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 4, Nov 2016
Previous report:	Annual report, Year 3, Nov 2015
Fellowship staff:	Dr Martin McPherson, Science Director, STC (lead Fellowship mentor) Prof. Nigel Paul, Lancaster University (Mentor)
(“Trainee ”)	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

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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 ....

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.

Objective T6. To expand the training objective of the fellowship program enabling Dr Davis to train other members of the team at STC. Much of this training will be given to Dr Beynon-Davies.

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 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 our 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.

Objective R7. The skills necessary to acquire project funding and run lighting projects are currently in development under objective R5 and through management of the AHDB funder research project 'Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs' 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 increased interactions with the network of contacts developed in training objectives T2-T5.

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	September 2017 and beyond.

		companies move into the area.	
Objective T3.	December 2013	Trainees have made many contacts 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 T6	September 2017	Dr Davis is training Dr Rhydian Beynon Davies on use of LED lighting for crop production.	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	Dr Davis is building links with several UK Universities.	September 2017 and beyond.
Objective R6	September 2017	Dr Beynon Davies have made contact across the industry.	September 2017 and beyond.

Summary of Progress

In its fourth year this Fellowship 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. Dr Davis has learned more regarding the spectral qualities of removable glass coatings. Dr Beynon-Davies has gained knowledge of soft fruit production under LED lighting.

Training objectives

Objective T1.

Competed year one.

Objective T2.

During the fourth year of the Fellowship Dr Davis has remained in contact with the multiple LED manufactures and tracked the changes and advances that have happened in the field. LED lights are gradually becoming more energy efficient though the spectra of the lamps have remained similar. More companies are attempting to move in to the Horticulture sector but in many cases these new entrants make similar mistakes due to a lack of plant knowledge. LED companies that have been working in horticulture some several years are investing in developing their understanding of crop responses to LED light. The work running in the AHDB Hort. Funded project CP125 has provided multiple opportunities for Dr Beynon-Davies to develop his understanding of plant light responses.

Dr Davis has learned about the range of removable glass coatings by visiting and performing measurements at the ADHBs Pot and Bedding Plant Centre collaboration with Jill England at ADAS.

Objective T3.

During the third year of the fellowship Dr Davis has remained in contact with a wide range of scientists around the world and is following their work on LED lighting systems. Through these contacts Dr Davis has been invited to be a Subject Editor for the open access Journal Frontiers in Plant Science. This will not only help Dr Davis remain up to date with the latest research but will also help grow his profile an reputation in academic research circles.

He continues to co-supervise a PhD student at York University whom is examining the role of the circadian clocks in abiotic stress responses. He is also a co-supervisor of the new PhD student on the “CP 164 SPECTRA: Whole plant spectral response models” at Lincoln University alongside Prof. Simon Pearson.

Objective T4.

During the fourth year of the fellowship Dr Davis has continued to manage the CP125 and the high-wire tomato project in STC LED4CROPS high-wire facility. These projects have helped him further develop his man and time management skills. Dr Davis 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 especially EU projects.

Objective T5.

Dr Davis has been developing links with in the N8 university group to increase the potential for collaborative research with UK Universities. All these efforts will help bring new technology and techniques to the industry. In addition STC has become a core member of the new Crop Health and Protection (CHAP) innovation centre which will help create many new opportunities to novel lighting projects. Dr Davis has been involved in several discussions as to how lighting can be involved in collaborative projects.

Objective T6.

The additional training provided to Dr Beynon-Davies has allowed him to make industry contacts and develop collaborative R&D projects which he has managed from start to finish.

Research Objectives

Objectives R1 & R2.

While the initial goals of these objectives have been completed further progress has been made in these areas. Continued contact with various LED manufactures and involvement in the CP139 project has allowed Dr Davis to remain abreast of advances in the LED technology.

Objective R3.

Results from the CP125 project continue to develop our knowledge and understanding of plant light responses. The research is now examining how blue and far-red light responses interact. The aim is to produce compact plants with advanced flowering.

Objective R4.

A technical review of LED lighting systems has been completed and published by AHDB.

Three articles have been 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 at academic and grower facing events.

Objective R5.

The funding secured for the CP125 project has created many interesting results and will continue to do so for the remainder of the project. A major focus of the final year of the Fellowship will be combining information developed as part of CP125 and CP139 to perform analyses of the economics of LED lighting systems.

Objective R6.

A peer reviewed review-paper has been accepted for publication in the Journal Energy and Food security. We are also preparing 3 additional publications (one on lettuce morphology, one on morphology and flowering petunia, one on basil growth and photosynthesis) based on the results generated as part of this fellowship and work associated with CP125.

Objective R7

Dr Davis has been included as a collaborator on new project titled “Optimising site-specific solar radiation modelling for its application in the horticultural, agricultural and photonics industries” that is funded by Academy of Finland.

During this year Dr Davis has attended several meetings in Europe to expand his network of contacts and with the aim of being involved in new international funded projects.

Dr Davis has been included on an EU H2020 funding bid, this bid is still pending. While these activities have been successful (STC are involved in three large EU funding bids) the recent BREXIT vote has resulted in some uncertainty as to how we can remain involved in future funding opportunities we will, however, continue to build our contacts to remain involved where possible.

Milestones not being reached

None

Do remaining milestones look realistic?

Yes.

Training undertaken

Dr Davis has trained Dr Beynon-Davies on the methods and approaches for examining plant responses to LED lighting and how to perform applied research projects.

Conferences attended

Innovate: Innovation in Greenhouses November 2015.

Sainsburys Farming conference December 2015.

AHDB Horticulture ‘Manipulating light for Horticulture’ January 2016, Speaker.

EUVRIN Founding meeting, Brussels, February 2016.

NCUB Food 4.0, London, April 2016.

Dr Beynon-Davies attended Green Tech.

Sainsbury's R&D corporate Breakfast, London, May 2016.

8th International Symposium on Light in Horticulture, East Lansing, MI, USA May 2016.

N8 Agri-food Launch, June 2016.

Fruit Focus, East Malling, July 2016.

FRUIT ATTRACTION, Madrid, October 2016, Speaker.

CGA/PTG event, October 2016, Speaker.

EUVRIN meeting, Brussels, October 2016.

Grower Visits

Yorkshire Botanical Limited, HNS, February 2016

Rothamsted, Research Sector, April 2016

Soft Fruit Panel Meeting, East Malling February 2016

AHDB Pot and Bedding Plant Centre, Baginton Nurseries, Ornamentals, August 2016.

Expertise gained by trainees

Dr Davis has continued to develop his understanding of crop light responses and is working to train Dr Beynon Davies in crop light responses, trial design and implementation.

Trainees have gained a great deal of information regarding tomato crop agronomy, the influence of lighting on tomato production as well as the economics of crop production under lights.

Dr Davis has gained knowledge of commercially available glass coatings.

Dr Rhydian Beynon-Davies received his PA1 qualification.

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

Involvement in bids for EU funding has help Dr Davis' understanding of international collaboration and funding.

Other achievements in the last year not originally in the objectives

During this year we have gained knowledge and understanding of fertigation techniques for hydroponic crops. This information is important for ensuring crops are grown to the correct standard and that crop light responses are credible.

Changes to Project

Are the current objectives still appropriate for the Fellowship?

Yes

GROWER SUMMARY: Modelling light responses

Headline

Our understanding of crop light responses has progressed considerably. We now have sufficient data to begin developing models that can be used to describe those responses and to predict how plants will respond to novel mixtures of light.

Background

The influence of different light spectra on plant morphology has been measured and documented for several species as part of the parallel CP125 project. These measurements have greatly improved our knowledge of crop light responses but alone they only provide examples of how plants respond to the light environment under which they were grown. In order to gain the greatest benefit from the measurements it would be useful to generate models that can predict how plant morphology changes with light intensity and quality. Such algorithms could be put to several different uses. For example to design light treatments to produce plants with specific size and morphologies (this has direct relevance to growers), to quantify the sensitivity of different crop species and varieties to different regions of the light spectra (this information could help growers select varieties that will perform well under their conditions but also has potential applications in crop breeding), or to test fundamental aspects of plant responses (this has the potential to identify new applications for spectral manipulation).

In this piece of work we have developed an algorithm that can be used to describe, understand and predict plant morphological responses to any mixture of red, blue, green and far-red light. The algorithm was parameterised to create a model of lettuce leaf length.

Summary

Based on our knowledge of plant light responses we generated five hypotheses aimed at describing the influence of light on lettuce leaf length:

1) There is a theoretical ‘dark-leaf-size’ (L_D) which is the length a leaf would grow in darkness if there was no resource limitation to growth.
2) Increasing blue light intensity provides a restriction (R_B) to leaf growth.
3) Increasing red light intensity provides a restriction (R_R) to leaf growth.
4) Increasing green light intensity reduces the restriction (R_G) to leaf growth.
5) Increasing far-red light intensity reduces the restriction (R_F) to leaf growth.

Each hypothesis was modelled with a non-linear equation assuming each response saturates at a given light intensity. The five parameters were combined to produce a single algorithm that would describe leaf length (L):

$$L = L_D - (R_B - R_G + R_R - R_{FR})$$

The model shows that the shortest leaves would be produced in light treatments containing between 40 and 90 % blue light. The model indicates that only 8 µmol m_{-2} s^{-1} of red light is sufficient to provide the maximum red light restriction on leaf length but that 40 µmol m_{-2} s^{-1} of blue light is required to provide the maximum restriction on leaf length.

