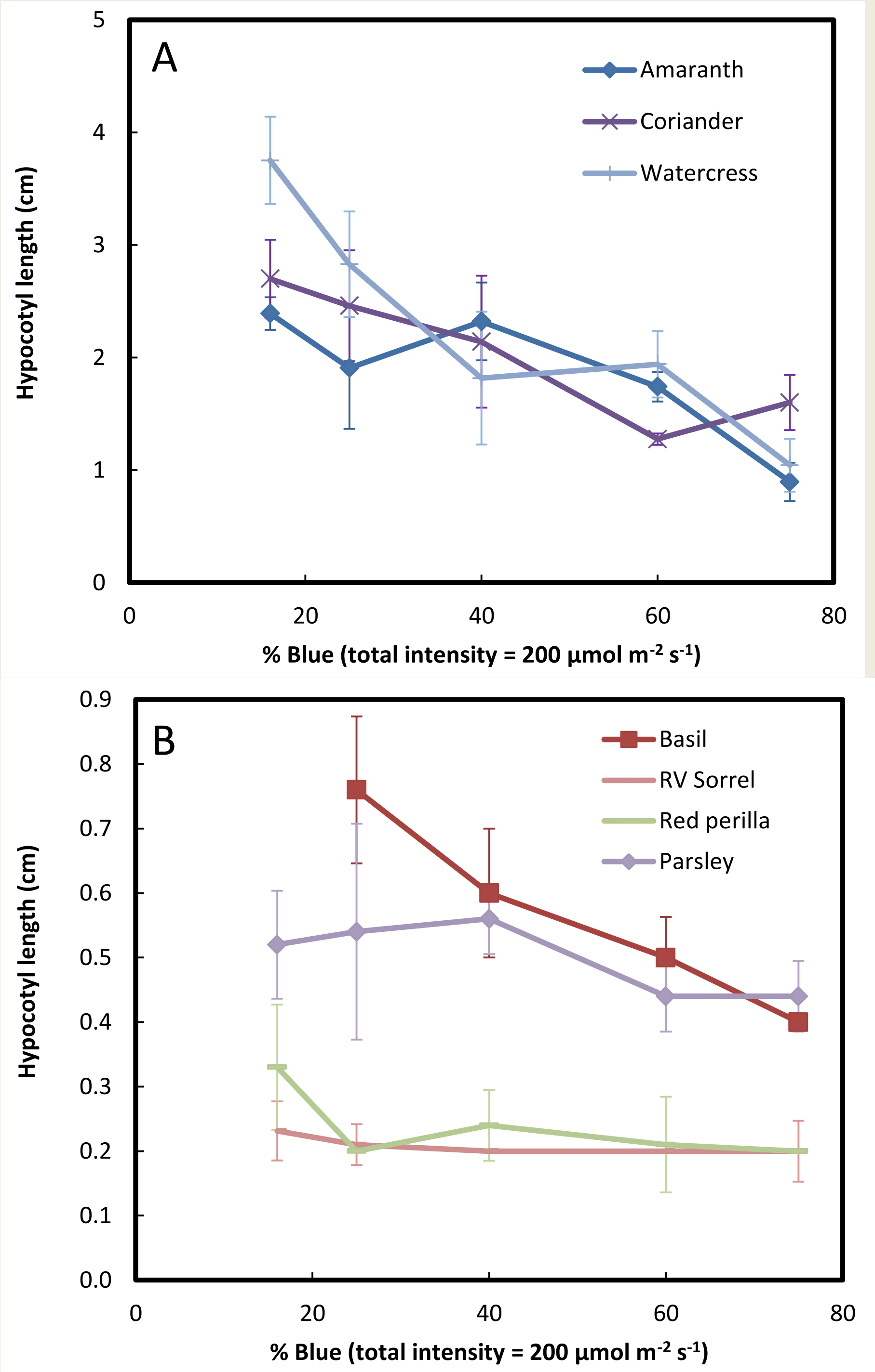

Figure 2. Influence of the percentage of blue light on the height of several different microherb seedlings. A) The three tallest species Red Amaranth, Coriander and Watercress that showed strong responses to light spectrum. B) The shorter species Basil, Red Perilla, Parsley and Red Veined Sorrel. The Sorrel and Perilla showed little response to % blue light. Error bars indicate the standard deviation.

