Project title:	Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs.
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Project leader:	Dr Phillip Davis, (STC)
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The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

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

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CONTENTS

GROWER SUMMARY

Headline

Manipulation of light quality using LEDs can be used to improve all stages of crop production and light spectra designed for plants can be designed to maximise growth, maximise growth regulation and/or to induce flowering. Insect colour perception is also altered under LED light but fluorescent yellow and green sticky traps improved trap effectiveness under red:blue light mixtures.

Summary

Report overview

The experiments reported here are arranged in 3 work packages.

Work package 1 - General agronomy under LED lighting.

This work package will examine the general agronomic practices required for plant production under LED lighting. One of the major benefits of LED lighting is low energy consumption compared to conventional lighting systems. The robust nature and ability to rapidly turn LEDs on and off also provides the possibility of further reducing energy consumption by either creating mobile light rigs that move over the crops at regular intervals or strobing the light to reduce energy consumption. Both these techniques can lower energy consumption, but this comes at the cost of a lower daily light integral (DLI). All plants have an optimal daily light integral at which growth rates are high and plant quality is optimal if no other factors are limiting. While there is some information regarding the optimal DLI for a range of species, these values have been defined under natural light conditions where the solar intensity varies greatly throughout the diurnal cycle. Under the constant conditions that can be achieved in LED light growth systems, there is little information regarding the optimal DLI.

This work package examined the effects of a mobile light system (DLI ~3.5 mol m^{-2} d^{-1}), a slow strobe light system (DLI 6 mol m^{-2} d^{-1}) and four constant-light-intensity treatments with different daily light integrals ranging from 6 mol m^{-2} d^{-1} to 22mol m^{-2} d^{-1}, on the propagation (first three weeks of growth) of two varieties of lettuce. In subsequent years the influence of DLI will be examined in other species.

Work package 2 - Influence of light quality on crops.

The experiments in work package 2 will examine the responses of plants to different light spectra with the aim of improving our understanding of the diversity of plant responses to light and to help commercial implementation of LED technologies. WP2 is divided into subsections

examining different aspects of light quality on plant morphology. This report contains results from four subsections of WP2:

WP 2.1a	Comparisons of plant growth under a range of commercially available LED light spectra.
WP 2.1b	Influence of red / blue ratio on plant growth.
WP 2.1c	Influence of red / far-red ratio on plant growth.
WP 2.3	Improving cutting propagation.

Several species were examined (basil, sage, cucumber, petunia, pansy, begonia, pelargonium, lettuce, photinia, elaeagnus, and rhododendron).

Work package 3 - Light quality and its influence on pests.

This report contains results from the first subsection of work package 3 (3a) - monitoring pests under LED light and methods for improving pest monitoring in LED light environments. In subsequent years this work package will examine the influence of light on pest performance of specific host crops, Lettuce, Cucumber and Verbena.

WP 1.2 Energy saving and daily light integral

As noted above daily light integral (DLI) is a useful measure of the light that is available for growth. Optimal daily light integrals are available for many species but these have been determined using natural sunlight, which varies in intensity through the day, and these DLI values may not be accurate / appropriate for the constant light conditions that occur in LED lit systems. Using a range of light treatments with different DLIs created with a mobile light, a strobe light and four constant light treatments with different light intensities, two lettuce varieties, Alega (a winter variety) and Amica (a summer variety) were grown for three weeks to assess the influence of DLI on growth and morphology.

The growth of both lettuce varieties was observed to increase as DLI integral increased (Figure GS1). In the lowest light treatment provided by the mobile light, the plants barely grew, only producing 2 true leaves. Plants grown under a variable light intensity (strobe light turning on and off every 8 seconds) grew more slowly than plants grown under a constant light even when the DLI was the same. The winter lettuce variety grew more rapidly than the summer variety in all treatments. The difference in growth between varieties was at least partially caused by differences in leaf morphology. The curled leaves of the summer variety were able to absorb less light than the flat leaves of the winter variety. Leaf flattening is a blue light response and this difference indicated that the summer variety tested was less sensitive to blue light than the winter variety tested.

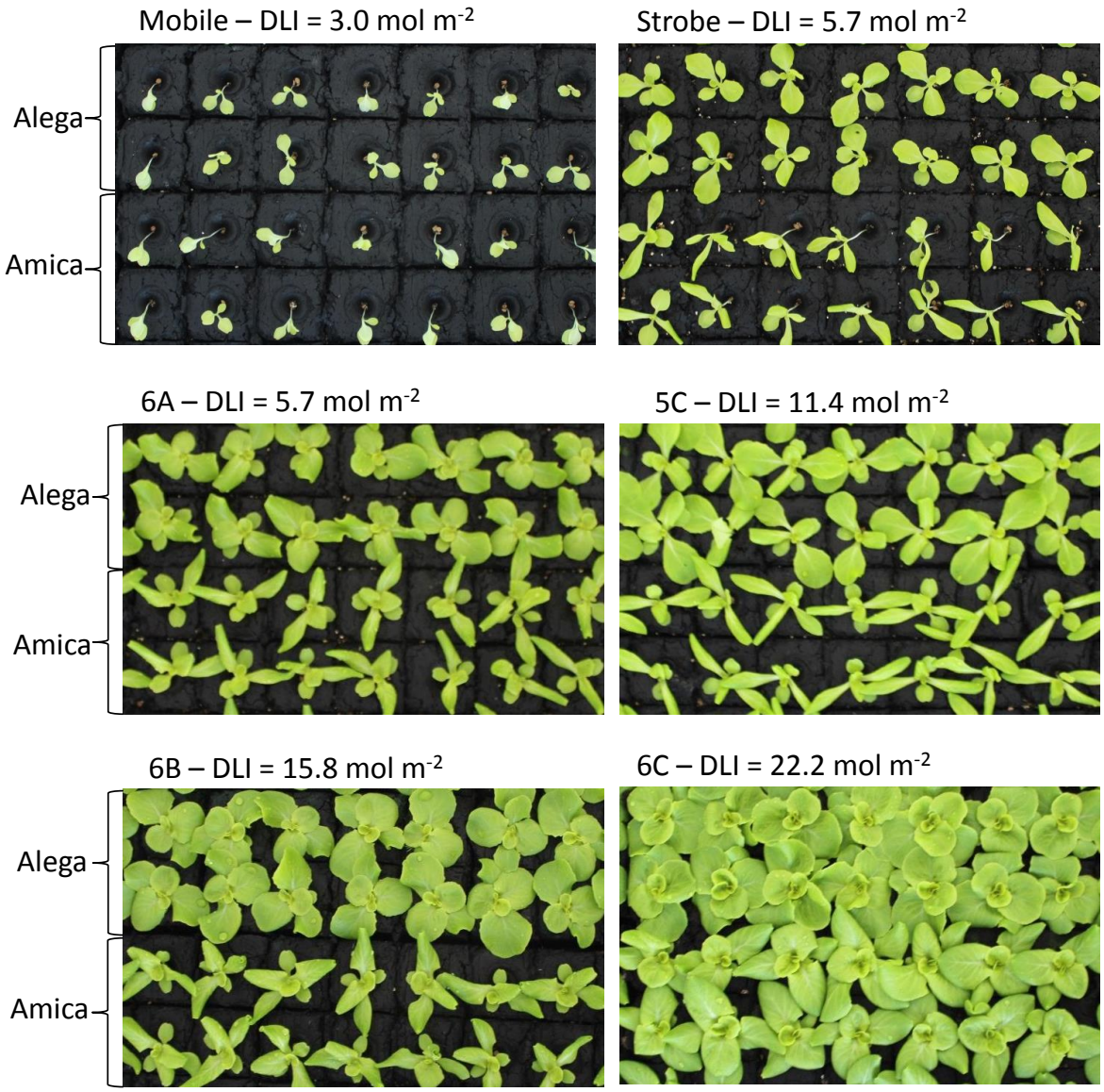


Figure GS1. Images of the two lettuce varieties, Alega (top two rows of plants in each picture) and Amica (bottom two rows of plants in each picture), grown under 6 different light treatments designed to assess the effects of energy saving lighting strategies and different daily light integrals on plant growth and morphology. Plants photographed after 19 days.

WP 2.1a Plant growth under different types of lamp

LEDs provide the ability to alter the spectrum of light and manipulate plant responses. The majority of the experiments in this report have been performed using Philips lamps; however, in this work package we examine plant growth under a range of lamps produced by different manufacturers in order to assess the benefits to plant production from using different regions of the spectrum. Using the same lettuce varieties as for WP 1.2, we examined growth over a three week period under five lamps, each providing a 'white' light that has been tailored for use with plants. The trial contained two Valoya lamps (AP673 and NS2) and three Solidlite lamps. All the lamps produced similar intensity (200μmol m^{-2} s^{-1}) and DLI, but their spectra

varied considerably. Each lamp produced a different blue, green, red, and far-red balance. Despite the similarity in the DLI provided by each lamp, biomass varied considerably between the light treatments. Crop biomass accumulation was found to correlate with the proportion of the light provided by the lamps that could be used for photosynthesis. It should be noted that not all plant-specific LEDs are designed to maximise growth rate: some are designed to control plant morphology, as discussed in more detail in sections 2.1b and 2.1c. These results highlight the need to select the correct light source for the plant production system being implemented.

WP 2.1b Influence of red / blue ratio on plant growth.

Many of the LED lamps that are available for horticultural purposes contain both red and blue LEDs. This is because these provide the most energy efficient light source and because plants can use this light most effectively for photosynthesis. Red and blue light are also highly important for controlling plant morphology and selecting the correct balance of red and blue light can allow crop morphology to be controlled. In these experiments eight species (basil, sage, cucumber, lettuce, petunia - Figure GS2, pelargonium, pansy, begonia) were grown under a range of red:blue light treatments to examine how they responded to the different light qualities (for most treatments the intensity was 200μmol m^{-2} s^{-1}). Plants grown under 100% red or 100% blue light were found to be poor quality and were etiolated. Growth rates were greatest in plants grown under red/blue mixtures containing 11-15% blue light. The most compact plants were observed under light containing about 60% blue light. The variation in red:blue light treatment ratios may provide sufficient growth control to replace plant growth regulators. While crop morphology was kept compact in the 60% blue treatments, this treatment was found to delay flowering compared to plants grown under 11-15% blue light. For methods to promote flowering see section 2.1c.

WP 2.1c Influence of red /far-red ratio on plant growth

Many of the issues encountered in horticulture during the winter months are associated with low light conditions. In low light conditions far-red light can cause plants to stretch and may even induce premature flowering. The experiments in WP2.1b examined the use of light treatments without far-red light to control plant morphology, but these treatments were not necessarily suitable for all crops. For example, the cucumber plants remained too compact and flowering was delayed in the ornamental species. The experiments reported in this section examine the use of far-red light in LED lit systems to quantify its effects in eight species (basil, sage, cucumber, lettuce, petunia, pelargonium, pansy, begonia) and identify cases where far-red light is beneficial to crop production systems. The intensity of PAR was 200μmol m^{-2} s^{-1} in all treatments while far-red ranged from 0 to 48 intensity μmol m^{-2} s^{-1}.

Figure GS2. Images of the petunia plants after 42 days growth under the different blue percentage light treatments.

The morphological responses to far-red differed greatly between species, with some showing very weak far-red responses (basil and sage) and others showing pronounced effects (cucumber, pansy and petunia). In far-red sensitive species, the addition of far-red caused stem elongation and reduced plant compactness. Many far-red responses increased progressively as more far-red was added, and inclusion of too much far-red (~40µmol m^{-2} s^{-1} in these experiments) resulted in leggy plants and reduced the number of side branches produced. Far-red light caused flowering to occur earlier and more extensively. Low levels of far red light have the potential to induce flowering while having only a mild impact on crop morphology. If the far-red treatments used in this work package were to be combined with the high blue treatments used in WP2.1b, it may be possible to produce compact plants that produce abundant flowers. These combined treatments will be examined in a later work package.

Figure GS3. The influence of far-red treatments on pansy flowering after 73 days growth.

FR = 0 FR = 18 FR = 24 FR = 40

WP 2.3. Improving HNS Propagation

Many HNS species are propagated via cuttings, which can take months to root. With spectral manipulation it may be possible to induce more rapid rooting and even improve cutting strike rate. In this trial, we examined the influence of red:blue ratio and red:far-red ratio on cutting percentage survival and rooting in three species, elaeagnus, rhododendron, and photinia, with the aim of identifying light treatments that could improve success. Only spectral quality varied between treatments: the light intensity was intensity 70µmol m^{-2} s^{-1} and the day length was 16 hour. In red:blue treatments, the survival of all species decreased as blue light percentage was increased. This was probably a result of blue-light-induced stomatal opening, which would lead to cutting dehydration even in the humid environment created for the trials. Elaeagnus was especially sensitive to blue light, with cuttings wilting, shedding leaves, and dying within the first few weeks of the trial when propagated under 60-100% blue. Interestingly, far-red light was also found to influence cutting survival, with percentage survival decreasing as far-red increased. Overall percentage rooting was generally low in these experiments (less than 40% in most cases) but there were distinctly different responses between the different species. For the red:blue treatments, elaeagnus was found to be unresponsive to changes in blue light percentage, rhododendron rooted most successfully (over 90%) under 33% blue light, and photinia rooting was greatest under 15% blue light. For the red:far-red treatments, the percentage of rooting was lowest in photinia and elaeagnus at 30µmol m^{-2} s^{-1} far-red but highest in rhododendron at 30µmol m^{-2} s^{-1} of far-red. These data suggest that cutting survival and cutting rooting are influenced by different light responses and that rooting in rhododendron has different light requirements to photinia and elaeagnus.