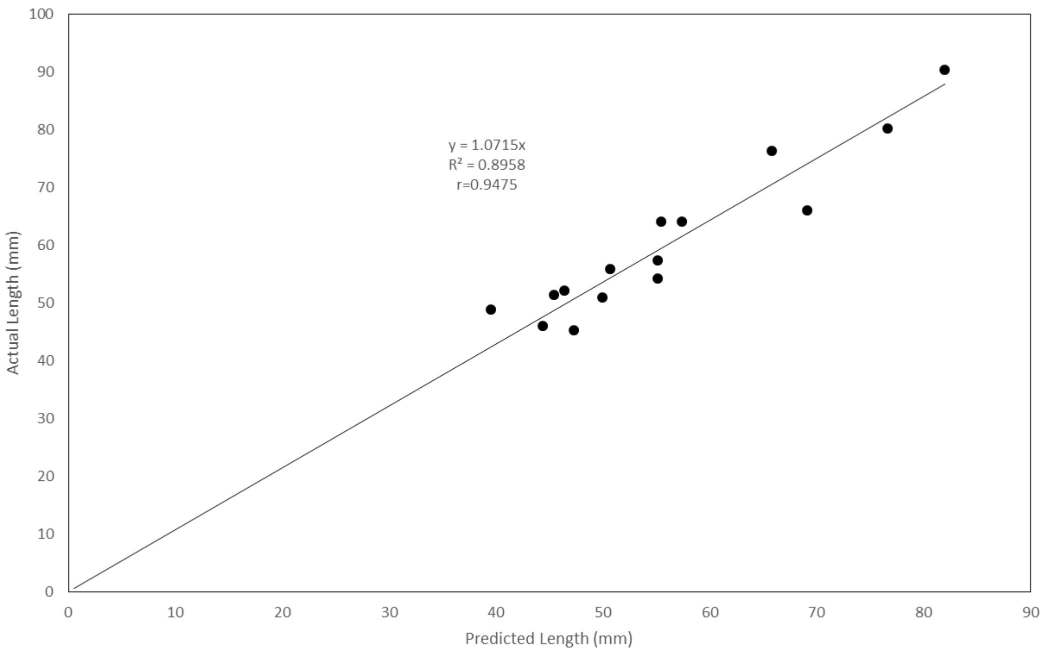

Figure 1. The validation of the leaf length model when parameterised for the Alega lettuce variety. Each data point represents the mean length of at least 8 leaves.

These models are expected to need refinement as more measurement conditions (for example no UV light treatments have been included so far), morphologies (different plant organs could respond differently) and species are tested but they have proved successful when tested against this leaf length data set. This modelling approach could be used to design light treatments that will produce lettuce plants with specific characteristics a key step in making the best use of LED lighting systems. The models will now be tested on other measured plant light responses, such as internode lengths. Ongoing development of the model will enable application to a wide range of plant responses. This work will feed in to the new ADHB funded studentship CP 164 - SPECTRA: Whole plant spectral response models.

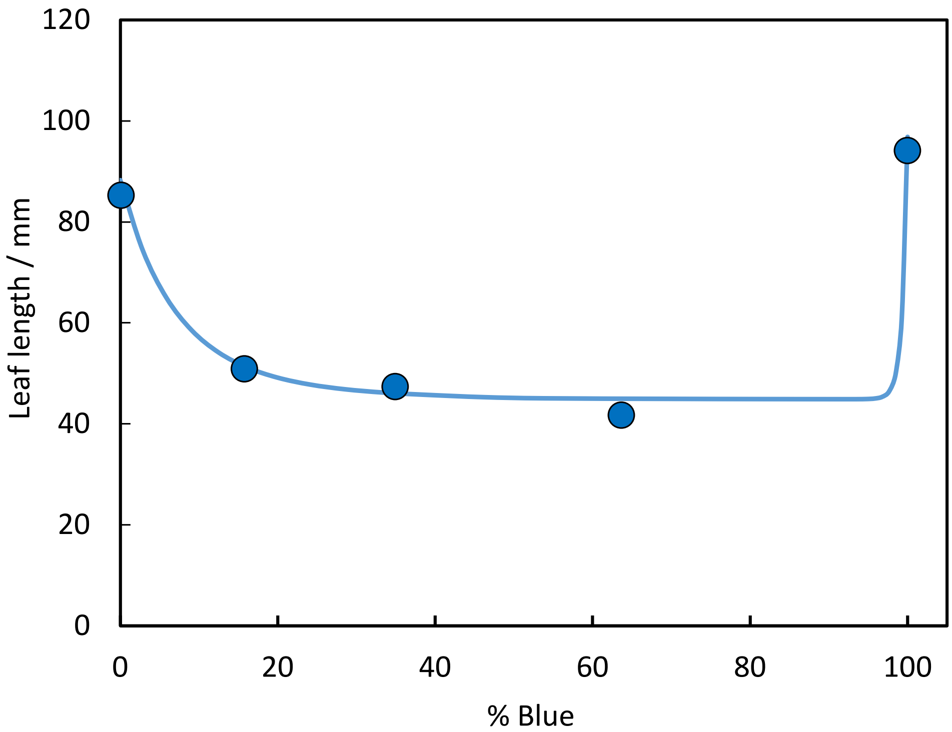

Figure 2. The leaf length of lettuce plants grown under light spectra containing different mixtures of red blue light. Circles indicate the mean measured value from 30 leaves and the line represents the model prediction of leaf length under any red: blue light mixture.

Financial Benefits

The procedures reported here provide the first steps in generating a whole plant model that describes plant morphological responses. Currently the model needs further development before it can be used in systems beyond lettuce leaf length. However, in the longer term the ability to model and predict plant light responses will help growers determined which lighting systems will be most likely to meet their needs. Given that LED lighting systems are expensive to install (£400,000 or more per hectare depending on the light level and type of installation) and that they have a significant influence on plant growth, morphology and quality it is important that the most appropriate lights are installed. Initially the models will help refine the range of light treatments required during scoping of different LED systems and any necessary R&D, reducing costs. Eventually the modelling process will be sufficiently accurate to select/design lighting systems for any crop in any situation. The models also hold the potential to allow decision support capabilities. For example sun light measurements could be supplied to the model to help growers to decide when lights need to be turned on, or if plant growth regulators should be applied. This could help reduce running costs, minimise the use of PGRs, improve plant quality and consistency thus reducing wastage. Even with the 30% energy saving LEDs provide compared to HPS lighting systems can still be expensive to run (with a light intensity of 100 μmol m^{-2} s^{-1} and an energy price of £0.09 kWh^{-1} it would cost ~£400 to light one hectare for 12 hours). Assuming the light spectra is correct plant quality will be improved by lighting production areas but better control of lighting systems will help ensure the benefits are not out weighted by the costs.

Action Points

Due to the early stage of this work the models currently have limited applications. This work will contribute to the PhD studentship program 'CP 164' that will aim to develop models with a wider scope and range of applications. If any growers or lighting manufacturers are interested in supporting or making use of this work they should contact Dr Davis as the models could be adapted for specific purposes to hasten their impact.

SCIENCE SECTION: Modelling light responses

Introduction

Many aspects of plant morphology and physiology are regulated by light. In micro-array experiments on *Arabidopsis thaliana* Ma et al (2001) found that 77% of expressed sequence tags (ESTs) were affected (either up or down regulated by two fold) when dark grown seedlings were exposed to 32h hours of white light. With this in mind it is not surprising to see the large differences in plant morphology and pigmentation that plants exhibit during photomorphogenesis. Four regions of the spectrum, UVB, UVA-blue, red and far-red are important for controlling plant morphology (Davis 2016). Plants contain a range of photoreceptors that are sensitive to specific regions of the spectrum (See Table 1). Each photoreceptor is responsible for inducing a subset of plant light responses. Some responses (such as stem elongation) are regulated by multiple photoreceptors and for maximum control of these responses multiple colours of light may be required. Other responses such as chloroplast movement are specific to one photoreceptor family (Phototropins) and are activated by one region of the spectrum (UVA-Blue).

Table 1. An over view of the photoreceptor families that are responsible for sensing light of different colours and some of the plant responses they induce.

Colour band	Photoreceptors	General responses
UVB	UVR8	Reduce stem elongation Pigment synthesis
UVA-Blue	Phototropins Cryptochromes Zeitlupe	Reduce stem elongation Stomatal opening Chloroplast movement Phototropism Circadian rhythm
Red	Phytochromes	Reduce stem elongation Delays flowering time Circadian rhythm
Far-red	Phytochromes	Increase stem elongation Speeds flowering time

Light responses have evolved to help plants acclimate to the variable environmental conditions they encounter and maximise their chances of survival or reproductive success. In many cases, especially in low light winter conditions, the biology of plants is in conflict with the aims of commercial plant production. For example plant morphology can become stretched during winter low light conditions. This stretching has evolved to help plants grow towards a more favourable light environment but for commercial systems compact plants are required year round. To counter act plant stretching in response to poor light conditions a great deal of time, effort and investment is devoted to maintaining crop morphology. With an improved understanding of crop light responses it may be possible to control plant growth using LED lighting systems providing an alternative or additive method of controlling plant quality.

As more research is performed on plant light responses under LED lighting our understanding of how to manipulate plant morphology has greatly increased. The data generated as part of the CP125 project (Davis et al 2015 & 2016) provides not only the opportunity to resolve the light responses of important crop species but also the chance to create models that can describe plant light responses. Such modelling exercises will help test theories regarding plants light responses that will further our understanding of light signalling. Robust models will also provide multiple opportunities to create new lighting control systems as they will be able to determine when lighting systems should be turned on and which regions of the spectrum should be used to maintain plant morphology. These models would help unlock the potential of variable spectrum LED lamps enabling the application of smart lighting systems that need light grower input to achieve the best results.

Here we report the development of a model designed to predict the length of lettuce leaves exposed to LED light treatments containing red, blue, green and far-red light of any combination.

Materials and methods

Plant material and treatment conditions

Seeds of *Lactuca sativa* Cv. 'Amica' (summer variety: Enza Zaden UK, Evesham, Worcestershire) and 'Alega' (winter variety: also Enza Zaden UK) were sown onto 5cm^2 peat blocks and covered with coarse vermiculite. In the LED4CROPS facility where all the red:blue:far-red experiments were performed the temperature was maintained at 21°C ± 1°C and the plants were irrigated three times per day (04:00, 10:00 and 16:00) using an automated ebb-flood system. The irrigation regime was sufficient to maintain the moisture content of the peat blocks at 84.5% ± 4.5% v/v. All the white light experiments were performed in a second growth facility where temperature was maintained at 21°C ± 3°C and the plants were hand watered with a dilute feed mix. Plants were grown under a total of 37 different light treatments, 21 were used to produce data for the model parameterisation (Table 2) and 16 were used to generate data for the model validation (Table 3). After three weeks growth under these conditions the length of the third true leaf was determined on at least 8 leaves for from replicate plants. For the parameterisation data each treatment was repeated 3 times. For the validation data set each treatment was performed once.