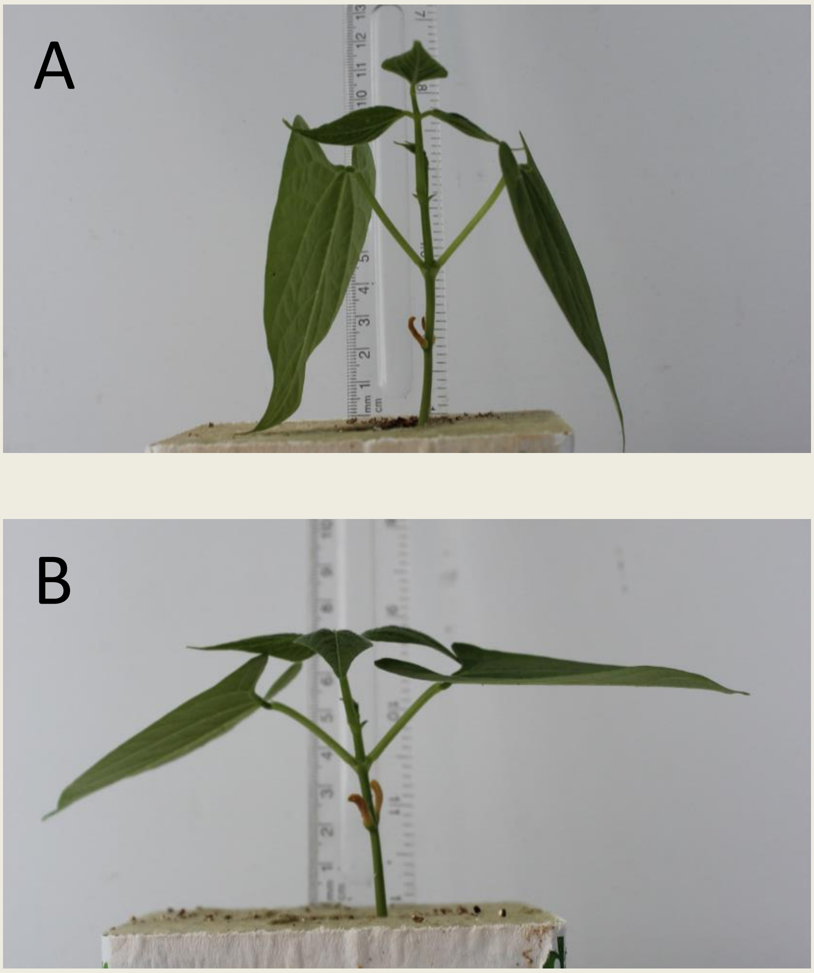

Figure 3. The influence of red and blue light on leaf angle. A) Bean seedling grown under 100% red light. B) Bean seedling grown under 80% red and 20% blue light.

Light recipe and marketable yield.

As found with the tomato and other plants investigated, dwarf bean stem heights and leaf area decreased as the proportion of blue light in the recipe increased. In bean crops, however, the harvestable yield is the beans rather than the plant itself. In this crop the aim would be to maximise bean production and not control the morphology of the plant. The results in this experiment showed that taller plants with larger leaf areas (plants grown in low blue light conditions) produced a larger yield of beans than shorter plants, both size and number of beans was found to increase. So unlike in the other crops investigated, where shorter plants may be beneficial, taller bean plants would appear to produce a better crop harvest, see figure 4. When the electrical use is assessed and the system efficiency determined (harvestable yield/ electrical inputs) the efficiency for beans was found to decreases as the blue percentage increased, see figure 5. Far-red light has been shown to increase plant heights and so a second experiment was performed on bean plants to examine the influence of far-red light on bean height and yield to examine whether increasing crop height with far-red light can increase bean yield even though far-red light is not able to drive photosynthesis. The far-red light caused a considerable increase in crop height. The plants grown under 48 µmol m^{-2} s^{-1} far-red were double the height of the control plants grown with no far-red light, see figure 6. The bean yield was also found to increase with the addition of far-red light, see figure 6. While the yields were greatest for the 48 µmol m^{-2} s^{-1} far-red light treatment the system efficiency was greatest for 9 µmol m^{-2} s^{-1} far-red light treatment, see figure 8.