WP3.1 Insect monitoring

Insect populations were monitored in the LED4CROPS facility using standard yellow and blue sticky traps. Sticky traps were found to be a useful tool for monitoring shore fly and fungus gnat populations but were less useful for potentially more serious pests such as aphid and

thrips, which were rarely caught on traps. The results indicated that insect colour perception was greatly altered under red:blue light mixtures, with fungus gnat preference for yellow relative to blue sticky traps being greatly reduced under red:blue light mixtures. Use of fluorescent yellow and green traps, which appear yellow and green even under the red:blue light mixtures, was found to restore insect colour preference. Numbers of insects caught on fluorescent traps under red:blue light mixtures were proportional to the amount of green light reflected by the trap.

Financial Benefits

In comparison to HPS lighting the currently available LEDs provide the potential to reduce energy consumption by up to 40%. Advances in LED technology will further reduce LED energy consumption over the coming years. The relatively high cost of LED units has, however, resulted in some uncertainty of the economic benefits of installing LEDs based purely on the energy savings provided by LEDs.

The results in this report demonstrate that the ability to control the light spectrum with LEDs creates the potential to produce better quality plants and reduce the need for plant growth regulators. These benefits have the potential to have a greater impact on business economics than electrical energy savings alone. The results from this trial provide the first steps in defining optimal lighting conditions for a range of crops. This information will help growers, considering investing in LED installations, ensure that light installations have the appropriate spectra for their crops. For certain crops there may not currently be a complete LED solution available. However, these data could help LED manufactures design lighting systems that meet the needs of different crops.

The energy use efficiency experiments (section 1.2) also show how light intensity can strongly influence how effectively plants convert light energy to growth. Providing too little or too much light reduces the return in plant growth from the electrical inputs which has implications regarding the systems running costs. Also the results demonstrate that lighting installations designed to reduce capital expenditure on lights (i.e. strobing and mobile systems) can result in poor growth and, therefore, poor return for the capital and running costs. Equally identifying the light intensity that produces optimal growth can prevent excessive capital and running costs.

Action Points

To make use of the data generated in this report, growers would need to invest in LED lighting systems. Costs of lights and economic analysis of the benefits are beyond the scope of this report and will be unique to each business. If investment in lighting is desired further R&D will be required to ensure that the lighting systems are appropriate for the crops of interest

and the environment where the lights will be installed. Some aspects of this work will performed in latter stages of this project. For example, there is clearly scope to combine the effects high-blue light percentage and far-red induced flowering to produce bedding plants with compact morphology and enhanced early flowering. Experiments designed to examine a range of light treatments with high blue percentage as well as far-red are currently underway as part of the year two experiments.

Even where light recipes have been defined for crops it is recommended that small onsite trials are carried out before large scale investments are made. This is for two responses 1) to ensure the light treatments are appropriate for the specific varieties being grown and 2) to help growers develop the required altered crop management strategies (it is expected that LED lighting systems will result in altered crop water and heating requirements). At latter stages in this project more information will be provided to help growers learn how to manipulate crops with LED lighting.

SCIENCE SECTION

Introduction

Maintaining high plant quality is of vital importance in commercial horticulture. In most cases, compact plants are most desirable and any etiolation (which often occurs in low light conditions encountered in the winter months) reduces plant quality and may affect sales. In the ornamental sector plant morphology is often controlled with plant growth regulators (PGRs) but changes to pesticide regulations may lead to reduced PGR availability. In addition, PGRs are usually unavailable for use in the protected edibles sectors, so alternative management strategies that span a range of crop sectors are desirable.

Plants use light through the process of photosynthesis to fix the carbohydrate that powers growth. The amount of light that plants receive influences the rate at which plants can grow but also has an influence on plant morphology and development. Plants possess several light sensitive compounds called photoreceptors which they use to sense their light environment. These photoreceptors are involved in regulating all aspects of plant biology and they enable plants to alter their morphology to match their environment. Photoreceptors also determine the optimal timing for the transition from vegetative to reproductive growth. Plant light responses have evolved to maximise the chance of survival and reproductive success, but not all these responses are desirable in commercial horticulture. Photoreceptors act to suppress etiolation, which occurs in low or poor-quality light conditions. As these responses are light regulated, spectral manipulation using LEDs, or potentially spectral filters, may allow control of plant morphology without the need for PGRs. Modification of the light spectrum in plant production facilities, using LEDs or spectral filters, will enable the manipulation of plants to either inhibit undesirable responses such as stretching (etiolation) or enhance desirable responses such as increased leaf or flower pigmentation. Successful implementation of spectral manipulation will allow improved plant quality and consistency while also reducing the need for plant growth regulators.

The photoreceptors can be roughly grouped according to the colour of light to which they are most sensitive: UVB light, blue light, or red and far-red light (Figure 1). UVB responses are regulated by the UVR8 photoreceptor. UVB light is highly damaging to plants and so these photoreceptors are very responsive to low intensities. UVB / UVR8 causes plants to increase their pigmentation, reduce stem extension, and increase the robustness of plant tissues. Blue light is sensed by several families of photoreceptor. The cryptochromes and phototropins regulate a wide range of blue responses (including plant height, pigmentation, leaf morphology, phototropism, stomatal opening, and circadian rhythms) that are relevant to producing high quality plants. The red and far-red responses are regulated by a family of

photoreceptors called the phytochromes. These are perhaps the most researched photoreceptors, and regulate many plant light responses (including plant height, pigmentation, leaf shape, circadian rhythms, induction of flowering, and day-length sensitivity). Many plant responses, for example plant height, are regulated by multiple photoreceptors and full control of these responses is likely to require developing light treatments that provide the correct balance of each colour. As multiple responses are under the control of light, light treatments designed to influence one aspect of plant quality may have negative impacts on other aspects. For example, light treatments designed to enhance leaf pigmentation may result in slow growth and delayed flowering. The experiments reported here are designed to increase our understanding regarding how several plant species relevant to the protected edible, protected ornamental, and hardy nursery stock sectors respond to different light qualities. This improved understanding will help the development of light regimes optimised for production of high quality plants with the characteristics required.

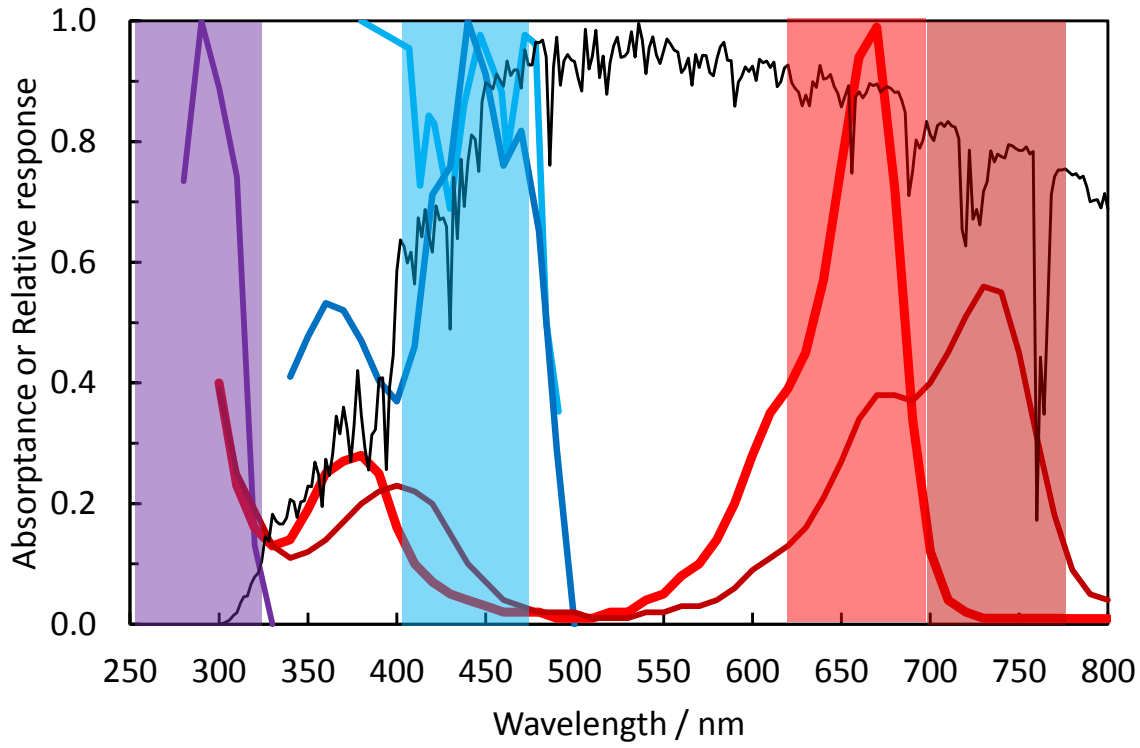


Figure 1. Plant light responses. Action spectra for UVR8 (purple line, Gardner *et al.,* 2009) cryptochrome (pale blue line, Briggs and Christie 2002) phototropin (dark blue line, Briggs and Christie 2002), and the absorption spectra of phytochrome B in its dark inactive state (dark red line) and its light activated state (red line). The black line shows the solar spectrum (expressed as relative photon irradiance) and the coloured bands indicate the regions of the spectrum with relevance to spectral manipulation for crops.

Even if optimal conditions for plants can be created, crops must be monitored to ensure pests and diseases are kept under control to prevent damage and loss of sales. It is important to understand how spectral manipulation of plants impacts both beneficial and pest insect species so IPM strategies and pollination can be maintained. As is the case for plants, light influences many aspects of insect biology (for example, circadian rhythms are entrained by light) and behaviour (e.g., light controls take-off and landing choices as well as migration direction). The light environment also has secondary impacts on insects. The emission of volatile compounds that can attract and deter insects is controlled by plant light responses. Light responses also alter the nutritional qualities of plants, and this can influence insect reproductive rates. A better understanding of how different light treatments influence insect fecundity could potentially allow the development of light treatments to reduce pest pressure or even light treatments that improve IPM strategies.

The monitoring of insect populations forms an important part of pest management strategies and sticky traps are a cost-effective management tool. The success of sticky traps, however, requires insects to be attracted towards the trap and trap colour is an important factor affecting the species that are trapped. If traps are not sufficiently attractive to insects, they will not provide a good indication of pest numbers and may even fail to trap important pest species. Trap effectiveness has previously been shown to be associated with the brightness and colour of the trap. In particular, many insects are strongly attracted to green light. The addition of green LEDs to yellow sticky traps can increase the effectiveness of traps to certain insect species (Nakamoto & Kuba 2004). No green light is present under red:blue LED light mixtures and yellow sticky traps do not appear yellow to human vision and presumably also appear different to insects. It is, therefore, expected that red:blue light mixtures will reduce the effectiveness of yellow traps. If this is the case alternative strategies may be required for the effective monitoring of pests under red:blue light environments.

Report overview

The experiments reported here are arranged in 3 work packages.

Work package 1 - General agronomy under LED lighting.

This work package will examine the general agronomic practices required for plant production under LED lighting. One of the major benefits of LED lighting is their low energy consumption compared to conventional lighting systems. Their robust nature and ability to rapidly turn on and off also provides the possibility of further reducing energy consumption by either creating mobile light rigs that move over the crops at regular intervals or strobing the light to reduce energy consumption. Both these techniques can lower energy consumption, but this comes at the cost of a lower daily light integral (DLI). All plants have an optimal daily light integral at

which growth rates are high and plant quality is optimal if no other factors are limiting. While there is some information regarding the optimal DLI for a range of species, these values have been defined under natural light conditions where the solar intensity varies greatly throughout the diurnal cycle. Under the constant conditions that can be achieved in LED light growth systems, there is little information regarding the optimal DLI.

This work package examined the effects of a mobile light system (DLI ~3.5 mol m^{-2} d^{-1}), a slow strobe light system (DLI 6 mol m^{-2} d^{-1}) and four constant-light-intensity treatments with different daily light integrals ranging from 6 mol m^{-2} d^{-1} to 22mol m^{-2} d^{-1}, on the propagation (first three weeks of growth) of lettuce.

Work package 2 - Influence of light quality on crops.

The experiments in work package 2 will examine the responses of plants to different light spectra with the aim of improving our understanding of the diversity of plant responses to light and to help commercial implementation of LED technologies. WP2 is divided into subsections examining different aspects of light quality on plant morphology. This report contains results from four subsections of WP2:

WP 2.1a Comparisons of plant growth under a range of commercially available LED light spectra.