Table 2. Spectral composition of the light treatments used to grow the plants for the parameterisation data set.

Treatment	Light Source manufacturer	Photon irradiance / μmol m^{-2} s^{-1}				
		PAR	Blue	Red	Green	Far-red
Parameterisation data set						
Red/blue ratio						
1	Philips Research modules 666nm	104	0	104	0	0
2	Philips Research modules 666nm	190	0	190	0	0
3	Philips Research modules 460 nm + 666nm	200	32	168	0	0
4	Philips Research modules 460nm 666nm	197	60	140	0	0
5	Philips Research modules 460nm 666nm	201	120	80	0	0
6	Philips Research modules 460nm	129	129	0	0	0
7	Philips Research modules 460nm	75	75	0	0	0
Intensity						
8	Philips DR/B production modules	103.5	10.9	91.8	0.8	0
9	Philips DR/B production modules	190	21.1	167.6	1.3	0
10	Philips DR/B production modules	290	29.3	258.7	2	0
11	Philips DR/B production modules	370	42.3	324.8	2.9	0
Far-red treatments						
12	Philips DR/B production modules + Research modules 735nm	184	20.24	163.76	0	5
13		169	18.59	150.41	0	15
14		172	19.69	152.31	0	30
15		193	21.23	171.77	0	45
White light spectra						
16	Valoya AP67	190.41	26.59	118.45	45.37	16.03
17	Valoya NS2	198.83	44.41	77.62	76.8	4.46
18	SolidLite DPA	201.89	48.46	99.64	53.79	23.94
19	SolidLite DPM	204.2	42.94	82.36	78.9	16.09
20	SolidLite CWW	201.85	62.14	66.63	73.08	11.58
21	Philips DR/W production modules	187.19	39.43	112.58	35.18	3.52

Table 3. Spectral composition of the light treatments used to grow the plants for the validation data set.

Treatment	Light Source manufacturer	Photon irradiance / μmol m^{-2} s^{-1}				
		PAR	Blue	Red	Green	Far-red
Validation data set						
Intensity plus far-red						
V1	Philips DR/B production modules + Research modules 735nm	103.5	10.9	91.8	0.8	45
V2	Philips DR/B production modules + Research modules 735nm	190	21.1	167.6	1.3	45
V3	Philips DR/B production modules + Research modules 735nm	290	29.3	258.7	2	45
V4	Philips DR/B production modules + Research modules 735nm	370	42.3	324.8	2.9	45
V5	Philips DR/B production modules	103.5	10.9	91.8	0.8	0
V6	Philips DR/B production modules	190	21.1	167.6	1.3	0
V7	Philips DR/B production modules	290	29.3	258.7	2	0
V8	Philips DR/B production modules	370	42.3	324.8	2.9	0
High blue plus far-red						
V9	Philips Research modules 460nm 666nm 735nm	196.41	62.63	133.78	0.00	1.20
V10	Philips Research modules 460nm 666nm 735nm	202.14	57.14	145.00	0.00	11.25
V11	Philips Research modules 460nm 666nm 735nm	197.71	60.32	137.39	0.00	35.20
V12	Philips Research modules 460nm 666nm 735nm	202.49	59.10	143.39	0.00	20.25
V13	Philips Research modules 460nm 666nm 735nm	201.93	126.84	75.09	0.00	0.55
V14	Philips Research modules 460nm 666nm 735nm	202.67	117.23	85.44	0.00	11.02
V15	Philips Research modules 460nm 666nm 735nm	189.04	104.20	84.84	0.00	18.45
V16	Philips Research modules 460nm 666nm 735nm	197.45	113.86	83.60	0.00	32.47

Model

Based on our knowledge of plant light responses we generated five hypotheses aimed at describing the influence of light on lettuce leaf length:

1) There is a theoretical 'dark-leaf-size' (L_D) which is the length a leaf would grow in darkness if there was no resource limitation to growth.
2) Increasing blue light intensity provides a restriction (R_B) to leaf growth.

3) Increasing red light intensity provides a restriction (R_R) to leaf growth.
4) Increasing green light intensity reduces the restriction (R_G) to leaf growth.
5) Increasing far-red light intensity reduces the restriction (R_F) to leaf growth.

The light responses increase in magnitude with increasing light but saturate at a given irradiance. The responses therefore require asymptotic terms and this can be approximated using negative exponential equations (2 & 3 below). During the model parameterisation the functions for R_{fr} and R_g were found to be linear over the light intensities examined and so the models were simplified to the linear functions.

Thus leaf length (L) was modelled using the algorithm:

$$L = L_D - (R_B - R_G + R_R - R_{FR}) \quad (1)$$

where

$$R_B = a * 1 - e^{(-\alpha\frac{b}{a})} \quad (2)$$

$$R_R = b * 1 - e^{(-\beta\frac{r}{b})} \quad (3)$$

$$R_{FR} = c * FR \quad (4)$$

$$R_G = d * G \quad (5)$$

where R_B, R_R , R_{FR} and R_G are the changes in leaf length in response blue, red, far-red and green light respectively. B, R, FR and G are the photon irradiances of blue red, far-red and green light respectively. a, b, c, d, α and β are the coefficients that describe the magnitude and shape to the light responses.

Model parameterisation

Model parameterisation was performed using a non-linear least squares procedure in R (R core team, 2015) using the 'nls' function and 'nlstools package' (Version 1.0-2; Baty & Delignette-Muller, 2015). Approximate starting values for each model parameter were provided based on a rough manual parametrisation performed using Microsoft Excel. Normality of residuals was checked using standard regression and Q-Q diagnostic plots in R. Bootstrap and t-based confidence intervals were calculated for each model parameter in each model. The fit of the final fitting models were compared using the Akaike information criteria (AIC) procedure.

Model validation

The fitted model was initially compared by linear regression against the parameterisation dataset that included data from red:blue ratio treatments, intensity treatments and far red supplementation experiments. This approach only tests if the model is able to explain the variation in the data used to fit the model. To validate the model linear regressions against a 'blind' dataset (data not used to parameterise the model) is required. Our validation data set contained light treatments with different blue:far-red combinations and PAR intensity plus far-red treatments.

Results and Discussion

The influence of the different light spectra on lettuce morphology and growth rates are described in the CP125 project reports, here we will discuss the fit of the model to the measured data.

The values assigned to the algorithm when fitted to the measured data of the Alega plants are presented in Table 4 along with the model fitting statistics. All model parameters were found to be significant indicating that all the parameters are useful when describing leaf length data. The bootstrap analysis indicates how sensitive the model is to variations in each parameter. For example the L_D value was found to remain within 4% of the selected value (140.23) in 95% of all potential model solutions, indicating that this is a major contributor to the accuracy of the model. The value of β, however, varied by 50% of the selected value in 95% of the potential model solutions, indicating the model is less sensitive to changes in this parameter. The fit of the model to the parametrisation data set is shown in Figure 3A. Overall the model is able to describe the majority of the measured variation and the correlation coefficient between the measured and modelled data was 0.97. When the model was used to predict leaf size for the validation data set the fit was also good (Figure 3B) and the correlation coefficient was 0.95. These models and approaches will contribute towards the work performed in the AHDB funded studentship 'SPECTRA: Whole plant spectral response models' (CP 164).

Table 4 Mean estimates of model coefficients for leaf length in *Lactuca sativa* cv. Alega, including standard error (SE) and t-based probability. Bootstrap parameter estimates at the 2.5% and 97.5% intervals are included. Significance codes: 0 '***', 0.001 '**', 0.01, '*' 0.05, '.' 0.1.

	t-based				Bootstrap		
Coefficient	**Value**	**SE**	**P-value**	**Significance**	**Median**	**2.5%**	**97.5%**
L_D	140.23	2.39	58.65	***	140.38	135.71	145.82
a	43.40	1.54	28.11	***	43.61	40.55	46.96
α	3.35	0.26	12.65	***	3.38	2.84	3.87
b	51.97	2.05	25.39	***	51.95	47.58	56.84
β	60.74	16.85	3.61	***	61.75	31.29	94.83
c	0.60	0.04	16.47	***	0.60	0.53	0.68
d	0.19	0.01	12.59	***	0.19	0.16	0.22