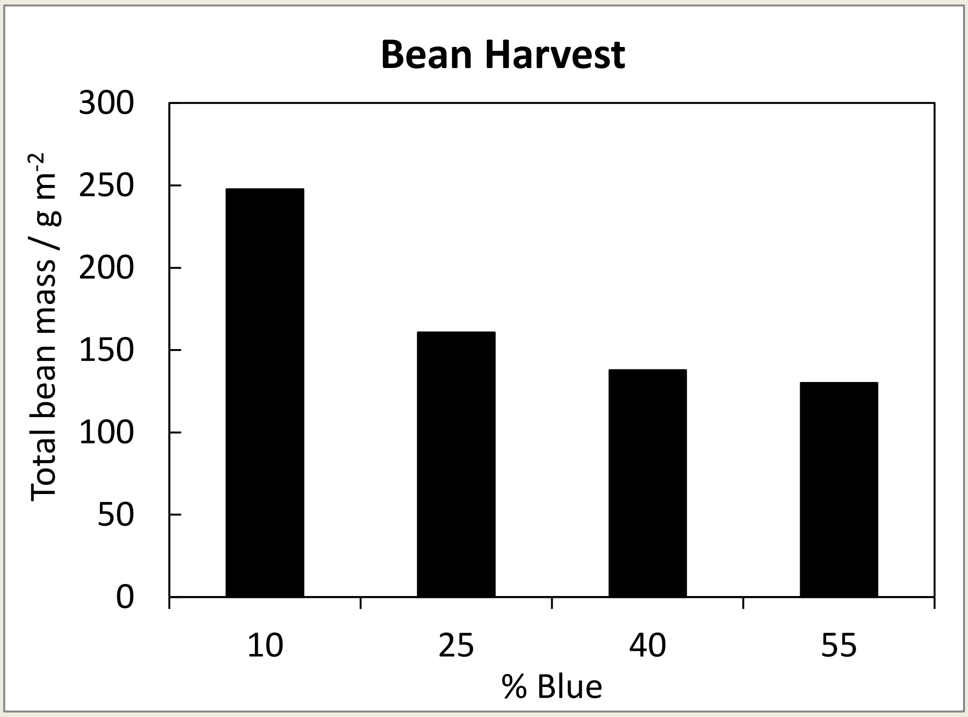

Figure 4. The influence of percentage of blue light on the yield of a Dwarf bean crop. In each treatment the total light intensity was kept constant (150 µmol m^{-2} s^{-1}).