WP 2.1b Influence of red / blue ratio on plant growth.

WP 2.1c Influence of red / far-red ratio on plant growth.

WP 2.3 Improving cutting propagation.

Several species were examined (basil, sage, cucumber, petunia, pansy, begonia, pelargonium, lettuce, photinia, elaeagnus, and rhododendron). Where appropriate, plants of the same species were grown simultaneously in multiple work packages. The results will be reported in groups based on work packages.

Work package 3 - Light quality and its influence on pests.

This report contains results from the first subsection of work package 3 (3a) - monitoring pests under LED light and methods for improving pest monitoring in LED light environments.

Material and methods

Climate in the LED4CROPs facility.

The temperature in the LED4CROPS facility was maintained at 21°C throughout the experiments. The humidity and CO_2 levels were monitored but not controlled. Crops were irrigated according to crop needs (see '*Plant material and crop measurements*' section for crop-specific details). Regular irrigation was provided by the automated ebb and flood irrigation system. The irrigation solution was maintained at an EC of 2 mS/cm and a pH of 5.5-6.5 (see Table 1 for details of the nutrient solution). When required, additional water was applied to plants by hand.

Table 1. Details of irrigation feed mixture. All values are given in mg/l.

	LED4CROPS		LED container
	Desired concentration	Mean measured concentration	Measured concentration
Nitrate N	122	194	5.2*
Sulphur	59	295	174.5
Boron	0.29	0.36	0.20
Copper	0.12	0.20	0.54
Manganese	0.34	0.51	0.33
Zinc	0.34	0.60	0.98
Iron	1.17	1.70	0.65
Chloride	96	47.8	105.5
Phosphorus	28	51.2	29.2
Potassium	265	242	114
Magnesium	42	47	19.91
Calcium	148	209	78.2
Sodium	21	50	22.1
Molybdenum	0.06	NA	NA

* Total nitrogen concentration was ~100mgl^{-1} and provided as a different form of nitrogen.

Climate in the LED Container facility.

The work performed using LED lighting systems manufactured by companies other than Philips were performed in an enclosed container facility fitted with LED lights. The temperature in the container LED facility was maintained as close to 21°C as possible. The structure was continuously vented (extraction fans) to prevent temperature increase (no air conditioning system was installed) and heated with three thermostat assisted heaters, temperature regulation was less precise than in the LED4CROPS facility. Temperature and relative humidity were measured and recorded. The plants were irrigated manually as required. Plants were fertilized as required using a weak Miracle Gro solution (see Table 1).

Light treatments

Across all experiments, photoperiod was maintained at 16 hours unless otherwise stated. Images of the different LED facilities are provided in Figure 2. The tables in this section indicate target light values during experimental setup. Some variation in the actual light intensities occurred during and between experiments based on location within the facility and location on the bench. All results are reported with the actual values recorded during the experiments.

WP 1.2. light treatments

All light treatments for WP1.2 were performed in the LED4CROPS facility using Philips GreenPower production DR/B modules. This experiment contained six light treatments (Table 2), each with a different electrical input and different daily light integral (DLI). The first light treatment 'Mobile' utilised a mobile LED light rack that passed over the plants every 56 seconds (Figure 2C). The light intensity fluctuated between 0 to 332 μmol m^{-2} s^{-1} as the LEDs passed over the plants. While this greatly reduces the energy inputs and capital costs, it also greatly reduces the light available for growth and the mean DLI was calculated to be 3.5 mol m^{-2} d^{-1}. The second light treatment 'Strobe' involved turning the LEDs on for 8 seconds and off for 8 seconds. This treatment halves the electrical inputs and the light available for growth and results in a DLI of 5.7 mol m^{-2} d^{-1}; however, the number of LED modules required is not reduced. The four remaining light treatments had constant light provided at different intensities ranging from 99 to 386 μmol m^{-2} s^{-1} (see Table 2) and DLIs between 5.7 and 22 mol m^{-2} d^{-1}. The low light treatment was set to have a light integral similar to that of the 'Strobe' light treatment.

Table 2. Details of 6 light treatments trialled in Work Package 1.2.

Treatment	Mobile	Strobe	Low	Standard	Medium	High
Light rack	9	8	6A	5C	6B	6C
Mean and (max) PAR photon irradiance / μmol m^{-2} s^{-1}	52.3[$] (332)	98.5 (198)	99.2 (99.2)	198 (198)	275 (275)	386 (386)
% blue	11	11	11	11	11	11
Number of LED modules	5 X 1m modules	10 X 1.5 modules	6 X 1.5 model	10 X 1.5 modules	16 X 1.5 modules	20 X 1.5 modules
Electrical input / W m^{-2}	21.3 + motor	66.7	80	133	213.3	266
Light field	fluctuating	on-off every 8s	continuous	continuous	continuous	continuous
DLI / mol m^{-2}	3.0[$]	5.7	5.7	11.4	15.8	22.2

[$] Values estimated based on the total electrical input.

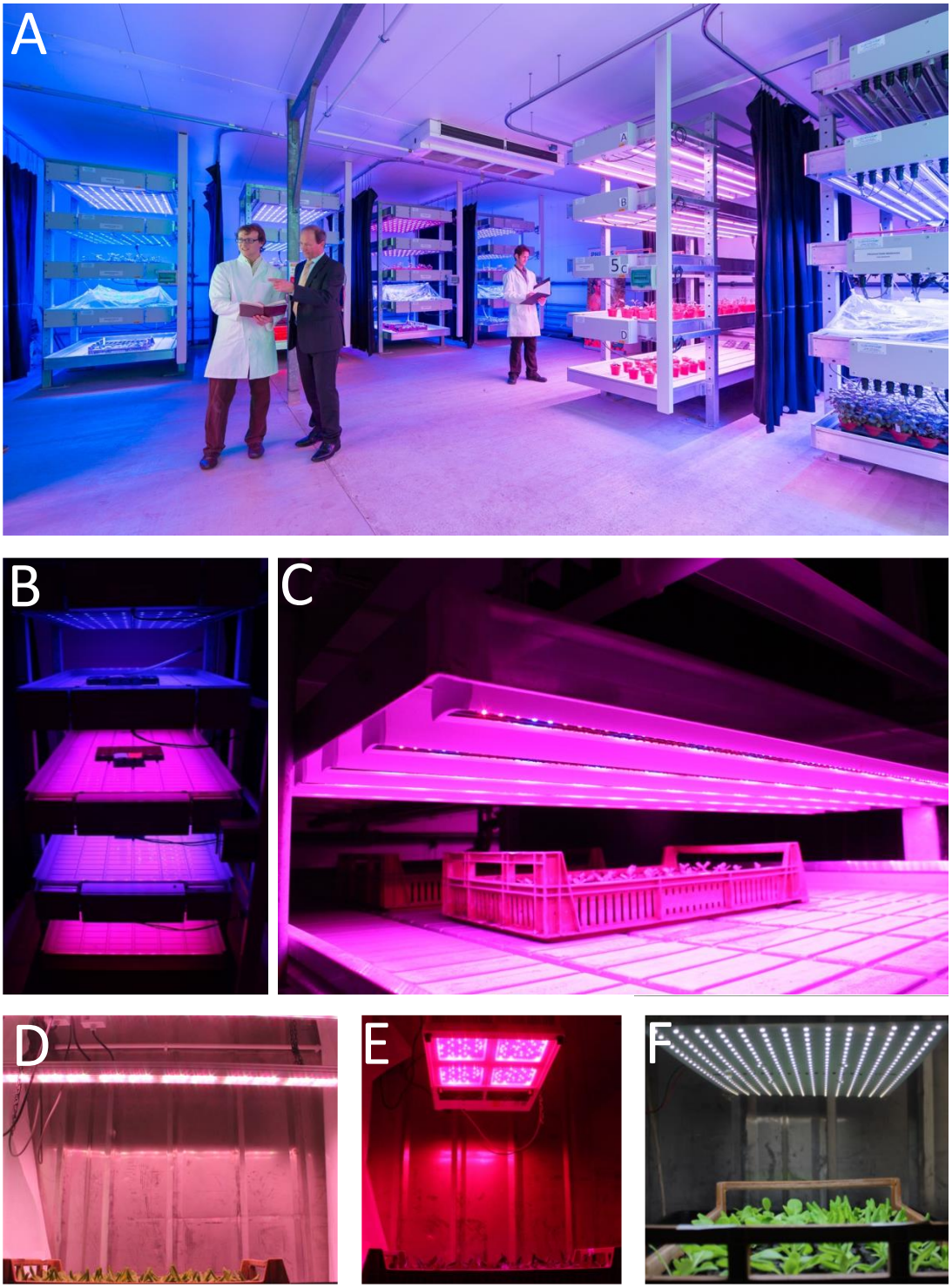


Figure 2. Images of LED facilities used in the experiments. **A-C)** Images from the LED4CROPS facility, **A)** general view of the LED4CROPs facility, **B)** a research rack with each shelf having a different red:blue treatment, **C)** the mobile light rack used in WP 1.2. **D-F)** Images from the LED container facility, **D)** a Valoya AP673 LED, **E)** a Heliospectra XX lamp with a red blue light treatment, **F)** a Solidlite LED lamp.

WP 2.1a. Light treatments

All experiments for WP2.1 were performed in the LED container facility. Five white light treatments were set up, each separated by a plastic screen to block direct light passing between the treatments. The different treatments were not completely enclosed in order to ensure good air movement and minimise local heating (Figure 2). Two models of Valoya LED light were used: NS2 and AP673. The NS2 spectrum contained a small amount of violet light but less far-red light while the AP673 contained no violet light and more far-red light (Figure 3 and Table 3). Three types of SolidLite LED models were used: DPA, DPM, and CWW. The CWW model had the highest proportion of blue light (31%) and the lowest far-red intensity and the greatest red:far red ratio (5.75). The DPM model contained the lowest blue light proportion (21%) and greatest proportion of green light (39%). The DPA model contained the highest proportion of red light (49%), a greater far-red intensity (23.94 μmol m^{-2} s^{-1}), and the lowest red far-red ratio (4.15).

Table 3. The five 'white-light' treatments examined in Work Package 2.1a. The photoperiod was maintained at 16 hours throughout.

Manufacturer	Valoya		SolidLite		
Model	NS2	AP673	DPM	DPA	CWW
PAR / μmol m^{-2} s^{-1}	194	190	204	200	202
DLI / mol m^{-2}	11.2	10.9	11.8	11.5	11.6
% blue	23	14	21	24	31
% green	40	24	39	27	36
% red	37	62	40	49	33
Far-red /μmol m^{-2} s^{-1}	4.46	16.03	16.09	23.94	11.58
Red:far-red ratio	16.23	7.38	5.11	4.15	5.75

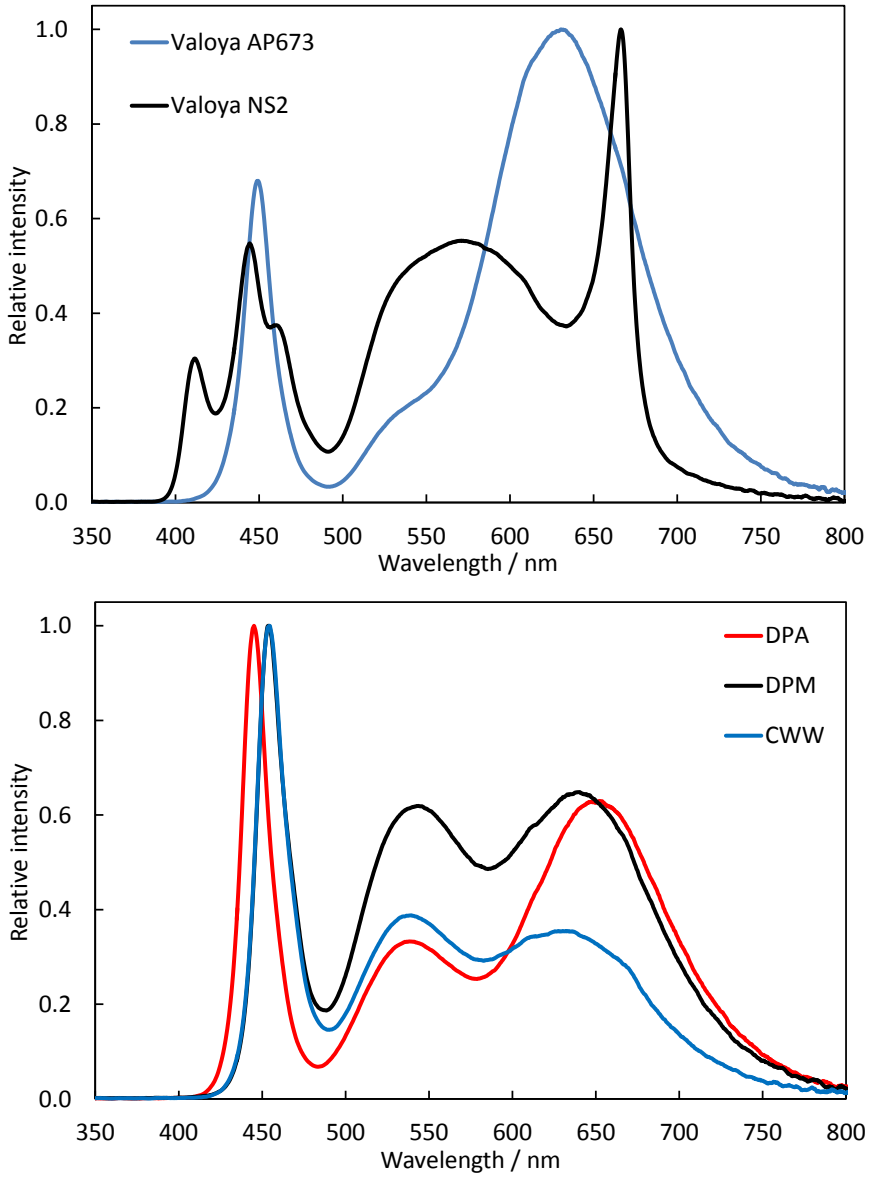


Figure 3. Light spectra of the different light treatments used in WP2.1a. More details of the light treatments are provided in Table 3.