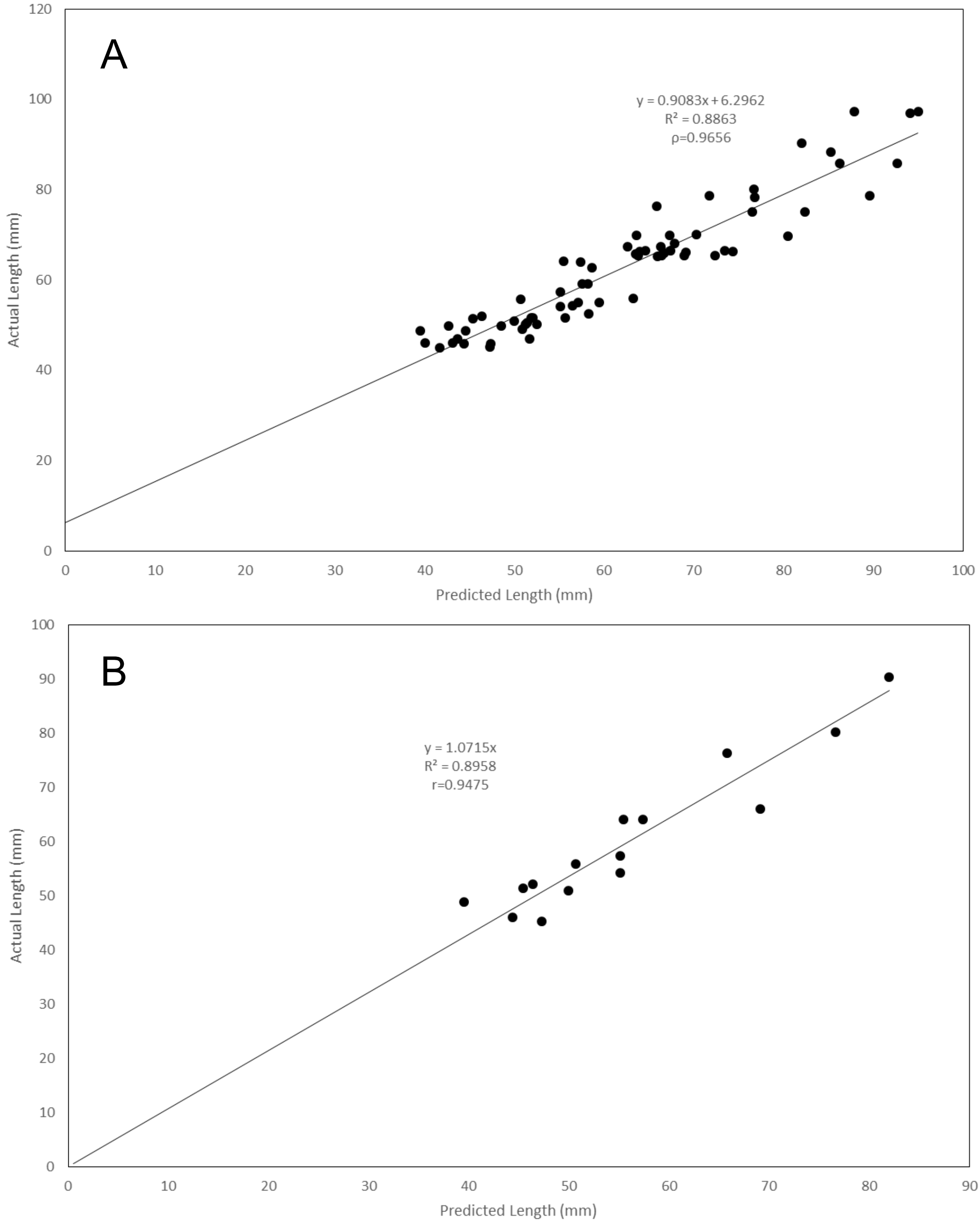

Figure 3. Plots of the modelled versus the measured Alega leaf lengths for **A)** the parameterisation data set and **B)** the validation data set.

The values assigned to the algorithm when fitted to the measured data from the Amica plants are presented in Table 5 along with the model fitting statistics. All model parameters were found to be significant indicating that all the parameters are useful when describing leaf length data. The bootstrap data indicates that the sensitivity of model to variations in the different parameters were similar for the Amica as they were with Alega lettuce variety. The values of the parameters, however, were different to account for the differences in leaf size and light sensitivity. The fit of the model to the parametrisation data set is shown in Figure 4A. Overall the model was able to describe the majority of the measured variation and the correlation coefficient between the measured and modelled data was 0.91. For the Amica plants the validation data set contained data from only nine light treatments. In this case the accuracy of the model (Figure 4B) was less good due to the presence of two stray data points, and the correlation coefficient was only 0.68.

Table 5. Mean estimates for model coefficients for leaf length in *Lactuca sativa* cv. Amica, including standard error (SE) and t-based probability. Bootstrap parameter estimates at the 2.5% and 97.5% intervals are included. Significance codes: 0 '***', 0.001 '**', 0.01, '*' 0.05, '.' 0.1.

	t-based				**Bootstrap**		
Coefficient	**Value**	**SE**	**P-value**	**Significance**	**Median**	**2.5%**	**97.5%**
L_D	147.73	2.56	57.64	***	147.67	143.64	152.72
a	36.20	1.71	21.16	***	36.35	33.23	39.65
α	1.37	0.14	9.92	***	1.37	1.09	1.70
b	57.58	2.39	24.06	***	57.59	53.42	62.26
β	89.28	19.14	4.67	***	88.88	53.34	128.13
c	0.29	0.04	7.46	***	0.28	0.21	0.36
d	0.14	0.02	9.17	***	0.14	0.11	0.17

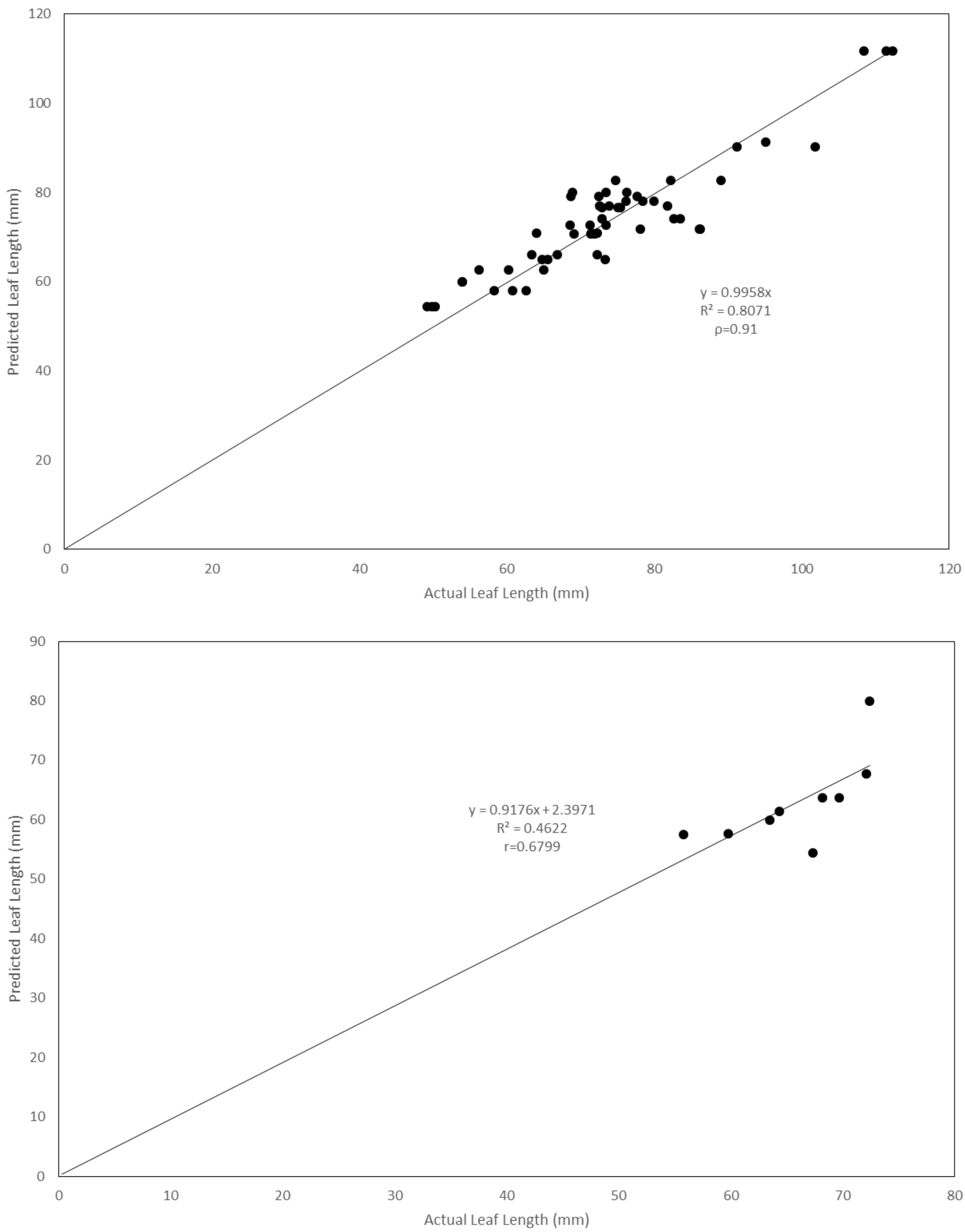

Figure 4. Plots of the modelled versus the measured Amica leaf length for **A)** the parameterisation data set and **B)** the validation data set.

With the models parameterised it is possible to use them to examine how light intensity and quality interact to influence leaf size. In Figure 5A the models are used to predict leaf size of the two lettuce varieties to two light intensities (100 and 200 μmol m^{-2} s^{-1}) and spectral qualities ranging from 100% blue through to 100% red (0% blue) light.