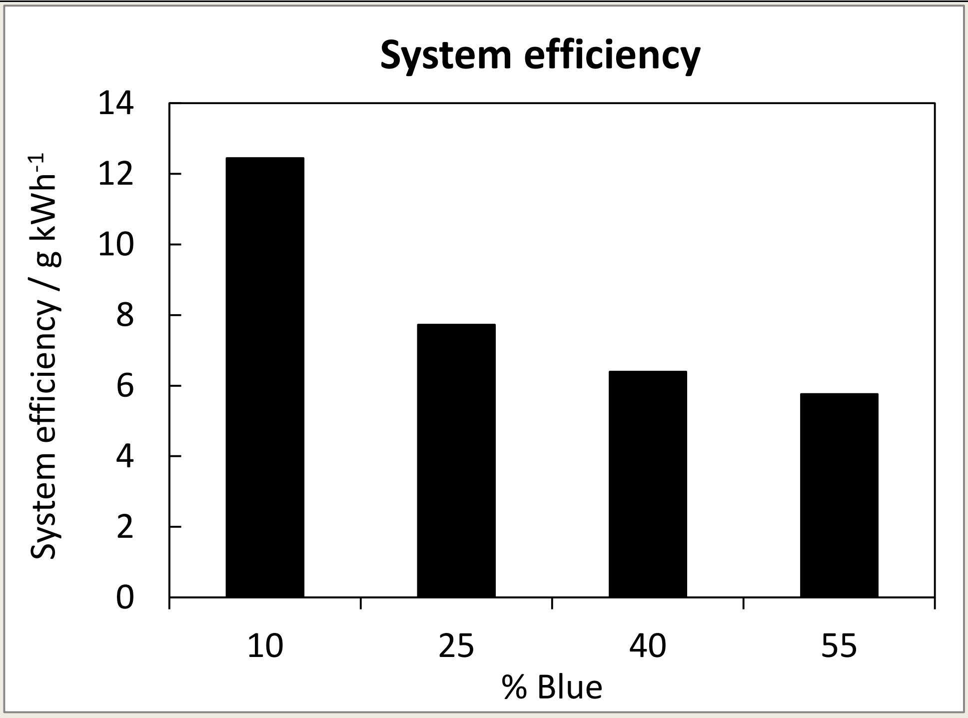

Figure 5. The calculated system efficiency determined as the total bean yield per m^2 divided by the total electrical use of LEDs over the cropping period.

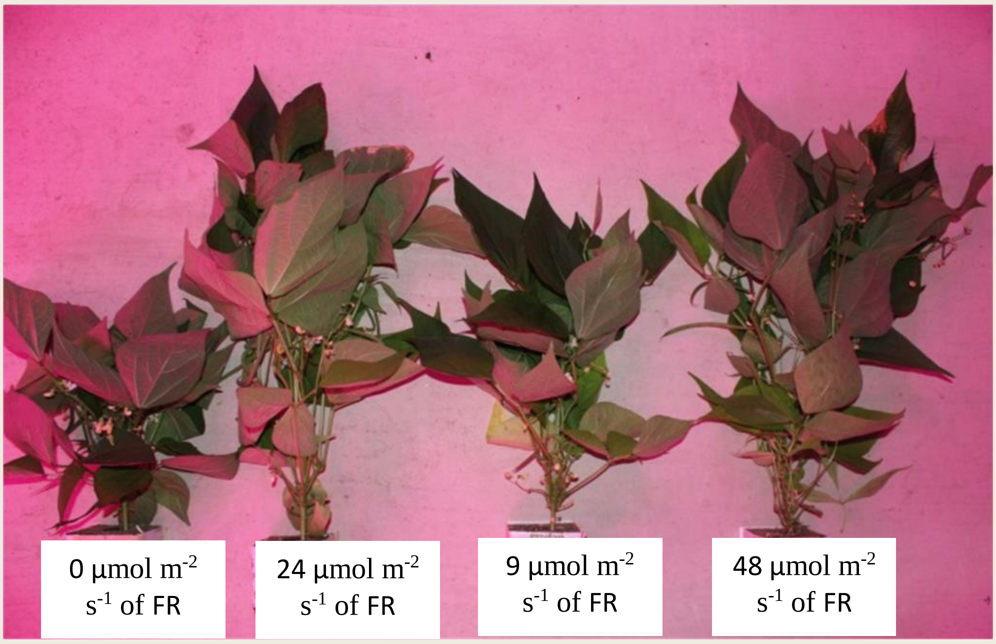

Figure 6. The influence of far-red light on bean plant height. In all treatments PAR was constant (186 µmol m^{-2} s^{-1}). Far-red (FR) light increased crop height and bean yield.