WP 2.1b light treatments

All the WP 2.1b light treatments were performed in the LED4CROPS facility using Philips GreenPower Research LED modules. The aim of these experiments was to assess the impact of different red:blue light ratios on plant development and morphology. Two colours of light were examined: red (666nm) and blue (460nm). Five light treatments were set up, ranging from 100% blue to 100% red (Figure 4 and Table 4). The 100% red (referred to as 0% B) treatment was not included in earlier experiments. The intensity of the treatments was set to be close to 200 µmol m^{-2} s^{-1}. For the 100% blue light treatment, however, the maximum light intensity achieved was 145 µmol m^{-2} s^{-1}. Initially, these light treatments were all located on research rack 1 (R1) on different shelves (R1A-R1D). This, however, resulted in a temperature gradient between the treatments with the bottom shelf in particular (location

R1D) having a lower temperature than the other treatments. To remove this issue the light treatments were re-organised in the facility so they were located on shelves B or C (the two middle shelves) on different research racks (R1C-R4C) where temperatures were found to be similar. For data analysis, data from an additional light treatment (the 0 far-red light treatment from WP2.1C; see next section) were included in the analysis where appropriate.

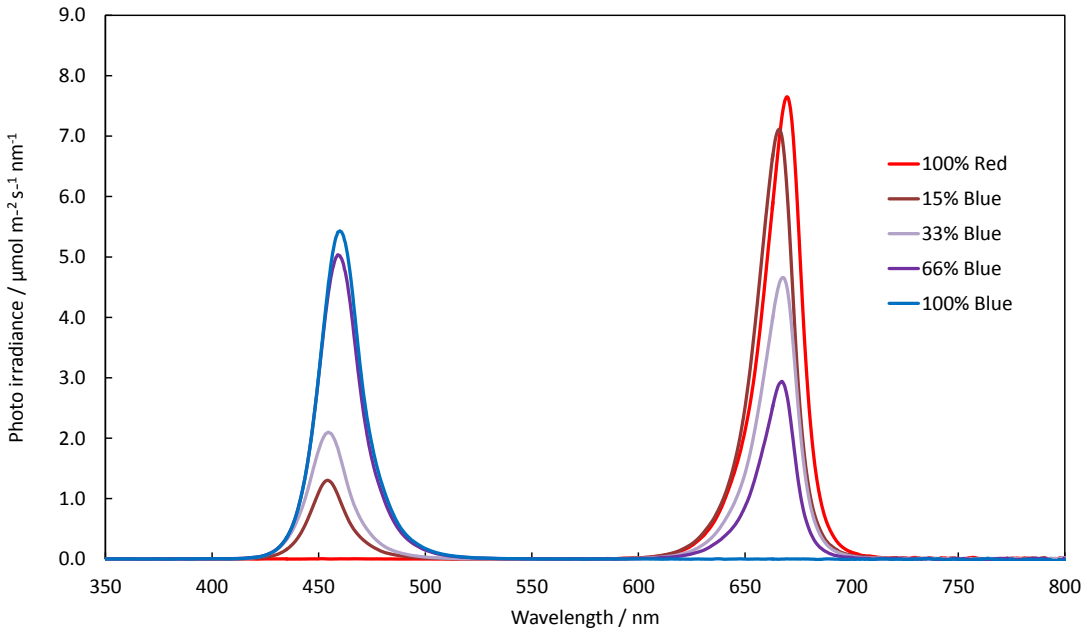


Figure 4. Light spectra of the different light treatments used in WP2.1

Table 4. The specifications of the light treatments used in Work Package 2.1b.

Light treatment	**100 % B**	**66 % B**	**58% B**	**33% B**	**15% B**	**11%B**	**0% B**
Location	R1A or R1C	R2C or R1C	R2C or R1C	R4C or R1B	R3C or R1D	12B*	R3B
PAR / µmol m^{-2} s^{-1}	145	200	200	200	200	200	200
DLI / mol m^{-2}	8.4	11.5	11.5	11.5	11.5	11.5	11.5
Blue photo irradiance	145	132	116	66	30	22	0
Red photo irradiance	0	68	84	134	170	178	200
% blue	100	66	58	33	15	11	0

***This is the same light treatment as the lowest far-red light treatment used in work package 2.1c and is not included in the analysis of all crops.

WP 2.1c light treatments

All the light treatments in WP 2.1c were performed in the LED4CROPS facility using Philips GreenPower DR:B production LED modules (11% blue) with Philips Green Power far-red research modules. The aim of these experiments was to assess the impact of different amounts of far-red light in a background of red and blue light on plant development and morphology. Three colours of light were examined: red (666nm),blue (470nm), and far-red (735nm). Four light treatments were each set up, ranging from 0 to 48 µmol m^{-2} s^{-1} of far-red light (Figure 5 and Table 5). The red blue light intensities were kept constant across all light treatments (200 µmol m^{-2} s^{-1}). Initially, these light treatments were all located on light rack 1 (PR12) on different shelves (PR12A-PR12D). This, however, resulted in a temperature gradient between the treatments, with the bottom shelf in particular (location PR12D) having a lower temperature than the other treatments. To remove this issue the light treatments were re-organised in the facility so they were located on shelves B or C (the two middle shelves) of two adjacent light racks (PR10 & PR11), where temperatures were found to be similar.

Table 5. The specification of the four light treatments examined in Work Package 2.1c.

Light treatment	**12B**	**12C**	**10B**	**10C**
Measured parameters				
PAR / µmol m^{-2} s^{-1}	200	200	200	200
DLI / mol m^{-2}	11.5	11.5	11.5	11.5
Far-red / µmol m^{-2} s^{-1}	1.51	19.21	42.69	15.68
% blue	11	11	11	11
Red:far-red ratio	117	8.8	4.2	10.2

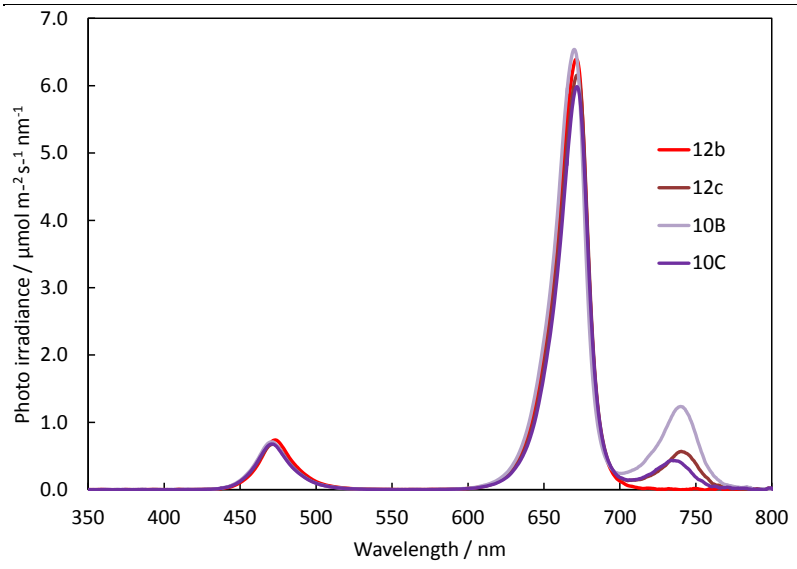


Figure 5. Light spectra of the four light treatments used in WP2.1c.

WP 2.3. Improving HNS propagation

All the WP 2.3 light treatments were performed in the LED4CROPS facility using Philips GreenPower Research LED modules or the Philips GreenPower DR:B production LED modules (11% blue) combined with the Philips Green Power far-red research modules. For the HNS cuttings, two sets of light treatments were performed: 1) red:blue and 2) far-red. In each set of experiments, the maximum light intensity was set to 100μmol m^{-2} s^{-1} to minimize the energy inputs and reduce the light and water stress of the cuttings. For the red:blue experiments the blue percentage was varied from 100% blue to 100% red (referred to as 0% Blue) with two intermediate treatments with 33% and 66% blue. Once the experiments were underway, measurements were made within the plastic tents used to keep the cuttings environment humid. The plastic sheeting and condensation on the sheeting was found to reduce the total light intensities by about 30% but not to alter the spectral quality of the light (Table 6).

Table 6. Details of the light treatments used in WP 2.3. Measurements were made below the plastic tent, which reduced light intensity by approximately 30%.

Red:Blue treatment	**1**	**2**	**3**	**4**
PAR / μmol m^{-2} s^{-1}	70	70	70	70
DLI / mol m^{-2}	4	4	4	4
% blue	0	33	66	100
Far-red treatments	**5**	**6**	**7**	**8**
PAR/ μmol m^{-2} s^{-1}	70	70	70	70
DLI / mol m^{-2}	4	4	4	4
% Blue	11	11	11	11
Far-red / μmol m^{-2} s^{-1}	0	15	30	48
Red:far-red ratio	>89	5.9	3.0	1.85

Plant material and crop measurements

Lettuce

Two varieties of lettuce seed were provided by Enza Zaden: Alega (a winter variety) and Amica (a summer variety). Seed were sown on 5 cm peat blocks and covered with vermiculite. Peat blocks were irrigated three times per day with the automated ebb and flood irrigation system to maintain peat block moisture content. Plants were grown for 3 weeks before assessment. Ten plants of each variety from each light treatment were assessed for plant fresh mass, plant dry mass, leaf number, leaf length, leaf width, and leaf shape. The seed were sown on the 6th May 2015 and plants were harvested on 27th May 2015.

Herbs

Seeds of basil (Sweat Genovese, CN seeds) and sage were sown on Levington M2 substrate in 1 inch cells on the 13th May 2014. Trays were covered with clear plastic until the seeds germinated. Plugs were potted up into six-packs at the appropriate stage. To prevent any influence of shading, only 2 plants (diagonal opposites) were potted into each six pack. Plants were assessed for plant height, internode length, leaf size, leaf shape as well as fresh biomass of leaves and stems.

Cucumber

Cucumber seeds of the Proloog RZ (Rijk Zwann) variety were sown on rockwool blocks and covered with vermiculite. Plants were placed under the light treatments and irrigated once per day using the automated ebb and flood irrigation system. Plants were assessed for plant height, internode length, leaf size, and leaf shape.

Bedding plants

Petunia (*Petunia hybrida,* Mirage Blue F1), begonia (*Begonia semperflorens,* Super Olympia red F1), and pansy (*Viola wittrockiana*, Dynamite Formula Mix F1) seed were supplied by CN Seeds. Seed were sown, on the 12th January 2015, on Levington F2+sand substrate in one inch cells. Plants were transplanted when the plug plants were of sufficient size. Plants were transplanted into six-packs filled with Leavington M2 substrate. Plants were irrigated once per day using the automated ebb and flood system. Plants were assessed at plug stage and once matured. Flower numbers were monitored until all treatments had achieved full flowering.

Propagation of Photinia, Elaeagnus, and Rhododendron.

Field-grown cutting material of Photinia Red Robin, *Elaeagnus ebbingei,* and a dwarf Rhododendron (Scarlet Wonder) were supplied by New Place Nurseries (Mr John Hedger). Photinia and rhododendron material was delivered on 10th September 2014. Elaeagnus material was delivered on the 23rd September 2014. All cuttings were trimmed and planted within 48 hours. Cuttings were dipped in 1% Rhizopon AA to promote rooting and planted in a 2:1 peat:perlite mixture. Trays were placed under the light treatments and enclosed under a clear polythene tent to maintain high humidity. The temperature and humidity within the tents were monitored daily and the plants misted as required. The tents were opened once per week to vent the system to maintain plant health. Plants were irrigated using the ebb and flood systems as required.

Photosynthesis measurements

Photosynthetic measurements on basil and sage were performed by Prof Carl Otto Ottosen of Aarhus University. Measurements were performed on the first fully expanded leaf using three Ciras 3 portable photosynthesis instruments. Photosynthetic light response curves were generated on at least three leaves (each leaf from a different plant) from each light treatment.