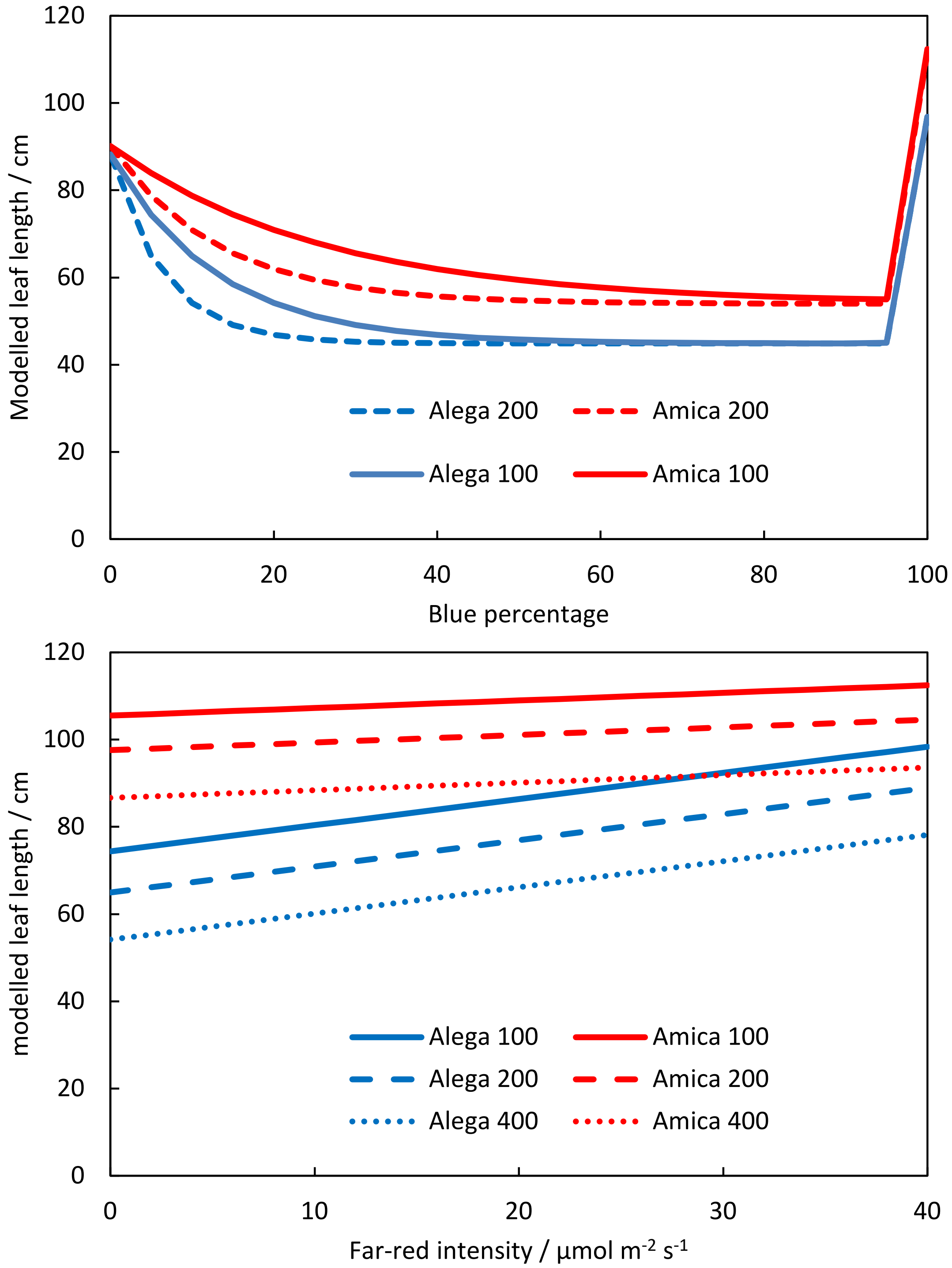

Figure 5. Model predictions of how the leaf length of Amica and Alega plants would change **A**) as blue light percentage and PAR intensity change (100 and 200 μmol m^{-2} s^{-1}) and B) PAR intensity and far-red light intensity change.

The model demonstrates that as light intensity decreases a higher proportion of blue light is required to create the most compact leaves. The model also indicates that Amica plants required a greater blue light percentage than the Alega plants to produce compact leaves. Our assumption from these data is that the light response pathways of varieties bred for bright summer conditions have become attenuated in comparison to winter varieties. This attenuation will enable summer plants produce large leaves under high light conditions maximising growth rates.

For both varieties the model predicts that very little red light is required to produce compact leaves. This suggest that lighting systems aimed at controlling lettuce morphology in glasshouses need to provide more blue light than red light. Figure 5B illustrates the influence of both PAR and far-red light intensity on the leaf length of both lettuce varieties. In this prediction leaves become shorter as light intensity increases but longer as the far-red increases. The model indicated that Amica leaves are considerably less sensitive to changes in far-red light intensity than those of the Alega variety.

The predictions the model makes will allow us to test our understanding of crop light responses by focusing future experiments. For example we could examine how much red light is actually required to produce compact leaves. LED lighting systems allow the creation of light environments that plants would never be exposed to in natural light environments. These modelling approaches will aid our attempts to create 'designer' light treatments for specific crops or growers and to ensure that light manipulate of crops achieve the desired goals and enables optimal plant quality year round.

Conclusions

- The model performed well when describing lettuce leaf lengths.
- Further development of the model will help refine its performance and broaden the range of morphological parameters it is able predict.
- Once fully parameterised the models will have multiple applications both for LED lighting systems but also as a decision making tool for glasshouse horticulture.

GROWER SUMMARY: Glass coatings (AHDB Pot and Bedding Plant Centre)

Headline

Trials at the AHDB Pot and Bedding Plant Centre at Bagintons Nursery are examining the durability of a range of glass coatings provided by several manufactures. The measurements performed in this work provide additional information on the performance of these coatings by examining how they influence the light spectrum/quality.

Background

Glasshouses are designed to maximise light transmission while minimising the effects of solar heating (taller glasshouses reduce the rate of solar heating). However, the large differences in light that occur through the seasons means that crops can receive too much light and heat in the summer and not enough light in the winter. Removable glass coatings provide a flexible method for altering the spectral properties of glasshouses through the seasons. At the AHDB Pot and Bedding Plant Centre a range of glass coatings are being trialled for durability and ease of use. Here we report on how the different coatings influence the light transmission spectra as well as the total amount of light.

Summary

Coatings designed to diffuse light (ReduFuse, D-fuse, Optifuse) or to provide shading (Eclipse, ReduSol, Q3 and Q4) were observed to have little influence of the spectrum of transmitted light but did change the total amount of light that was transmitted (Figure 6). All products were observed to diffuse light, though these measurements were designed to assess shading and spectral effects rather than to quantify the extent of diffusion (Haze factors). Products designed to reduce the solar heating caused by the sunlight (Q Heat, TransPAR, ReduHeat) were observed to reduce the transmission of light with wavelengths greater than 650nm (so they reduce transmission of the red region of the PAR spectrum) and to reduce the transmission of UV light, wavelengths shorter than 400nm. The reduction of UV transmission may have little impact of crop performance when used on glass structures because glass also absorb UV light (glass removes 50% of light with a wavelength of 350nm and blocks the majority of light below 300nm) but may have greater effects if used on structures constructed from UV transmitting plastics. The products produced by the different manufactures were observed to have similar light transmitting qualities. The measured transmittance values were found to be very similar to those reported by the manufactures.

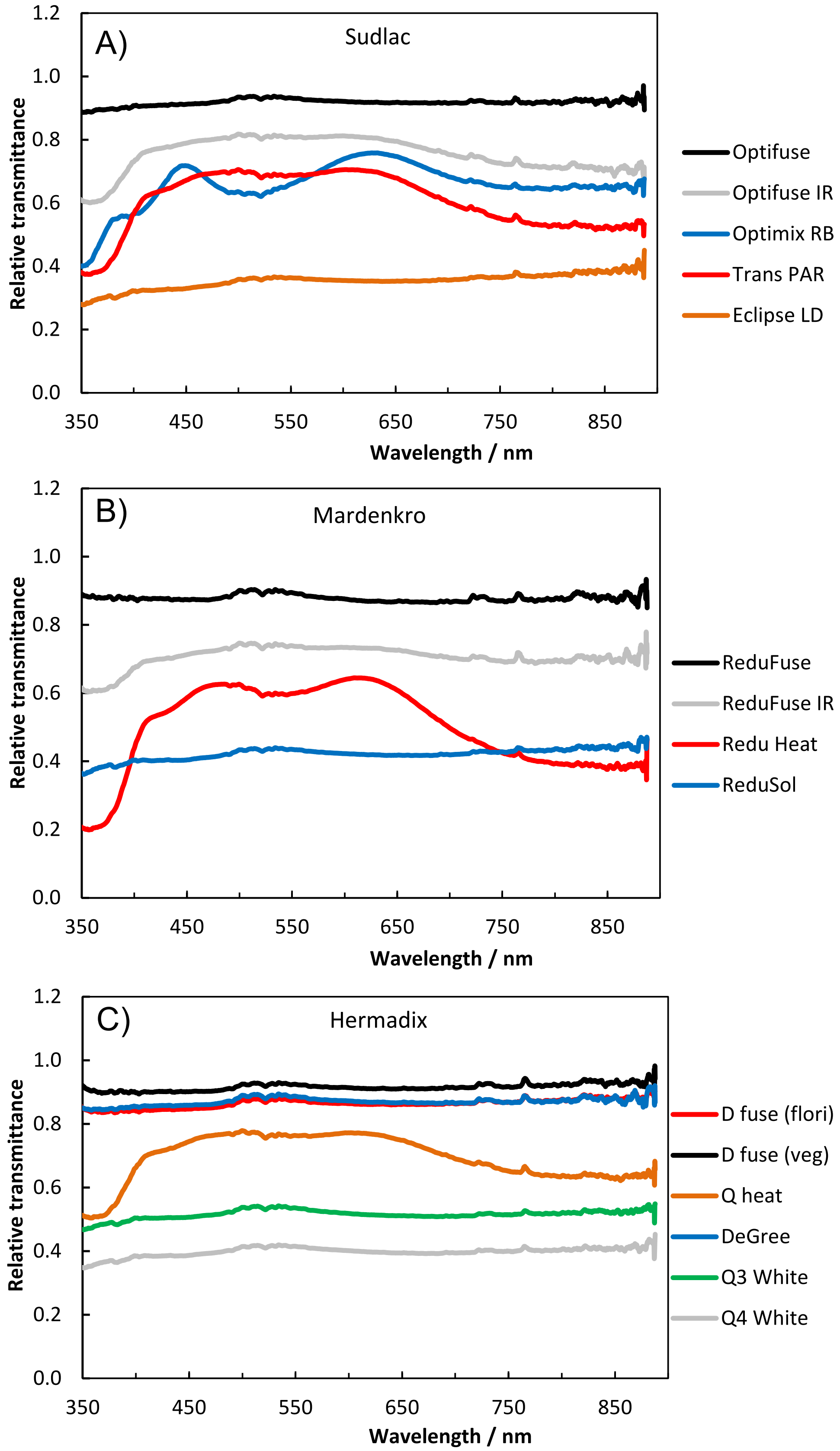

Figure 6. The relative mean transmission spectra of the different glass coatings. Spectra are grouped based on the manufacturer that produced the products **A)** Sudlac, **B)** Mardenkro

and **C)** Hermadix. Transmission spectra were calculated relative to the transmission of glass and so exclude the influence of glass.