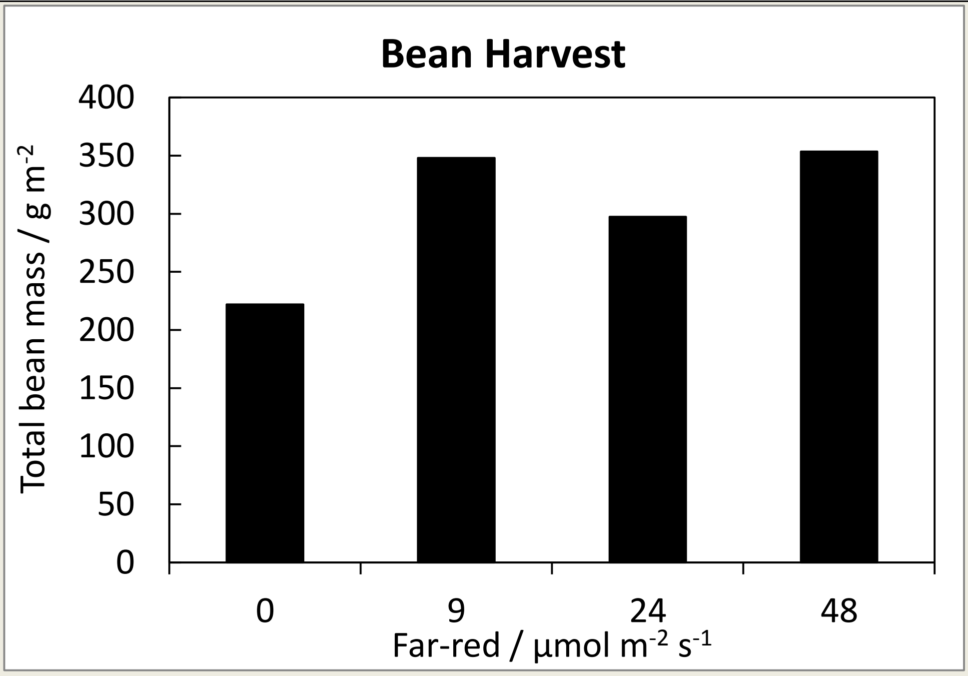

Figure 7. Bean harvest from plants grown with different amounts of far-red light. In all treatments PAR was constant (186 µmol m^{-2} s^{-1}).

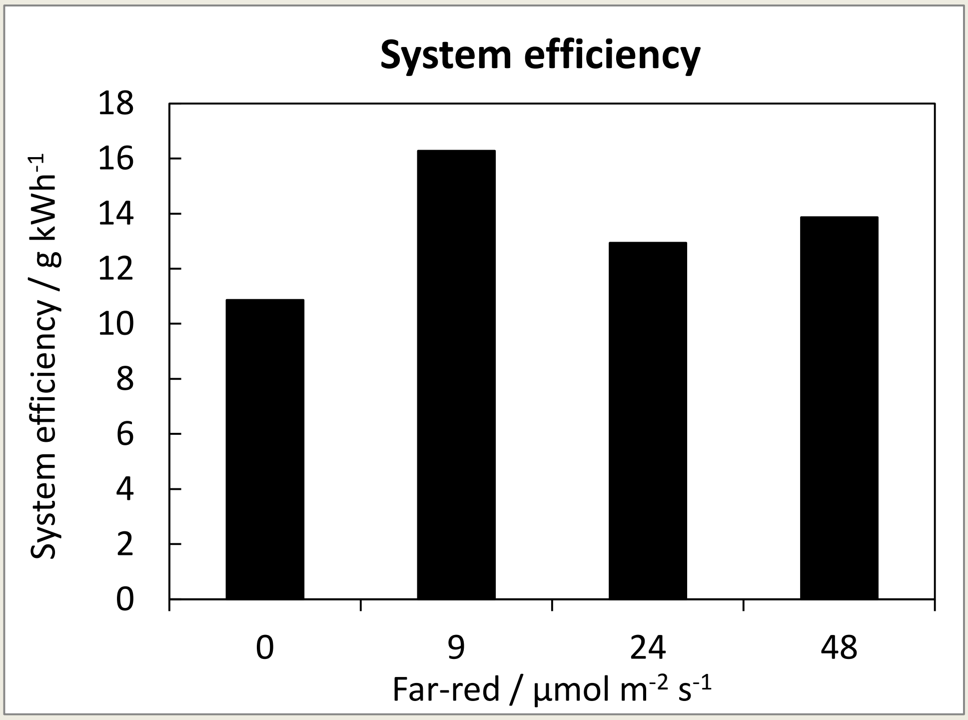

Figure 8. The influence of far-red light treatments on the calculated system efficiency determined as the total bean yield per m^2 divided by the total electrical use of LEDs over the cropping period.