Photosynthetic measurements on pelargonium were performed by Mr Richard Boyle of Lancaster University. Measurements were performed on the first fully expanded leaf using a Licor 6400. Photosynthetic light response curves were generated on at least three leaves (each leaf from a different plant) from each light treatment.

Leaf morphology

Total leaf area of individual plants was determined by detaching leaves and placing them on a Li-Cor Li-3100 area meter. Two types of leaf shape assessments were made. For the first and most simple assessment, the length and width of leaf blades were assessed. Petiole lengths were also measured for leaves with a defined boundary between the leaf blade and the petiole. In leaves like those found on Lettuce, where there is no distinct petiole (the leaf blade extends all the way back to the stem), only leaf length was determined. The second and more detailed assessment of leaf morphology was performed by imaging leaves using a flatbed scanner. The scanned images were subsequently analysed by the LeafAnalyser software package, available at http://www.plant-image-analysis.org/software/leafanalyser (Weight *et al*., 2008).

Leaves are rarely perfectly flat and usually exhibit some form of curvature. Leaves can be curled in two directions, displaying lateral (Figure 6A) and longitudinal curvature (Figure 6B). In lateral curvature, the sides of the leave curl downward. In longitudinal curvature, the tip of

the leaf curls downward. Leaves often curl in both directions, creating a concave surface when viewed from below. Unless otherwise stated, the measurements of leaf curvature made in these experiments assess lateral curvature. Leaf curvature was measured by determining the projected leaf width and the width of the leaf after uncurling. Curvature, or leaf curling index (CI) was then quantified as the ratio between the two measurements (CI = projected width / unrolled width). Flat leaves have a CI close to 1 while heavily curved leaves have values less than 0.5.

The angle at which leaves are held relative to the floor is important for the appearance of a crop but also has implications for how effectively plants can capture light. Both petiole and leaf angle are influenced by light quality. Leaf and petiole angles were determined using a protractor held against the stem of the plant. The vertical (usually in line with the stem) is assigned an angle of 0° (see Figure 6C). A leaf held parallel to the floor would have an angle close to 90° while a leaf hanging downward will have an angle of greater than 90°. For leaves exhibiting longitudinal curvature, determining leaf angle can be challenging. In these cases, petiole angle is often a more robust measurement.

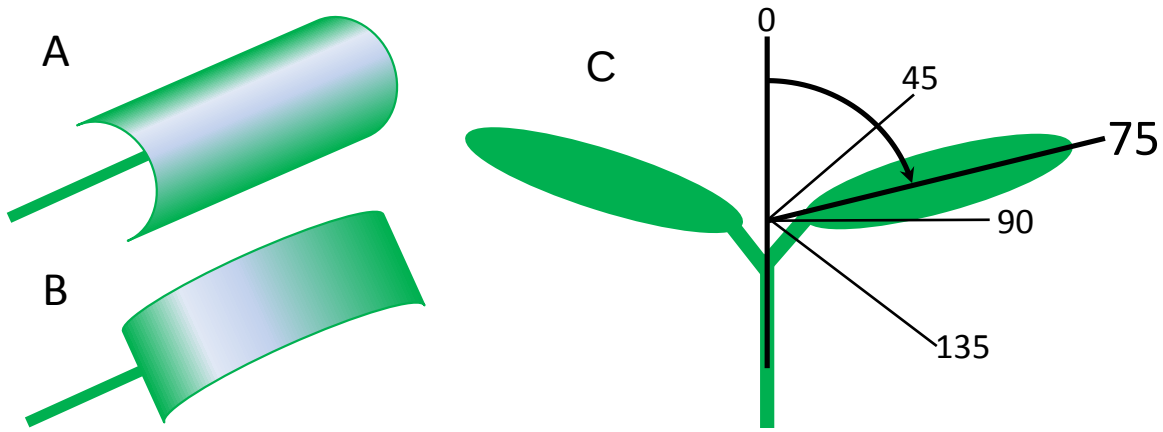


Figure 6. Diagrammatic representation of the two directions of leaf curling. **A)** Lateral curvature. **B)** Longitudinal curvature. **C)** Diagram showing how leaf lamina angle was measured.

Results

WP 1.2 Energy saving and daily light integral

Both Alega and Amica Lettuce varieties germinated within 3 days of sowing and produced plants that were disease free but that varied considerably in size and quality between the light treatments (Figure 7). Morphology differed between the two varieties, with the Amica variety having a more curled leaf. To assess the effect of light treatment on leaf morphology, the length and width of the second true leaf were measured (NOTE: the plants grown under the mobile light treatment grew so slowly that they did not possess a second true leaf and so are excluded from this analysis). Leaves of Amica were longer than those of Alega but were similar in width (Figure 8). The length of both varieties was observed to decrease as the light intensity increased, though this relationship was more pronounced for Alega than for Amica. Leaf width was found to increase slightly as light intensity increased, and this relationship was more pronounced in Amica than in Alega. The curling index (CI, calculated as projected leaf width / flattened leaf width) demonstrated that Amica leaves were more curled than the Alega leaves in all light treatments. Both species were found to have a more pronounced curvature at intermediate light intensities. In the two light treatments that received the same DLI (strobe and low light-6A), the plants of both varieties grew more slowly under the strobe treatment but had longer leaves that were slightly wider and less curled.

Plant fresh weight (Figure 9A) and dry weight (data not shown as the dry mass shows the same trends as the fresh weight data) increased as DLI increased. The plants grown under the strobe light gained considerably less biomass than the plants grown under the constant light treatment with the same DLI, and the plants under the mobile light rack barely grew at all. The energy use efficiency (EUE = plant fresh weight per square meter / LED electricity consumption per square meter; Figure 9B) of the different light treatments was calculated to determine the optimal light conditions for crop production. For the Alega variety the energy use efficiency was greatest under a DLI of 16 mol m^{-2} d^{-1} but for Amica it was greatest under the 22 mol m^{-2} d^{-1} treatment. For both varieties, a large drop in EUE was observed for the plants grown in the strobe light treatment compared to the constant light treatments with the same DLI. The EUE of Alega was greater than that of Amica in all treatments. One possible explanation for this is the difference in leaf area available to capture the light between the varieties, which was caused by the different leaf curvatures. To test this, the EUE data were plotted versus the DLI multiplied by the CI (Figure 9C). The data from the two varieties were found to be more similar when the DLI data was corrected for leaf curvature, suggesting that the differences in EUE between Amica and Alega were partially caused by differences in light interception between the varieties.

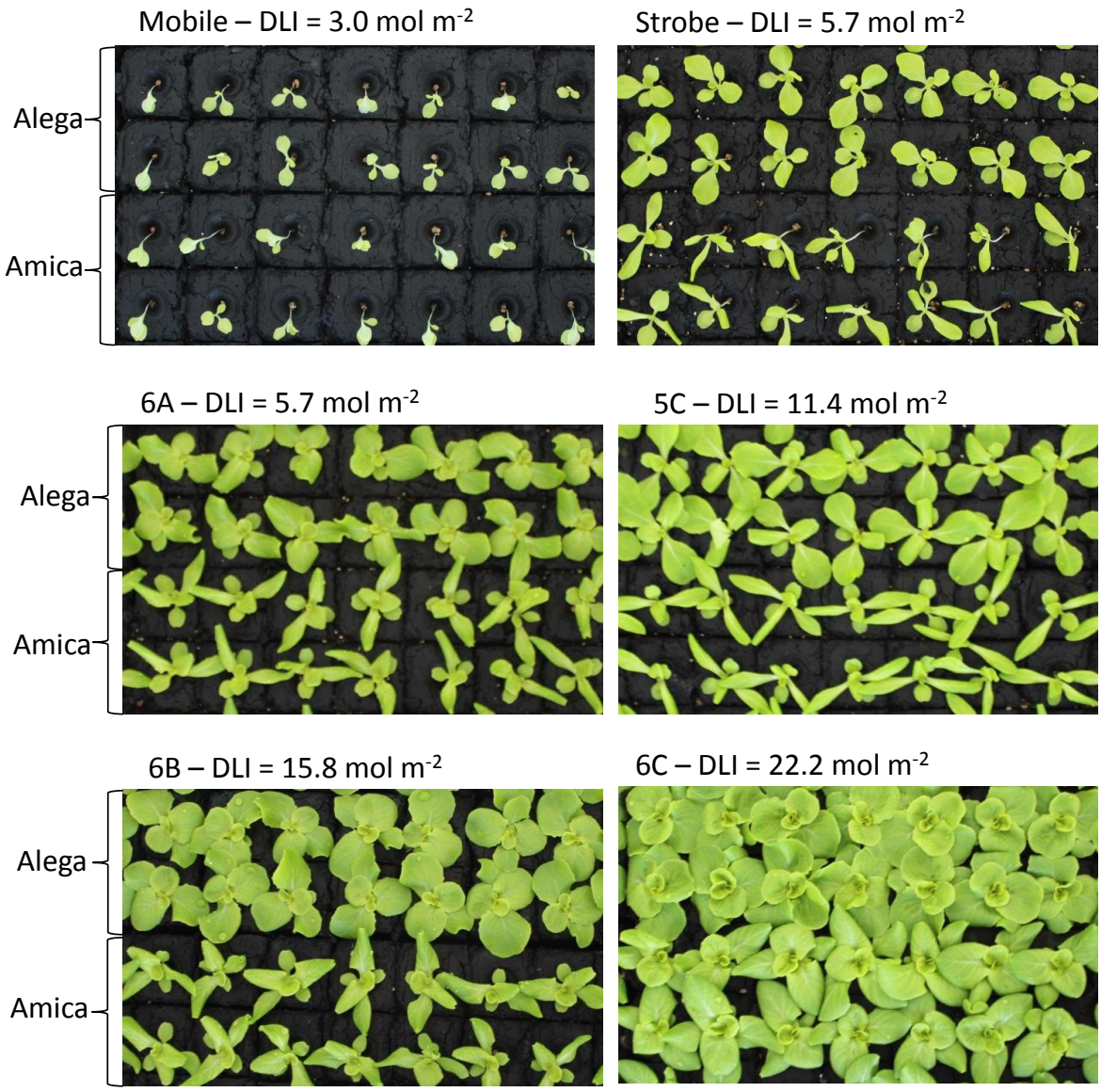


Figure 7. Images of the two Lettuce varieties, Alega (top two rows of plants in each picture) and Amica (bottom two rows of plants in each picture), grown under 6 different light treatments designed to assess the effects of energy saving lighting strategies and different daily light integrals on plant growth and morphology 19 days after sowing.

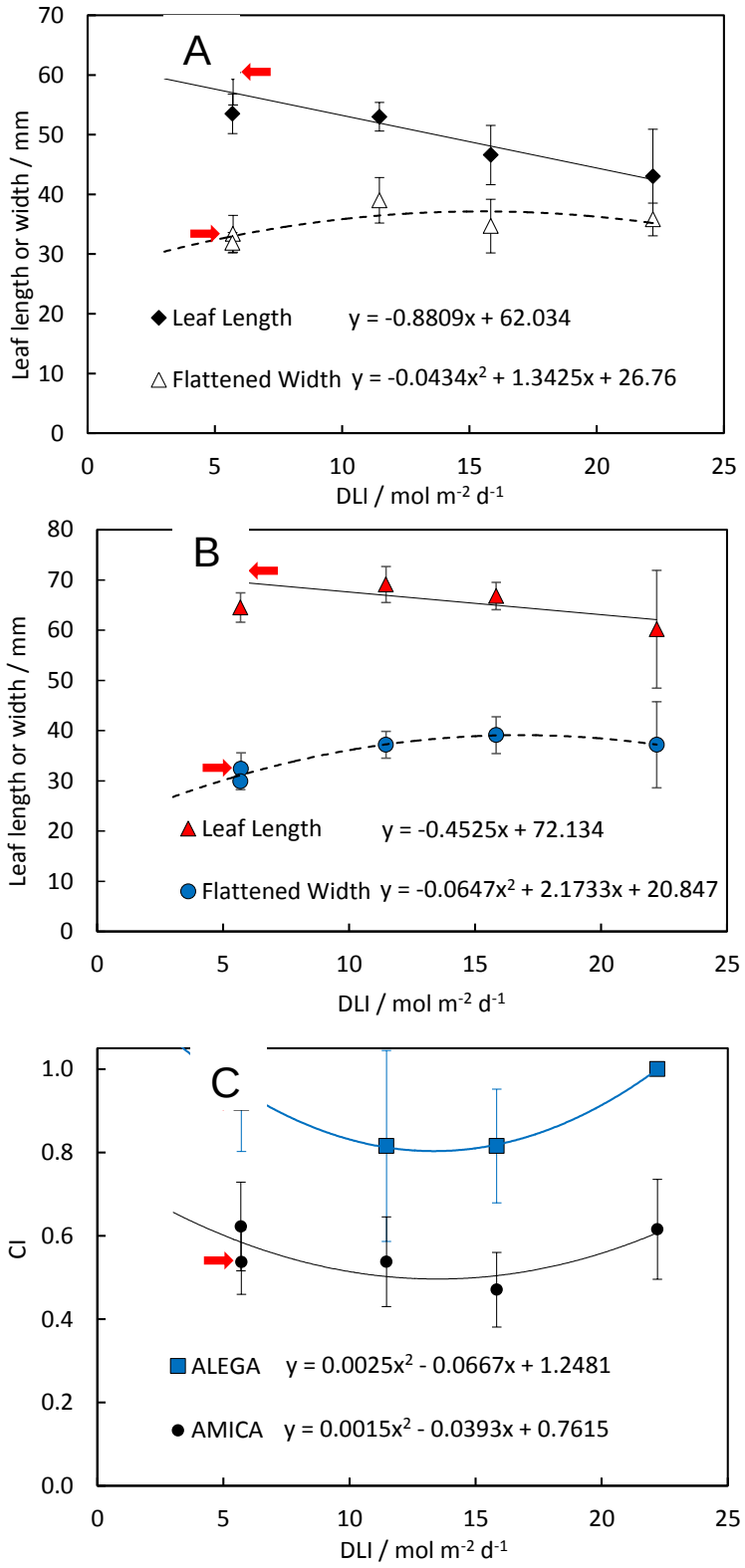


Figure 8. The influence of DLI on leaf size and morphology. **A)** Length and flattened width of the Alega Lettuce variety. **B)** Length and flattened width of the Amica Lettuce variety. **C)** The curling index, calculated as the projected leaf width divided by the flattened leaf width, for both Lettuce varieties. Error bars indicate standard deviation. Red arrows indicate the data points from the strobe light treatment. Error bars indicate standard deviation.