Financial Benefits

These measurements will allow growers to make informed decisions when they choose which glass coating to use on their glasshouse. The data will help growers select a coating that meets their needs and compare the products produced by different manufacturers. When combined with the coating durability assessments that are ongoing at the AHDB Pot and Bedding Plant Centre, growers will be able to identify the most cost effective product for their situation and crop needs. With the cost of glass coatings ranging from between £540 to £5280 +VAT per hectare significant savings could be achieved by selecting a lower cost product that is able to provide the desired light environment. While shading is required for some scorch prone crops too much shading can reduce growth rates and may impact cropping schedules. These results show that if correctly followed the manufactures guidelines will results in the desired levels of shading. Further information on the durability and costs of the different coatings can be found in the AHDB Pot and Bedding Plant Centre - New product opportunities for pot and bedding plant growers (PO 019) reports.

Action Points

1. When planning to apply a glass coating growers should first define the reason for applying the coating (to diffuse light, to reduce light intensity or to reduce solar heating).

2. Determine the range of products that could be used to achieve those goals, the application rate required and the costs of the comparable products.

3. Determine the duration over which you will require the coating to last. For example according to the manufactures product information the two Hermadix products Q3 White and Q4 White can both be used to provide between 80 and 40% shading to a glasshouse, depending on the application rates (our results indicate that the manufactures guidance is accurate). However, at 45% shading the Q4 White coating could last to up to four weeks longer than the Q3 White coating due to its greater weather durability. The ongoing trials at the AHDB Pot and Bedding Plant Centre will provide useful information regarding the life span of the coatings included in the trials and in UK weather conditions.

4. When assessing the costs of a coating also ensure you examine the costs associated with removing the product at the end of the season.

5. Always follow the manufactures application instructions to ensure an even coat is applied throughout the glasshouse.

6. Following the application of any coating, crop performance should be monitored closely to ensure the crop is responding as desired.

SCIENCE SECTION: Glass coatings (AHDB Pot and Bedding Plant Centre)

Introduction

Many crops are grown in glasshouses to provide protection from the variable climate allowing season extension and optimization of the climate. However, the reliance on sunlight means that plants are exposed to variable light intensity, quality and structure as the weather and seasons change. All aspects of light quality can affect plant growth rate, morphology and overall quality. Each species and often each variety of a species will have different requirements for light, too little light and plants will stretch and bolt while too much light can burn leaves and result in stunted growth. Variable light intensity can slow plant growth as plants can take up to 30 minutes to achieve their maximum photosynthetic rates (Urban et al, 2007; Martin et al, 2013). Large drops in light intensity can cause stomata to close. If the stomata are slow to open when the light intensity increases growth rates can be effected as photosynthesis is limited because closed stomata reduce access to CO_2. The structure of light entering the glasshouse can have important effects on crop growth rates. Direct sunlight is bright but creates shadows within glasshouses that can result in uneven crop grow and quality. Direct light also results in shadows within canopies. In contrast diffuse light is observed to be more spatially uniform and penetrate deeper into plant canopies. Plant light use efficiency is greater under diffuse than direct light (Black et al 2006). In addition to the direct effects of light on crops changes in solar radiation cause large differences in temperature and relative humidity within glasshouses that can influence crop quality (Li et al, 2014) and glasshouse climates must be managed accordingly. Not all the light energy received in glasshouses can be used by plants for photosynthesis. Near-infra-red (NIR) and longer wavelengths of light can drive temperature changes in glasshouse making management of the climate challenging. Solar heating can be useful in cooler climates or during the cooler months of the year but in summer and in warmer countries too much heat can result in temperatures than will kill crops and cooling glasshouse can be expensive or use valuable water.

Glasshouses are designed to maximise the amount of light that enters the crop growth area. However, maximum light transmittance during the summer months may result in too much light hitting plants and a climate that is too warm. Over recent years diffuse glass has received considerable interest as it can improve yields and reduce glasshouse heating during the summer months. However, diffuse glass is considerably more expensive than standard float glass and it is impractical to re-glaze existing structures. Glass coatings provide a low cost, removable method of changing the properties of glasshouses from season to season aiding growers to produce high quality crops through the seasons. Several manufactures produce a range of glass coatings with different properties aimed to either diffuse light, provide shade, reflect infrared light to reduce glasshouse heating or even to alter the spectrum of light.

In order to learn more regarding the spectral properties of different glass coatings light measurements were made at the ongoing glass coatings trials at the AHBD Pot and Bedding Plant Centre. Here we report on the measured transmission spectra of these materials.

Materials and methods

Glass coatings

The glass coatings trial was set up at the AHDB Pot and Bedding Plant Centre by ADAS staff. In summary, glass coating products were applied via a hand-held sprayer to new glass panes on 14th July 2016, and set out in a wooden A-frame structure (Figure 7). Standard un-treated glass was used as a control. 15 different types of glass coating, from 3 different manufacturers (see Table 6) were examined as well as an untreated diffuse glass. Each treatment was replicated three times.

Figure 7. Photograph of the glass coatings trial plots at the AHDB Pot and Bedding Plant Centre.

Light measurements

Measurements were made at the AHDBs Pot and Bedding Plant Centre at Baginton Nurseries on the 26th August 16. Light measurements were made between 11am and 2pm using a hand held portable Jaz spectroradiometer. To ensure the light measurements only recorded light that passed through the glass the sensor was placed inside a black plant pot that was placed against the under surface of the glass. For measurements of unfiltered sunlight the sensor and plant pot were mounted at the same angle and direction as for the glass transmittance measurements. During the measurement period few clouds obscured the sun allowing rapid measurement progress. To avoid noise in the data, measurements were only made under full sun conditions (measurements were suspended even if cloud partially obscured the sun). For each pane of glass five measurements were made, one at the centre and one near each corner of the pane. Two light transmittance spectra were calculated for each treatment: 1) The mean light transmittance relative to unfiltered sunlight (calculated as the measure light transmittance of the three replicated samples divided by the mean solar radiation) and 2) the light transmittance relative to the light transmission of untreated glass (calculated as the measure light transmittance of the three replicated samples divided by the three replicated plain glass samples).

Results

To estimate the overall influence of glass type and glass coating on plant growth rate we determined the percentage transmission of sunlight over the PAR region of the spectrum (sunlight percentage transmission). For the standard untreated glass the PAR sunlight percentage transmission was 84% (Table 6). The diffuse glass was observed to have similar sunlight percentage transmission to the standard untreated glass (83%). For the glass coatings PAR sunlight transmission varied considerably with the greatest values associated with coatings designed to diffuse light (D-fuse Floriculture = 72%, D-fuse Vegetable = 77%, ReduFuse = 74% and Optifuse = 77%) and the lowest associated with products designed to provide shading during the summer months (Q3 = 44%, Q4 = 30%, ReduSol = 35% and Eclipse LD = 30%). Coatings designed to alter the spectrum in some way, for example to remove the heat from the light, had intermediate PAR transmission values (Q heat = 63%, ReduFuse IR = 61%. ReduHeat =50%, Optifuse IR = 67% and TransPAR = 57%).

To understand how the different coating products influenced the light spectrum we also determined the percentage of light transmission relative to that of the control untreated glass (product percentage transmission). This calculation removes the absorbance that was associated with the glass revealing the spectral properties of the coatings. The product percentage transmission spectra, along with the sunlight percentage transmission spectra are presented in Figures 8, 9 and 10 for the Mardenkro (and the untreated glass panes), Hermadix and Sudlac products respectively.

The diffuse glass was found to have a higher light transmission in the UV end of the spectrum and the far-red region of the spectrum (Figure 8 and Table 6) than the standard untreated glass. This may be caused by different iron contents in the different types of glass used to produce these panes.

Table 6. The light transmission data for the different glass types and glass coating examined. Transmission data were calculated relative to sunlight over the PAR (400-700nm) range (sunlight percentage transmission) and relative to the control untreated glass over several different wavelength ranges (product percentage transmission).

			Sunlight % transmission	Product % transmission					
Product	Manufacturer	Ratio	PAR	PAR	315-400nm	400-500nm	500-600nm	600-700nm	700-800nm
Untreated glass	N/A		84.0	-	-	-	-	-	-
Untreated diffused glass	N/A		82.6	98.4	109.9	97.4	98.1	99.1	104.1
D-Fuse Floriculture	Hermadix	1:5	72.4	86.3	84.3	85.1	87.1	86.2	87.0
D-Fuse Vegetable	Hermadix	1:5	76.7	91.3	90.6	90.5	92.1	91.1	91.9
DeGree	Hermadix	1:4	73.2	87.2	85.0	86.3	88.3	86.8	87.0
Q Heat	Hermadix	1:3	63.1	75.2	55.9	74.5	76.6	74.3	65.9
Q3	Hermadix	1:5	43.6	51.9	48.7	51.2	53.1	51.2	51.6
Q4	Hermadix	1:5	30.3	40.0	36.7	39.2	41.1	39.5	40.0
ReduFuse	Mardenkro	1:5	73.8	87.9	88.2	87.8	89.0	86.9	87.3
ReduFuse IR	Mardenkro	1:4	61.0	72.6	63.0	71.6	73.7	72.3	69.7
ReduHeat	Mardenkro	1:3	50.3	59.9	27.5	58.7	61.0	59.6	43.5
ReduSol	Mardenkro	1:5	35.4	42.1	38.5	41.0	43.1	41.9	42.8
Optifuse	Sudlac	1:5	77.3	92.1	89.6	91.5	92.9	91.7	91.8
Optifuse IR	Sudlac	1:4	67.0	79.8	65.0	79.0	81.0	79.1	73.1
Optimix RB	Sudlac	1:4	58.2	69.3	50.6	66.1	66.9	73.5	65.8
TransPAR	Sudlac	1:3	57.0	67.9	44.0	67.1	69.3	67.1	55.9
Eclipse LD	Sudlac	1:5	29.5	35.2	30.2	33.5	36.0	35.4	36.6

Mardenkro Products. The ReduFuse and ReduSol coatings were found to have flat product percentage transmission spectra (Figure 8) but with large differences in the magnitude of transmission, ~88% at ~42% respectively (Table 6). The ReduFuse IR and the ReduHeat were both found to reduce the product percentage transmission of UV light, compared to PAR wavelengths. The ReduHeat coating had a more pronounced effect at reducing far-red and NIR than the ReduFuse IR coating. These measurements don't cover the entire NIR range so may be missing the region of the spectrum where the ReduFuse IR coating is most effective.