Discussion

Light recipes and plant production.

Food crop producers rarely have the benefit of PGRs for controlling plant morphology. This means many other methods have been investigated to control plant morphology with varying levels of success. The results presented here indicate that crop morphology can be strongly influenced by altering the spectrum of light under which plants are grown. In fact many of the problems encountered by growers with regards to morphology result from poor quality lighting, either low natural light conditions or HPS lighting. Across all the species examined increased blue light caused a reduction in plant height. In addition to the direct benefits of spectral manipulation for controlling plant morphology this method is fully compatible with other existing methods for controlling crop morphology and when combined a greater control of morphology may be possible allowing growers to alter crop performance to match changes in the market. While in many cases compact plants are beneficial

These results indicate that LED lighting in the absence of sunlight can produce healthy crops and that the spectrum of that light can have a considerable influence on the morphology and yield of those crops. By performing the results in a closed building with no natural light the responses of the plants to carefully defined light spectrum can be accurately assessed in a way that is not possible in glasshouses where fluctuations in natural sunlight through the day and from day to day alter the plant responses and confuse interpretation.

Benefits beyond the examined crops.

The response to increased blue light was consistent across the plants examined in these experiments, more blue light = shorter plants. This suggests that blue light will have a similar effect on other plants. In production of many plants, particularly bedding plants, crop morphology is controlled via the use of plant growth regulators (PGRs). The loss of PGRs as a tool would cause significant problems in production of these crops if they are to meet the desired specifications of retailers and customers. The preliminary findings performed in these experiments have demonstrated that light quality has a large influence on plant morphology and that careful selection of the LED light recipe can control plant morphology. Defining the optimum light spectra for each crop, or at least each crop type, will be key in reducing the use of PGRs and improving crop performance especially when the methods are applied in a glasshouse setting where fluctuations in the background sunlight will influence plant responses. While increased levels of blue light are likely to provide a certain level crop growth regulation it is likely that increased blue light will also affect other qualities of crops. Further experiments will be required to assess how blue light influences other crop qualities such as flavour and pigmentation.

Economics of different light spectra.

LED lighting is currently expensive to buy but in comparison to HPS lighting they are reported to reduce energy consumption by up to 60% (online technical specification for Fionia lamps - http://www.fionialighting.dk/modules/Filarkiv/upl/FL300%20Fixture%20-%20Technical%20specification.pdf) though currently there are few independent assessments of LEDs available in the literature. Over the coming years the prices of LEDs are expected to drop and energy prices are expected to increase. With these predicted market forces at some point it will be more economical to use LED rather than HPS lighting. At the point when this economic shift occurs it will be important to know how to make the most out of the lighting systems and how to operate them most efficiently. The control of the plant morphology, via spectral manipulation using LEDs, provides several potential benefits to growers and customers, as discussed above, but different spectra also require different energy inputs and this must be considered when designing lighting systems. Per Watt of electricity, red LEDs produce more photons than blue LEDs. This means that red LEDs can produce more useable light for photosynthesis and efficient plant production than blue LEDs. The system efficiency data presented here (Figure 5) demonstrates that increasing blue light percentage does reduce plant growth rates and increases energy inputs. Our data also high light the fact that additional far-red light can increase both yields and system efficiency (Figure 8) though identifying the optimal light dose is important. It is, therefore, important when designing light mixtures for crop production to assess the benefits of including light from different regions of the spectrum in comparison with the additional costs associated with that light.