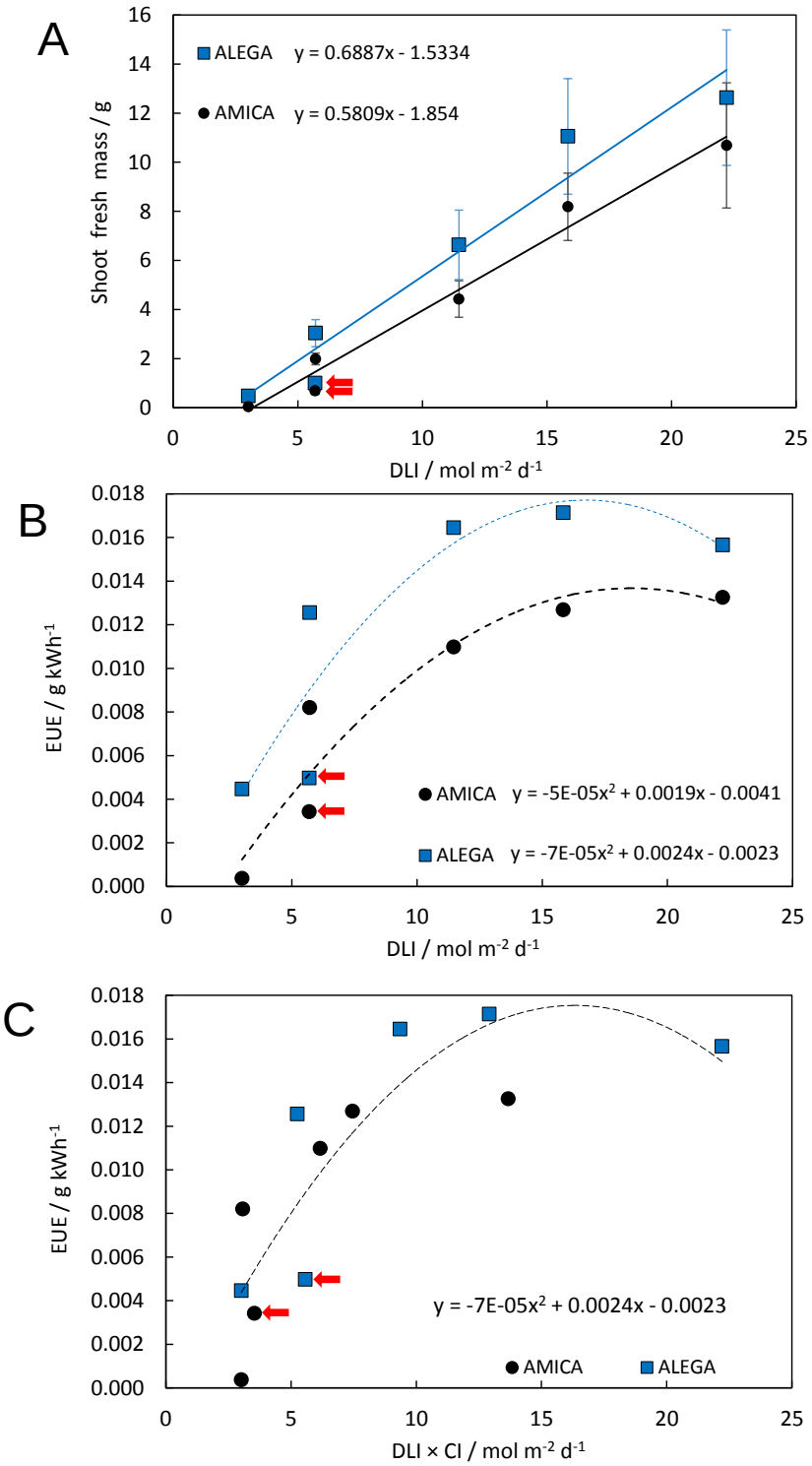


Figure 9. Crop growth and energy use efficiency. **A)** Influence of daily light integral (DLI) on the shoot fresh biomass production of the two lettuce varieties Alega and Amica. **B)** The influence of DLI on the lifetime energy used efficiency (EUE) of the two lettuce varieties. **C)** The influence of the leaf curling index (CI) corrected DLI, determined as DLI × CI, on the EUE of the two lettuce varieties. The regression line in this plot is fitted to both data sets. Red arrows indicated the data points from the strobe light treatment. Error bars indicate standard deviation.

Discussion

WP 1.2 Energy saving and daily light integral

Alega is a winter lettuce variety and Amica is a summer variety. Both varieties were found to have increasing growth rates as light intensity and DLI increased, though the summer variety grew at a slower rate than the winter variety. Under the highest DLI, the relationship with growth became non-linear, with a slightly lower growth rate than would have been projected from the lower DLI treatments. This decrease in growth had two potential causes: 1) the plants were approaching light saturation, or 2) the plants were large enough to cause shading between the plants causing competition for light that reduced growth. After three weeks, the larger plants were in need of spacing and some treatments would have been ready for transplanting after 2-2.5 weeks. While the plants grew increasingly quickly with the increasing light levels, energy use efficiency (calculated as fresh weight per meter squared divided by kWh of electricity used per meter squared over the three weeks) did not increase linearly with increasing light intensity. The energy use efficiency was greatest at ~15 mol m^{-2} d^{-1} for the winter variety (Alega) but greatest at 22 mol m^{-2} d^{-1} for the summer variety. These differences highlight the need to balance the design of a lighting installation between the cost of the installation (more lights require a greater cost) the running costs (more light requires more electricity), the output of the crop production facility (more light produces plants faster) and the efficiency with which the plants use the light (more light does not necessarily mean better light use efficiency).

Leaf size and morphology was observed to change in the two varieties in response to DLI. Under very low light levels, leaves were small (see images of plants grown under the mobile light rack) as the plants were severely light limited. Leaf length was observed to be at its maximum under the light treatments with a DLI of 5 mol m^{-2} d^{-1}. At higher DLI, leaf length was found to decrease. Leaf width, in contrast, was found to increase as light intensity increased, up to about 15mol m^{-2} d^{-1}. These changes resulted in a significant change in leaf shape and plant appearance. While the leaf sizes decreased as DLI increased, the plants were larger and had a greater number of leaves. Alterations to the DLI could potentially be used to alter growth rates to meet changes in market demand, but could also be used to create plants that are more compact and robust. In these experiments, the winter variety was more efficient at converting the light provided at low DLI to biomass than the summer variety. While there are potentially differences in the photosynthetic abilities of the two varieties, our data suggest that a large portion of the varietal difference was caused by differences in leaf morphology. The leaves of the summer variety remained significantly more curled that those of the winter variety and this would directly influence the amount of light the plants could

capture. Leaf flattening is known to be regulated by blue light intensity and so may indicate differences in the sensitivity of the photoreceptors between the two varieties. Temperature can also influence photosynthesis, leaf expansion, growth rates and photobiology so any differences in the sensitivity of the two varieties to temperature may be influencing/causing the differences between the varieties. To identify if any interactions between temperature and light responses are underling the differences between varieties would require additional growth experiments performed under a range of temperatures and light treatments. It may be beneficial to develop light treatments for crops grown in different temperatures that can be implemented in glasshouses during different seasons.

Growth rates and energy use efficiency were greatly reduced under the two intermittent light treatments that were designed to reduce energy consumption (strobe and mobile light treatments). The lower light intensity is only partly the cause of the low growth rates. Comparison of the constant 'low light' and the 'strobe' treatments (both treatments had the same DLI) shows a 60% reduction in EUE for both lettuce varieties when grown under the strobe light. The low EUE in the strobe treatment is probably caused by the inability of the plants to make use of the light provided. Plants require time to upregulate their photosynthetic machinery after illumination and it can take plants up to 30 mins to achieve maximum photosynthetic rate (Urban et al 2007). The 8s duty cycle employed in this trial was presumably too short to allow photosynthetic upregulation. The mobile light rack used in this trial also resulted in poor EUE and growth rates. In this case there was likely to be too little light to power growth but, because the lights only passed over the plants once per minute, the duration when the plants were illuminated was also unlikely to be sufficient to fully activate photosynthesis. Mobile systems could potentially be improved by having the light pass over the plants more regularly but this would both increase the electrical usage and probably the number of lights required.

Results

WP 2.1a Compare plant growth under different types of lamp

Lettuce plants were grown for 21 days under five different white LEDs, each with a slightly different light spectrum. The different treatments were provided by two Valoya lights (NS2 and AP673) and three Solidlite units (DPM, DPA & CWW). Under all light treatments, plants were healthy and showed no signs of pests or disease (Figure 10). The leaves of the Amica variety were more curled than those of the Alega variety. Plant growth, assessed as fresh mass at final harvest, was found to be influenced by the proportion of the incident light that could be used for photosynthesis (the lamp photosynthetic efficiency, Figure 11). Biomass was greatest under the Valoya AP673 lamp, where the calculated lamp photosynthetic efficiency was 89.9%. Growth was lowest under the CWW Solidlite lamp, where the lamp photosynthetic efficiency was 83.9%.

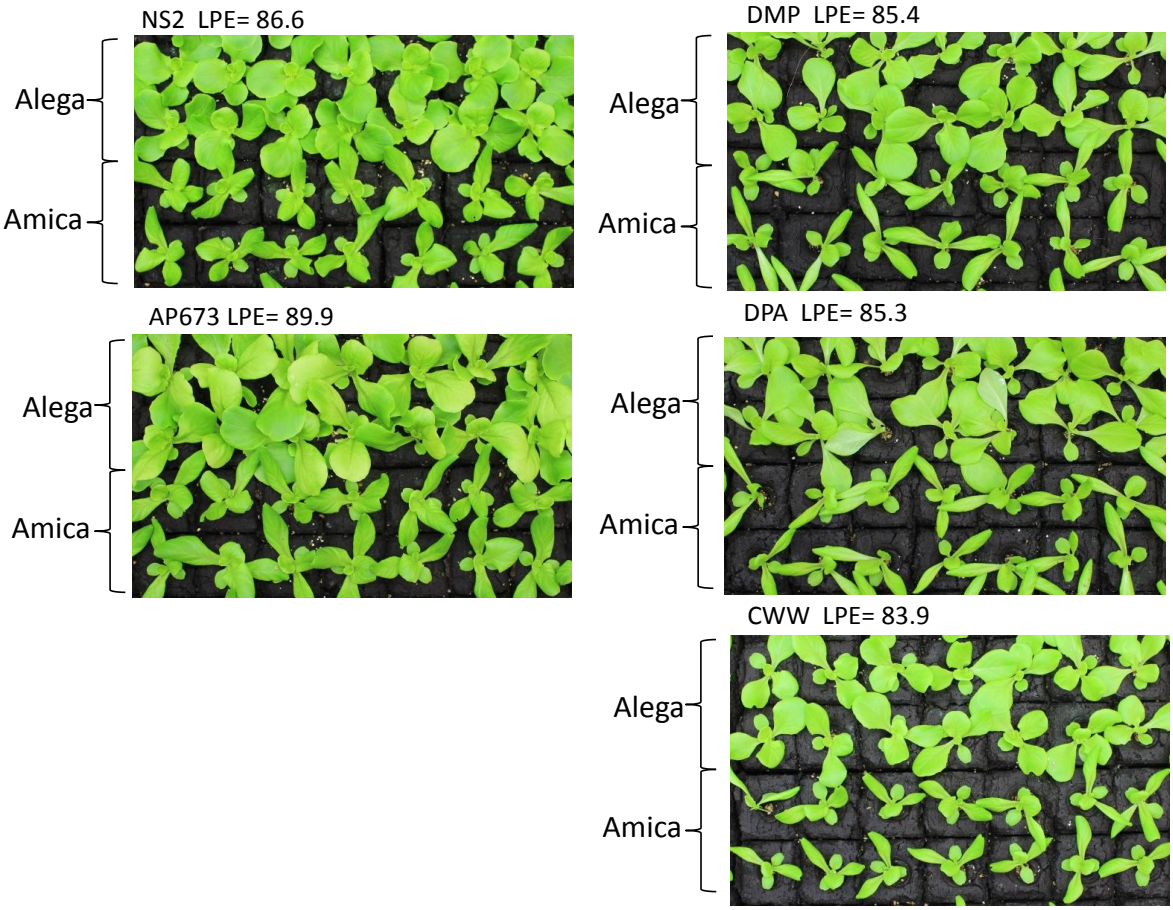


Figure 10. Photographs of two lettuce varieties taken after 19 days growth (Alega and Amica) under five different white light LED spectra. NS2 and AP673 were Valoya LED lamps and DMP, DPA, and CWW were Solidlite lamps. Lamp photosynthetic efficiencies (LEP) values for each lamp are provided.