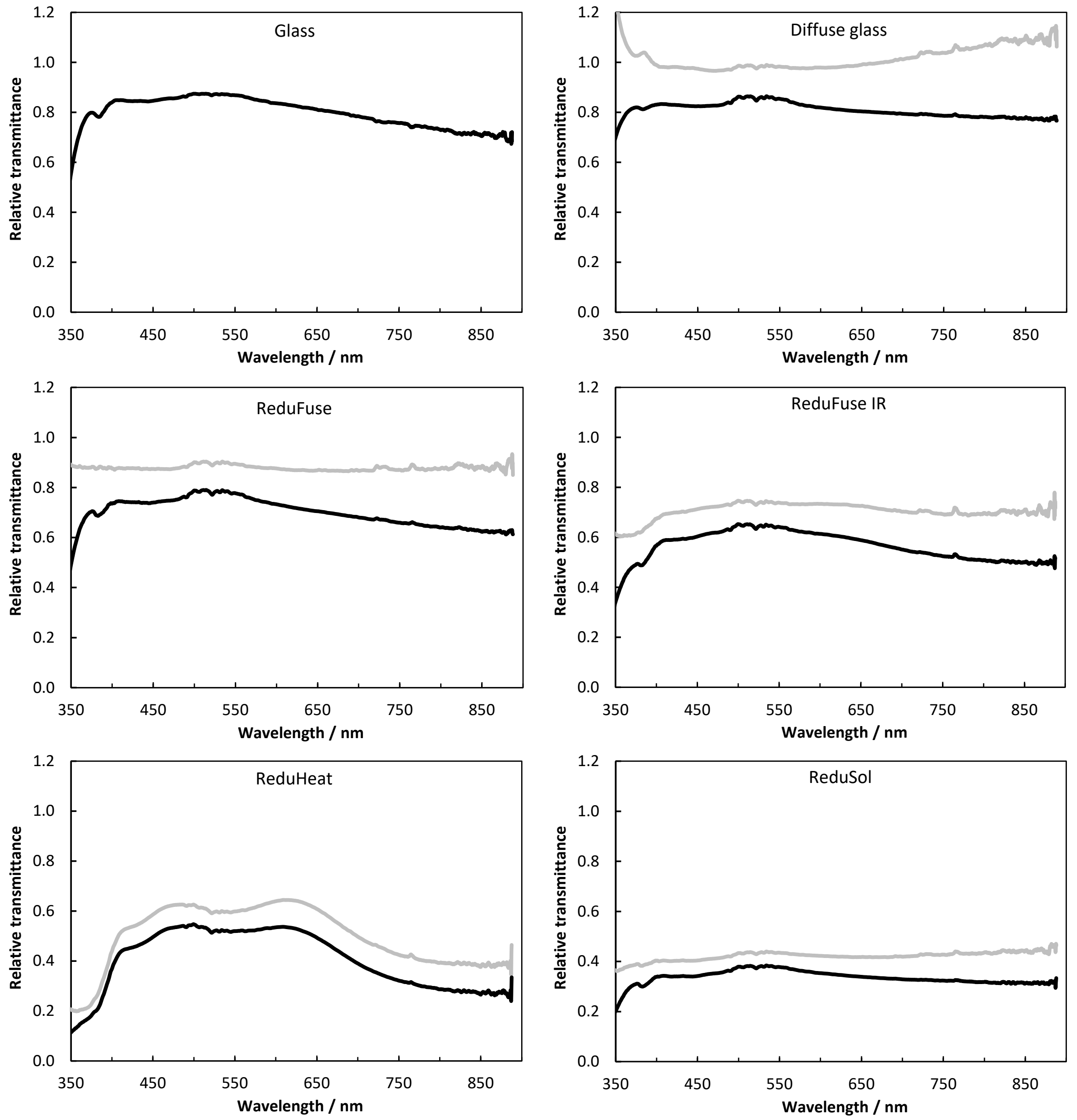

Figure 8. The light transmission spectra of the two untreated glass types (standard glass and diffuse glass) and the glass panes treated with the Mardenkro products from the Redu range. Black lines indicate the transmittance calculated relative to direct solar radiation (sunlight percentage transmission) and the grey lines indicate the transmittance calculated relative to the transmittance of standard glass (product percentage transmission).

Hermadix Products. The D-fuse Floriculture, D-fuse Vegetable and the DeGree product % transmission spectra (Figure 9 and Table 6) were very similar in magnitude and shape (all flat spectra). The Q3 and Q4 coatings also had flat spectra but transmitted considerably less light (52% and 40%respectively). No evidence of enhanced NIR reflection by the DeGree coating (compared to the D-fuse products) was apparent in these measurements. However, these measurements don't cover the entire NIR range so may be missing the region of the spectrum where this coating is effective. The Q Heat coating reduced the relative percentage transmission of UV light and far-red and NIR light compared to PAR wavelengths, the reflection was greater in the UV region than the Far-red and NIR regions examined with these measurements.

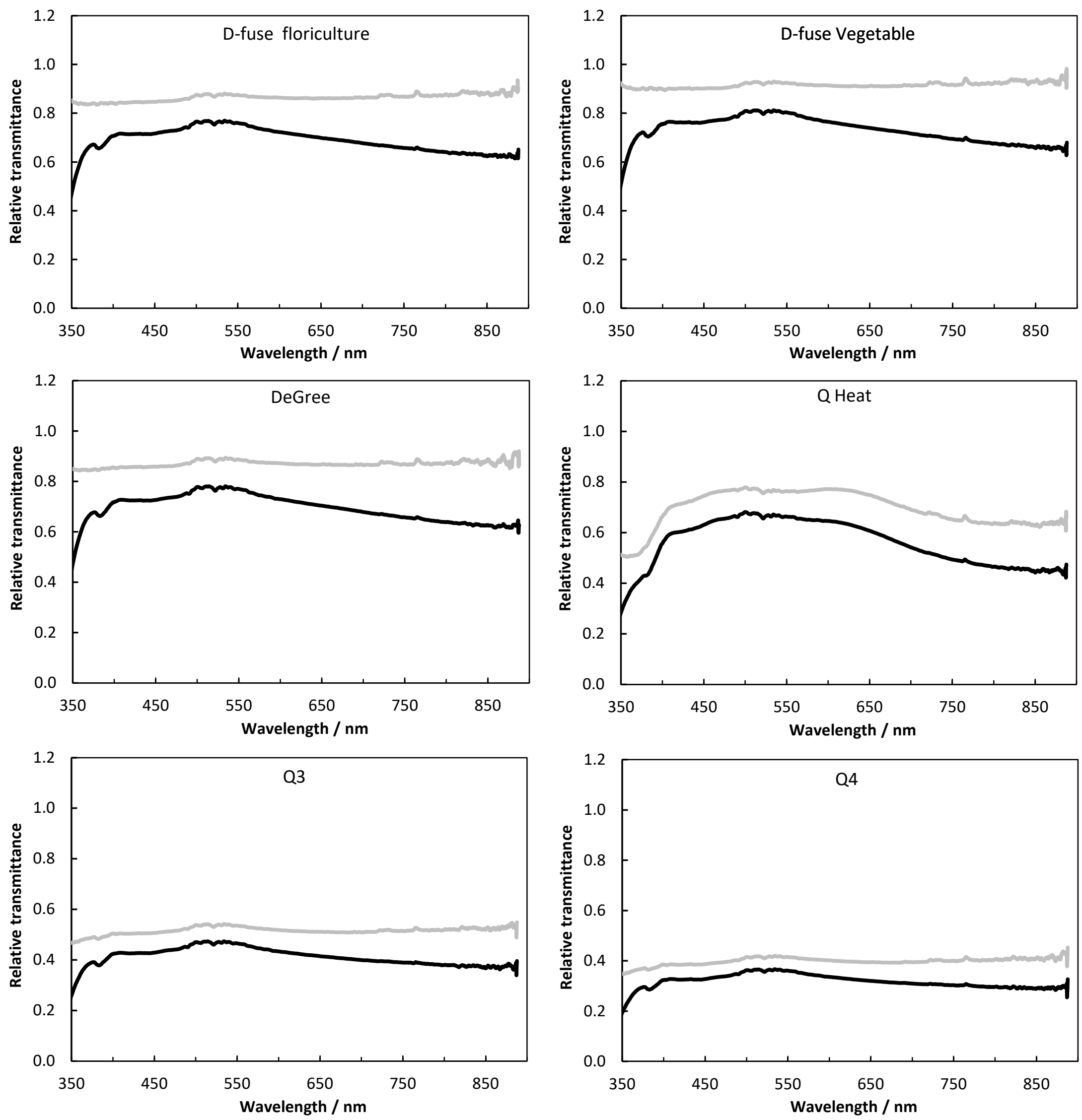

Figure 9. The light transmission spectra of glass panes treated with the Hermadix products. Black lines indicate the transmittance calculated relative to direct solar radiation (sunlight percentage transmission) and the grey lines indicate the transmittance calculated relative to the transmittance of standard glass (product percentage transmission).

Sudlac products. The Optifuse and the Eclipse LD coatings were both found to have flat product % transmission but large differences in transmission, 92% and 35% respectively. The Optifuse IR coating was observed to reduce the transmission of UV, far-red and NIR radiation. TransPAR had a lower PAR transmittance than the Optifuse IR but also had a stronger influence on the UV, Far-red and NIR transmittance. Optimix RB was the only product tested that is designed to alter the colour balance of visible light and reflection of green light can be seen from certain angles when the material is viewed from above. There were noticeable peaks in the transmission spectra at about 450nm (blue) and 630nm (red). Transmission in the green region (500-550nm) was approximately 10% lower than the red and blue region of the spectrum.