Other colours

These experiments have so far been focused on three colours of light (far-red, red and blue). Developing accurate recipes with these three colours is time consuming due to all the possible combinations that can be tested. However, it will be necessary to expand the experiments to other colours over the coming years as other colours of light (green and UVB) potentially have benefits to the plants and, therefore, the horticulture industry.

Conclusions

Light of specific wavelengths can be used to alter plant morphology. Red and blue light act to reduce crop height while far-red light increases crop height. Reducing plant height through spectral manipulation also has the effect of reducing leaf area which may reduce plant growth rate and crop yield. Spectral manipulation can also alter other morphological parameters such as leaf angle which will influence appearance and growth rate.

The far-red light was able to increase harvestable yield in the bean crop probably via its influence on leaf area though it is also possible than some plant responses may require or be enhanced by the addition of far-red light. By including far-red light and a high proportion of blue light it may be possible to boost crop leaf area and yield while also keeping plants compact.

Different crops or different applications of the same crop will require different light recipes to optimize crop quality and harvestable yield. The benefits of different light mixtures should be examined in comparison with overall energy inputs.

Knowledge and Technology Transfer

PRESENTED AT

HDC Focus on Light Spectrum, STC, December 2012.

Brassica Growers Association Technical Committee, January 2013.

British Protected Ornamentals Association Technical Seminar, Oxfordshire, July 2013.

The Great Yorkshire show, Harrogate, July 2013 – presenter on the NFU stand.

HDC Studentship Conference, Pershore College, September 2013.

Tomato Growers Annual Meeting, Coventry, September 2013.

GreenGrowing Workshop, Lokeren, Belgium. October 2013.

TV APPEARANCES / FILM CREWS

Bang Goes the Theory, BBC1 2013

Discovery Channel Program to be shown early 2014

PUBLICATIONS

Authored by Dr Davis

LED4CROPS: The future is Bright the Future is Pink - HDC Energy news, March 2013.

A clearer view on LEDs - HDC news, June 2013, 194: 19-21.

Coloured judgement. HDC News, February 2014, 200:12-13.

Articles featuring Dr Davis

Match the Light. HDC News February, 2013, 190:16-17.

Glossary

PGR = Plant growth regulator

PAR = Photosynthetically active radiation (400-700nm) measured in units of µmol m^{-2} s^{-1}.

HPS = High pressure sodium lamp.

HID = High intensity discharge lamp.

References

Briggs, W.R. and Christie, J.M. (2002). Phototropins 1 and 2: versatile plant blue-light receptors. Trends in Plant Science 7:204-210.

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Quail, P.H. (1991). Phytochrome: A light-activated molecular switch that regulate plant gene expression. Annual Review of Genetics 25:389-409.

Rizzini, L. Favory, J-J. Cloix, C. et al (2011). Perception of UV-B by the Arabidopsis UVR8 protein. Science 332:103-106.

Appendices

Appendix I - Analysis of contacts made during year one.

In this analysis I have assessed the number of companies I have had contact with from the different sectors of the horticulture industry. The analysis has been performed as a company count rather than a person count to remove bias were I have met several people from individual companies.

GROWERS

PE = 17

Tomato = 6

Herbs = 4

Salads = 3

PO = 17

Bedding= 5

Cut flowers = 2

Bulbs and stocks = 4

Soft fruit = 3

Strawberries **=** 1

Field Vegetables = 1

More emphasis will be placed on HNS and PO companies during the second and third years.

HORTICULTURE SUPPLIERS AND SUPPORT

Seed companies = 5

Substrate manufactures = 5

Consultants = 5

Pesticides companies = 2

Spectral filters = 1

Glasshouse/poly tunnel builders = 3

TECHNOLOGY COMPANIES

Lighting companies = 7

Electronics and sensor companies =4

FOOD PROCESSORS AND RETAILERS

Retailers = 2

Processors = 4

FUNDING AND RESEARCH

NGOs = 4

Funding agencies = 4

Universities

- UK = 6
- Europe = 6
- USA and Canada = 5
- Asia = 1