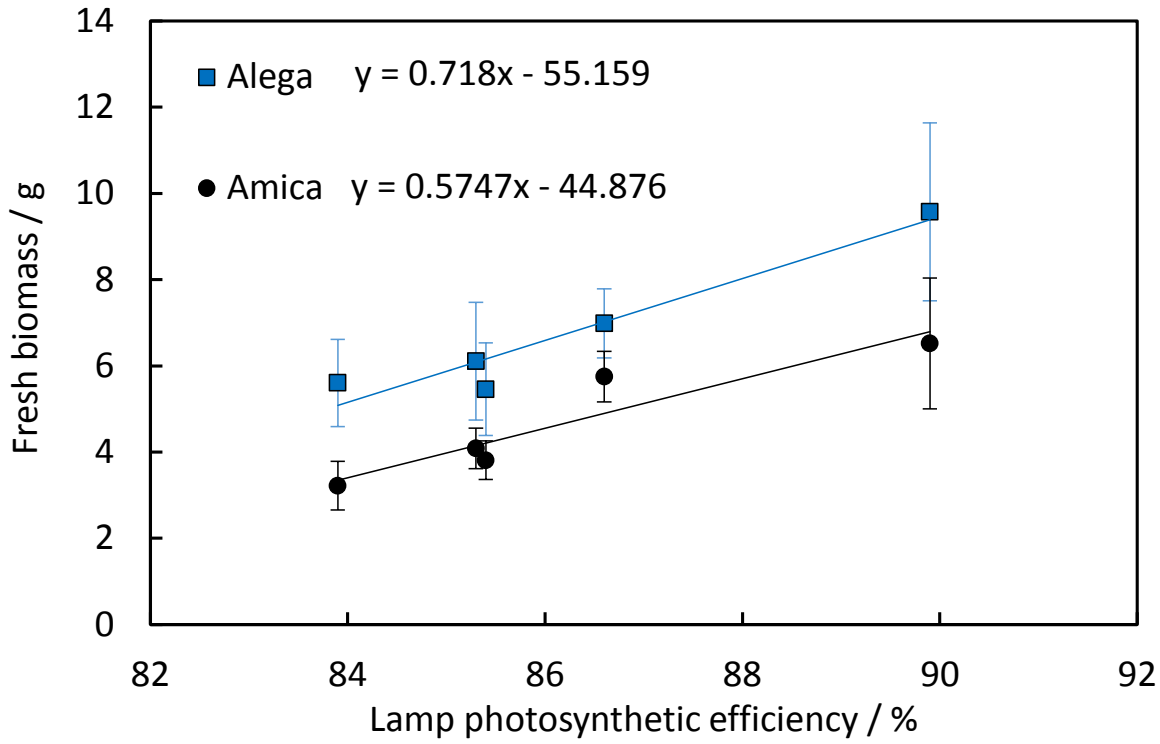


Figure 11. The influence of the lamp photosynthetic efficiency (calculated using the lamp emission spectrum, the photosynthetic action spectra provided by McCree 1971, and the mean leaf light absorptance spectrum of 25 plant species provided by Davis *et al*. 2011) on the fresh biomass accumulation of the two lettuce varieties. Error bars indicate standard deviation.

Discussion WP 2.1a Plant growth under different lights

In these experiments, five 'white-light' LED lamps were used to grow a summer (Amica) and a winter (Alega) lettuce variety. Each white-light had a different red:green:blue:far-red balance but a similar light intensity and DLI. Despite the plants receiving a similar amount of photosynthetically active radiation (PAR), there were significant differences in the biomass produced for each light treatment. The calculated lamp photosynthetic efficiency was found to correlate with biomass, indicating that the spectrum of the lamp is highly important for how effectively plants can utilise the light provided for growth (NOTE: not all light treatments are designed to maximise plant growth rate). Further work will be required to assess whether other aspects of light quality are contributing the difference in growth rate between the lamps but these results highlight the need for plant growth lights that have spectra designed for plants and the limitations to crop energy use efficiency that non-optimal light treatments impose on crop production systems. The difference in biomass production between the summer and winter varieties highlights the need to select crops that are appropriate for the crop production system or to select a light treatment to match the plant species/variety. These results also indicate that for optimal crop production under LED lighting, crop breeding may need to account for the light spectrum plants are likely to be grown under.

Results

WP 2.1b Influence of red / blue ratio on plant growth.

Protected edible plants

Basil

Basil plant growth was found to be sensitive to the different light treatments. Images of plants from the different light treatments are shown in Figure 12. At all stages of growth, the basil plants were tallest in the 11% blue light treatment and shortest in the 100% blue light treatments (Figure 13). The plants grown in the 15% blue light were shorter than expected at each sampling date. The basil plants in the 15% blue treatments were located on the bottom shelf of the rack which, on inspection, was found to have a slightly lower temperature as this shelf had no LEDs providing warmth from below. Plant biomass was found to correlate with plant height (data not shown) and was lowest under the 100% blue light treatment. The lengths of the first two internodes of the basil plants followed the same trends as plant height, with internodes becoming progressively shorter as the blue light percentage increased (Figure 14). In addition to the large differences in plant height, leaf morphology was strongly affected by the blue light percentage. The angle at which the leaves were held relative to the vertical changed with blue light percentage (Figure 15). In 100% blue light the leaves were held at a 100° angle from the vertical (almost parallel to the floor). As the blue light percentage decreased the leaf angle increased, indicating that the leaves took on a more epinastic phenotype (hanging downward). Not only were the leaves held at different angles, but the leaves in the lower blue light percentages were more curled, while those in the 100% blue treatment were very flat.

To gain a greater understanding of the physiological state of the basil plants grown under the different light treatments, photosynthetic measurements were made on plants from four of the red:blue light treatments (15, 33, 66, and 100% blue) and a control group of plants grown under the red:white LED light. All the photosynthesis measurements were made under the same light source so any differences in the light response were associated with the different physiological state of the leaves, not with differences in the incident light. The photosynthetic light response curves are shown in Figure 16. The greatest photosynthetic rates were achieved in plants grown under 100% blue light, despite these plants growing more slowly than those in the other light treatments. The lowest photosynthetic rates were observed in the red:white light treatment. When the maximum gross photosynthetic rates were plotted versus the blue percentage contained within the light, photosynthetic potential (P_{max}) was found to increase with increasing blue light percentage. Respiration rates were found to decrease (become less negative) as blue percentage increased.

Figure 12. Photographs of basil plants grown under the different light treatments at different stages of growth (24 days and 34 days).

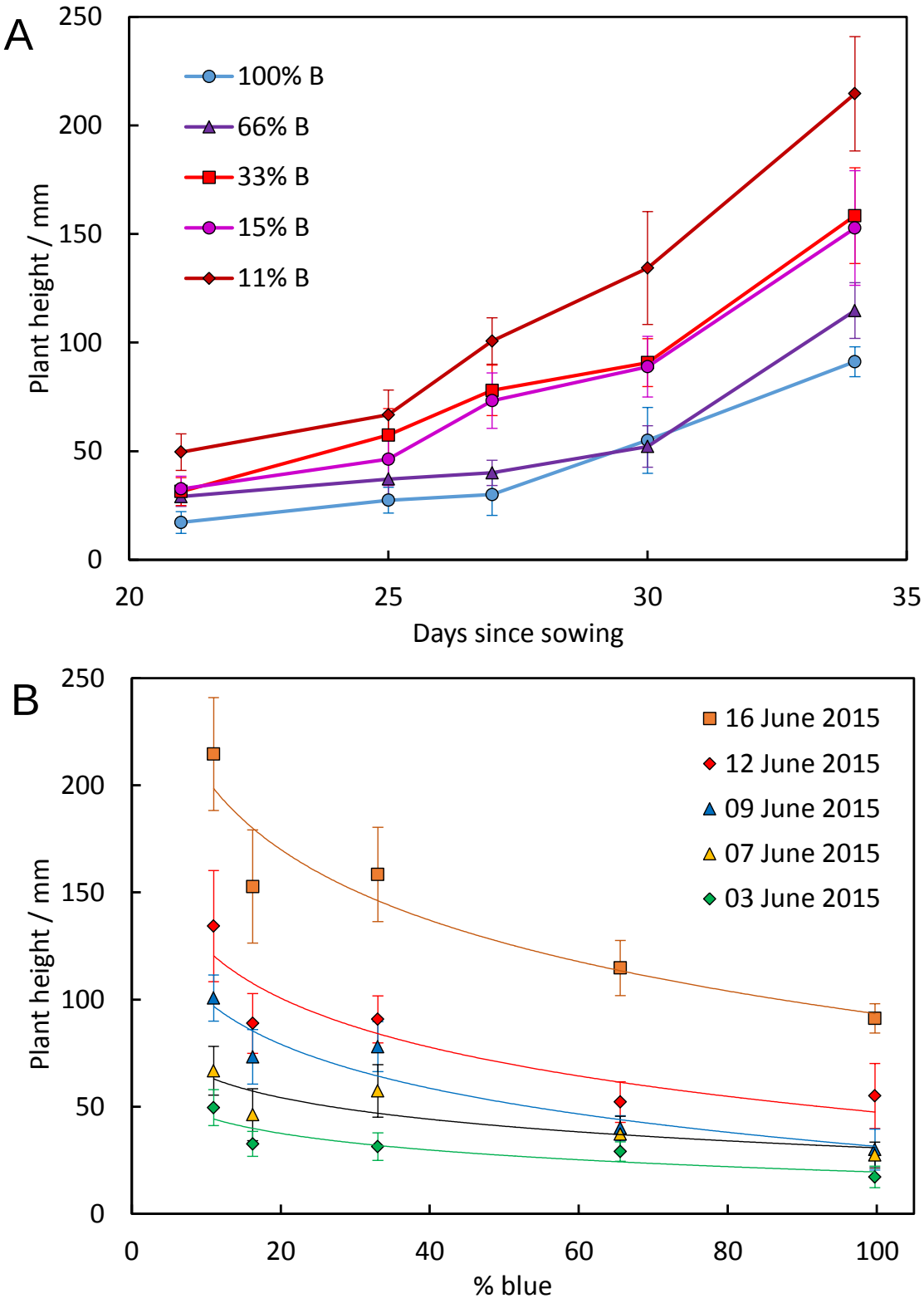


Figure 13. The influence of blue light treatment on basil plant height. A) Plant height presented as a time course through the experiment for each light treatment. B) Plant height plotted versus percentage of blue in the light treatment for each sampling date. Error bars indicate standard deviation.

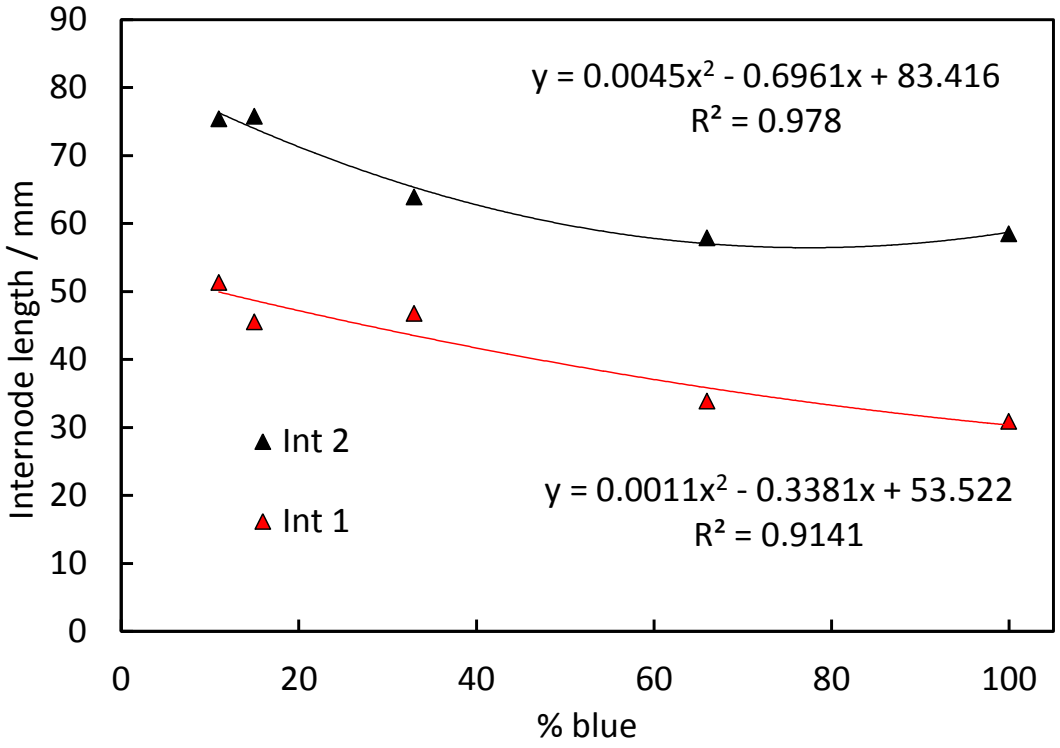


Figure 14. Influence of blue light percentage (% blue) on the length of the 1st two internodes of the basil plants grown under the examined red:blue treatments.