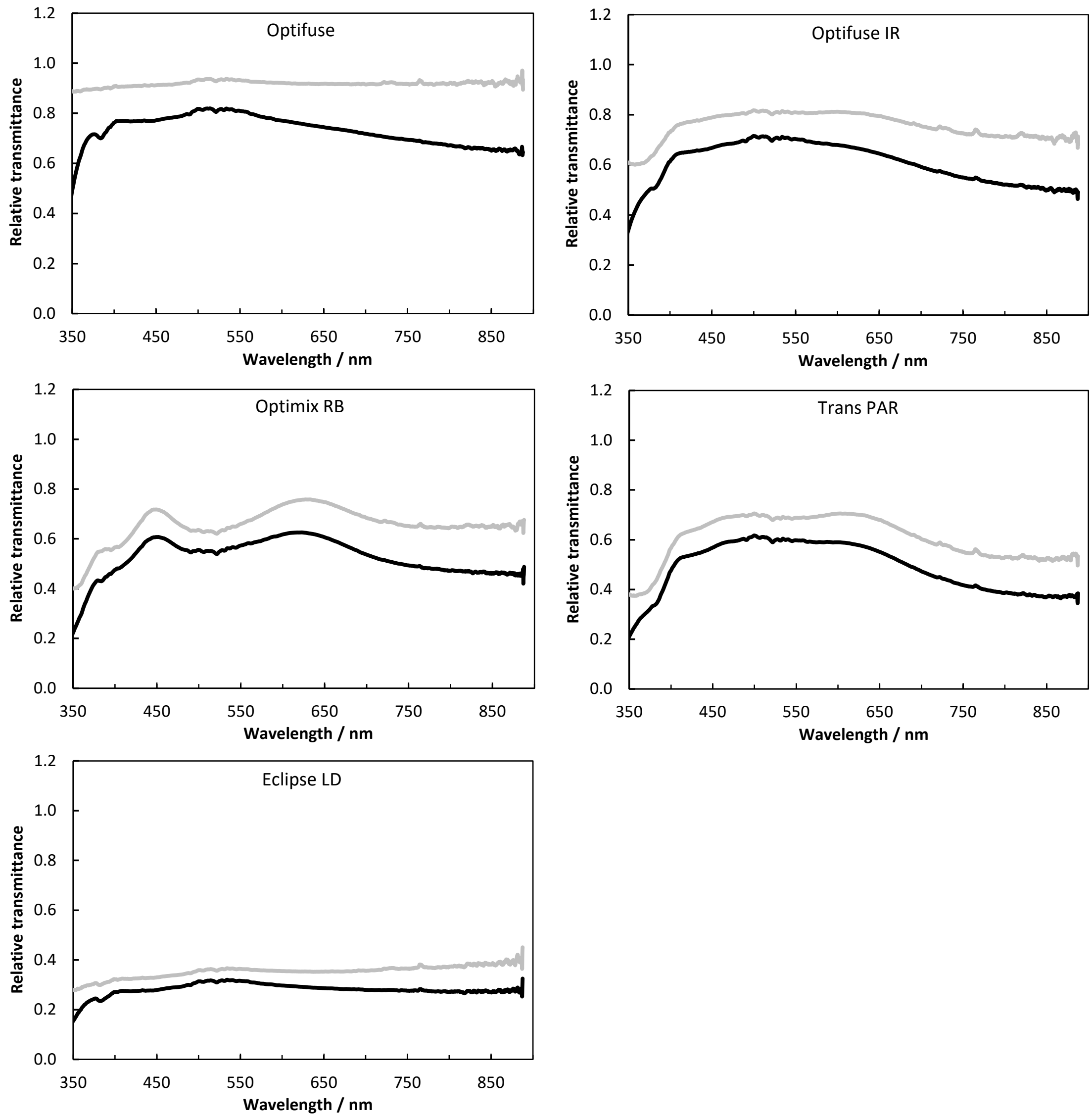

Figure 10. The light transmission spectra of glass panes treated with the Sudlac products. Black lines indicate the transmittance calculated relative to direct solar radiation (sunlight percentage transmission) and the grey lines indicate the transmittance calculated relative to the transmittance of standard glass (product percentage transmission).

Discussion

The absolute transmission values presented here should only be used as guidance as they are influenced by the location of the sun (which changes with time of day and day of year) and the amount of product applied to each treatment. However, the light transmission of the different coatings varied as expected with shading material reducing light transmission to a greater extent than diffusing materials. The properties of the materials fell within the specification ranges provided by the manufactures and so achieving the desired amount of shading or light diffusion should be possible if the manufacturer's instructions are followed. The spectral effects of the different coating observed here were consistent with the manufactures claims and with the results of Hemming *et al* 2006.

All the glass coatings resulted in the transmitted light having a diffuse structure, however, the measurements performed here were unable to determine how diffuse the light field was. It is likely that each material resulted in a different amount of diffusion. For example D-Fuse floriculture, D-Fuse vegetable and DeGree have very similar transmission values and spectra in the data reported here. However, the manufacture states that these three products result in different haze factors, a measure of how strongly they diffuse the light. More detailed measurements will be required to examine how these materials influence light structure.

Diffuse light has the potential to improve crop yields by both increasing light capture deep in the canopy and by lowering the temperature of leaves (Hemming et al 2007). However, additional trials are required to determine how different haze factors actually influence plant growth rate and quality. For more information on effects of diffusing materials see AHDB project 'Optical coatings to increase the yield and quality of protected salads, fruit and ornamental crops' (CP147).

During these measurements the sensor head of the spectroradiometer was enclosed in a black plant pot to avoid unfiltered light entering the sensor and influencing the transmission spectra. This results in the measurement being directional, only light from an area of 28cm^2 (the size of the pot) directly in front of the sensor is measured. For none diffusing materials (in this case only the standard glass) and direct sunlight conditions (as were encountered during the measurement period) the measurements would result in accurate assessments of light transmission. For diffusing materials this measurement methods will result in an underestimate of the actual light transmittance. This is because the plant pot would prevent the measurement of low angle light and for materials with higher haze factors (greater light diffusion) a larger proportion of light will not reach the sensor head. To gain more accurate estimates of absolute light transmission either measurements need to be made in coated glasshouses (ideally in association with plant growth trials) or measurements that can account for the angular distribution of the light are required (hemispherical measurements). While there is some uncertainty associated with the absolute light transmittance the relative differences in transmission between the products are expected to be correct. Furthermore the shapes of measured transmission spectra are also found to match those reported by the manufacturers.

In general the coatings from the three manufactures had similar spectral properties. Diffusing and shading materials generally had relatively flat transmission spectra. Materials designed to reduce the heating effects of sunlight reduced transmission in the UV, far-red and NIR regions of the spectrum. While these materials reduced light NIR transmission to a greater extent than PAR light transmission, a greater reduction in heat wavelengths was also associated a greater reduction in PAR light.

Conclusions

- The glass coatings provide a low cost removable method of altering the light transmitting properties of glasshouses.
- All glass coatings resulted in diffused light environment.
- There were large differences in total amount of light transmitted by the different materials.
- Coatings designed to reduce solar heating of glasshouse were also found to reduce UV light transmission.
- Products produced by the different manufactures for the same purposes have similar influences on the spectrum of transmitted light.
- Trials of plant growth under structures treated with different glass coatings will be required to determine how they influence different aspects of plant growth and climate management.

Knowledge and Technology Transfer

Interest in the LED work at STC remains high and we are still receiving large numbers of visitors. In the last 12 months we have received over 50 visits to the LED facilities. Visits are logged as diary events recorded in the calendar and are not a count of the number of people that have visited the facilities. Visitor groups range in size from individuals to large groups with over 50 visitors. Many additional interested parties have visited the facilities but have not been logged. The number of academic visitors has also increased this year indicating an increased academic awareness of the work we are performing in the LED facilities but also a shift in the funding landscape that may increase the diversity of avenues available for STC to become involved in new research projects.

Publications

AHDB publications:

Lighting: The Principles and Practice.

Lighting: The principles (Dr Phillip Davis – Author)

Lighting: The review (Dr Phillip Davis – Co-author with Spence Gunn)

Lighting: In practice (Dr Phillip Davis contributed to the information contained within this report).

Peer reviewed articles

Phillip A. Davis & Claire Burns (In press) Photobiology in protected horticulture. Food and Energy Security.

Presentations,

Dr Davis presented an overview of the research of project CP125 at the AHDB Horticulture 'Manipulating light for Horticulture' Conference. January 2016.

Soft Fruit panel Meeting at STC. Panel given a tour of the LED facilities.

Dr Davis presented his ongoing research at the CGA/PGA meeting October 2016.

Outreach activities

The LED4CROPS website is now live www.LED4CROPS.co.uk. This website will continue to be developed and over time we will add videos to demonstrate plant light responses. Please contact us if there is more information you would like to see on the website.

Dr Phillip Davis and Dr Rhydian Beynon-Davies manned a stand at the great Yorkshire show. The Multi-tiered LED lighting systems for crop production were demonstrated and many interested attendees came over to discuss out work. Interestingly this year many people reported having seen the technology on various TV shows and were keen to learn more about the technology.

The BBC's Gardeners World team filmed in the LED4CROPS facilities during August 2016 for a program that will be aired sometime in November 2016.

Glossary

Cryptochrome	A photoreceptor that is sensitive to blue and UVA light.
HPS	High pressure sodium lighting.
LED	Light emitting diodes.
PAR	Photosynthetically active radiation (PAR) is light with wavelengths in the range of 400-700nm that can be used by plants for the process of photosynthesis.
PGR	Plant growth regulators.
Photomorphogenesis	The processes that causes plant morphology and pigmentation to change following exposure to light. These processes are activated and controlled by several photoreceptors.
Photon irradiance	A measurement of the number of photons incident on a surface, which has units of μmol[photons] m^{-2} s^{-1}.
Photoreceptor	Light-sensitive proteins that initiate light responses.
Phototropin	A photoreceptor that detects blue and UVA light.
Phytochrome	A photoreceptor that can sense the red:far-red ratio of light.
UVR8	A photoreceptor that is able to detect UVB light.

References

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