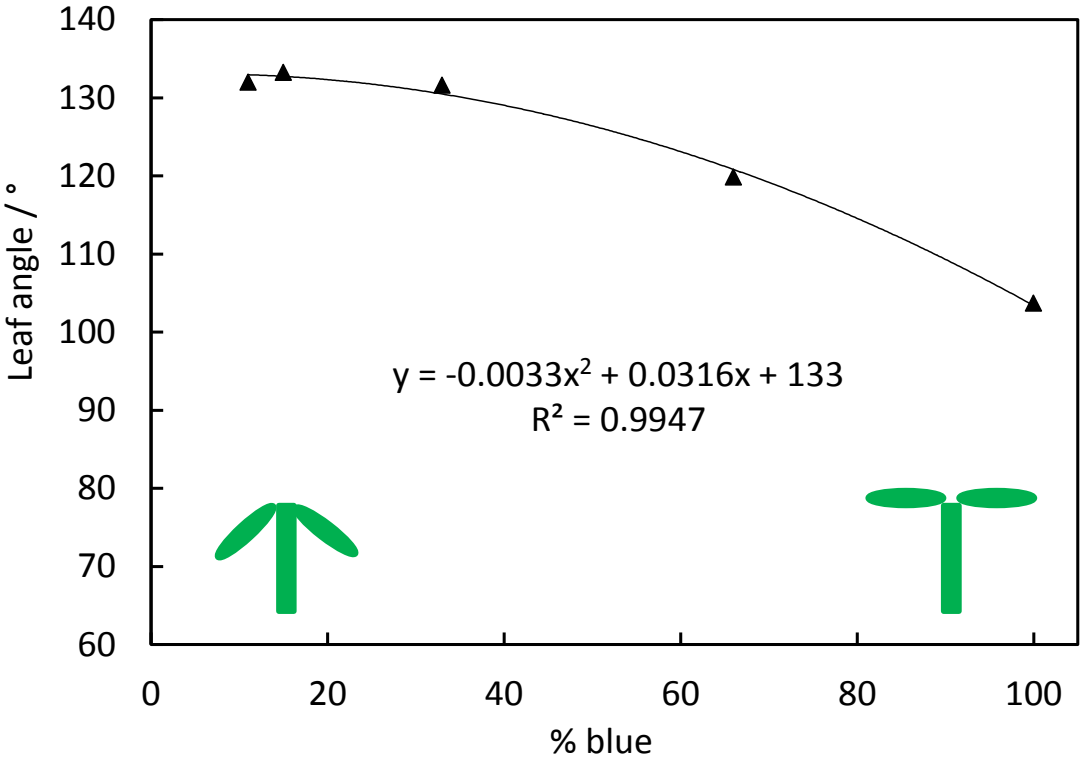


Figure 15. Influence of blue light percentage on leaf angle of basil plants grown under the different red:blue light treatments. The diagrams at each side of the graph demonstrate the appearance of the plants at the two treatment extremes.

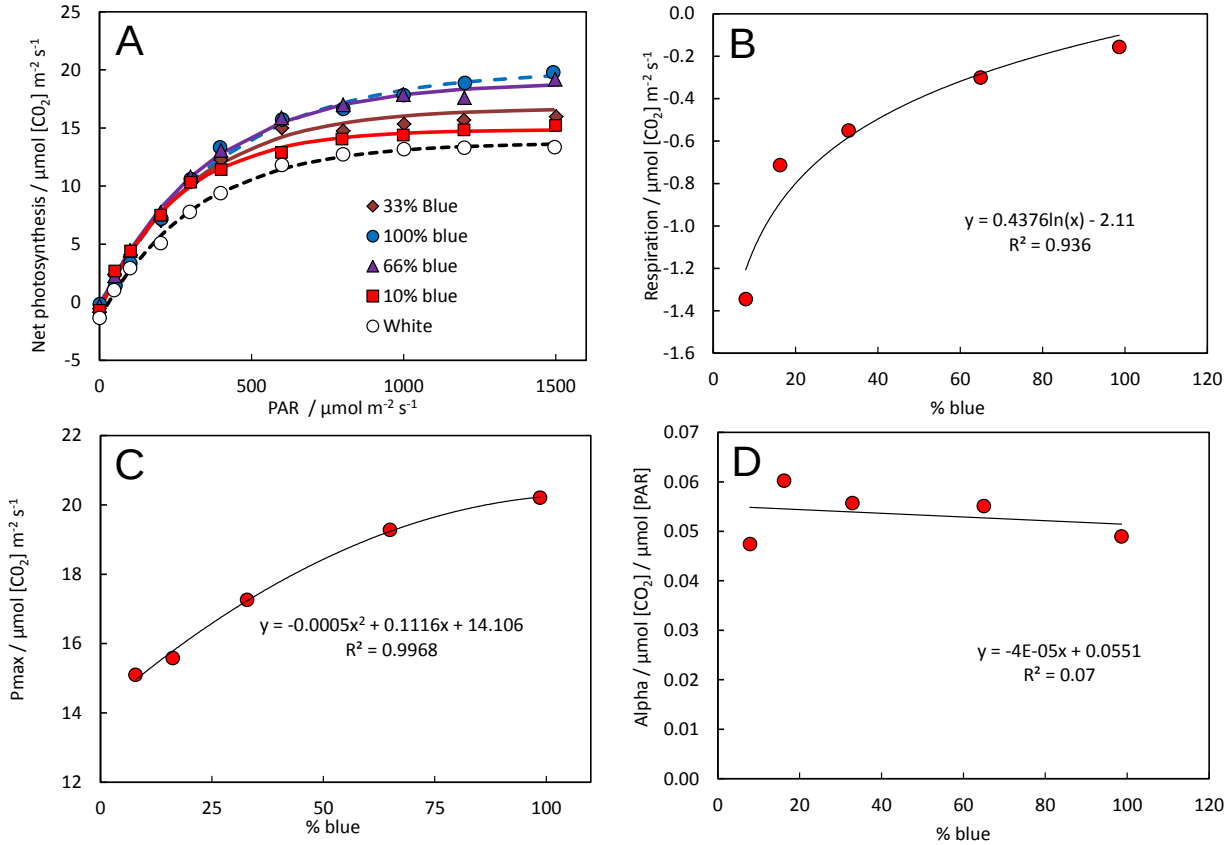


Figure 16. **A)** Net photosynthetic light response curves of basil plants grown under five different light treatments. The influence of blue percentage (% blue) on **B)** the measured respiration rate in darkness, **C)** maximum gross photosynthetic rate (P_{max}) and **D)** the slope of the net photosynthesis curve in light limiting conditions (Alpha).

Sage

The sage plants grew less quickly than the basil plants but still produced healthy plant material (see Figure 17). The size and morphology of the plants was influenced by the light treatments. On the 3rd June 2014 the sage plants grown under 100% blue light were the tallest plants; however, by the 23rd June, these were the shortest plants. The plants grown under 11% blue light were the tallest for the majority of the experiment (Figure 18). At the end of the experiment, plant height was found to correlate negatively with blue percentage (Figure 18B). Plant mass and internodes were found to respond to the light treatments in the same manner as plant height, such that more blue light resulted in smaller plants (Figure 19). The number of side branches produced by the sage plants also decreased as the blue percentage of light increase. These differences are likely to be a result of the slower growth of plants in 100% blue light. The leaf:stem mass ratio was found to increase with blue percentage, though this was likely due to the reduced growth of the plant under the higher blue percentages. The sage leaves were flat (no leaf curling was observed) and held at a

similar angle in all light treatments. Leaf size was found to decrease as blue percentage increased.

Figure 17. Photographs of representative plants from the four red:blue light treatments taken after 55 days growth. The plants were plants at opposite end of the six pack to avoid shading within the plant canopy.

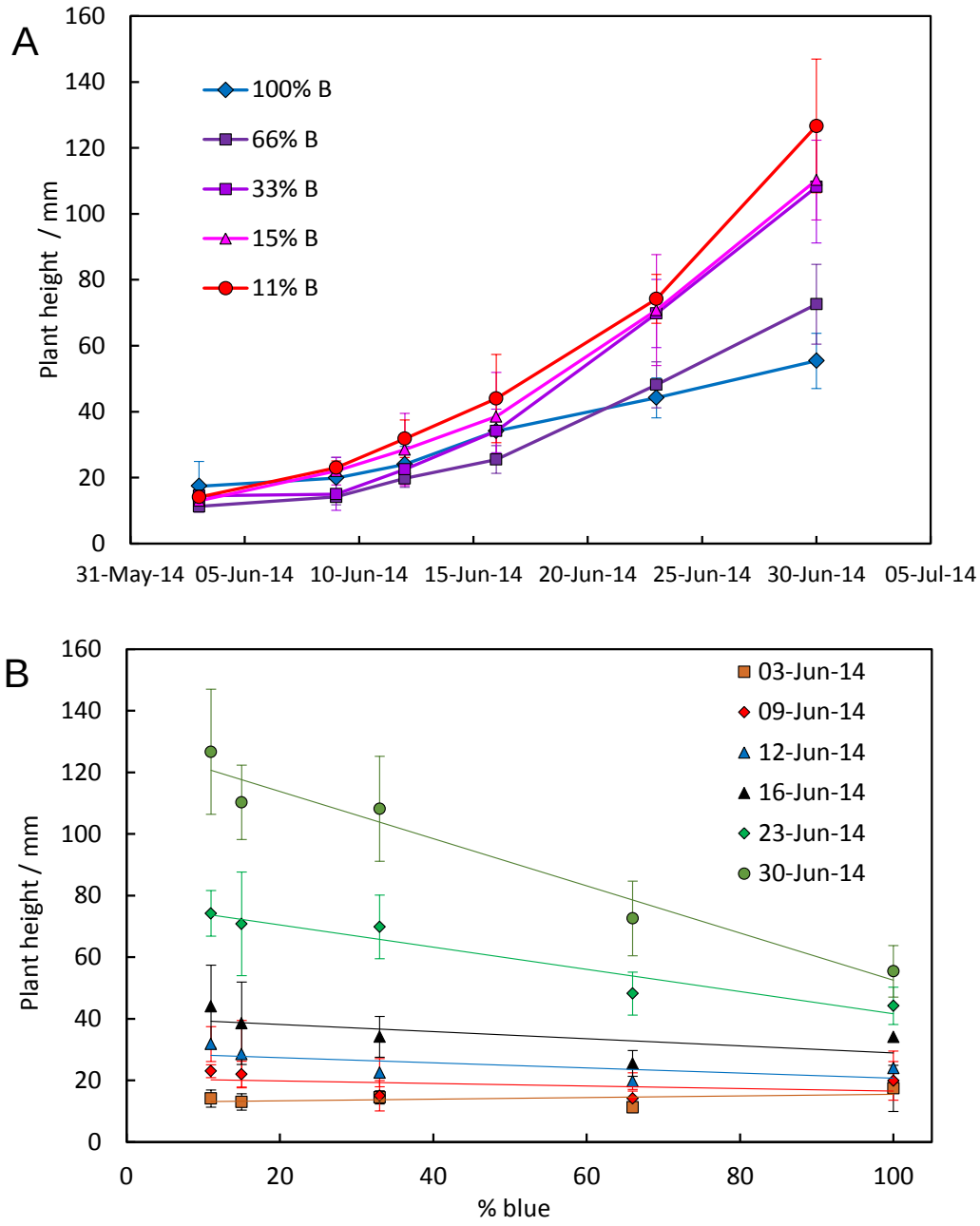


Figure 18. Influence of blue light treatments on sage plant height. **A)** Plant height presented as a time course through the experiment for each light treatment. **B)** Plant height plotted versus percentage of blue in the light treatment for each sampling date. Error bars indicate standard deviation n > 5.

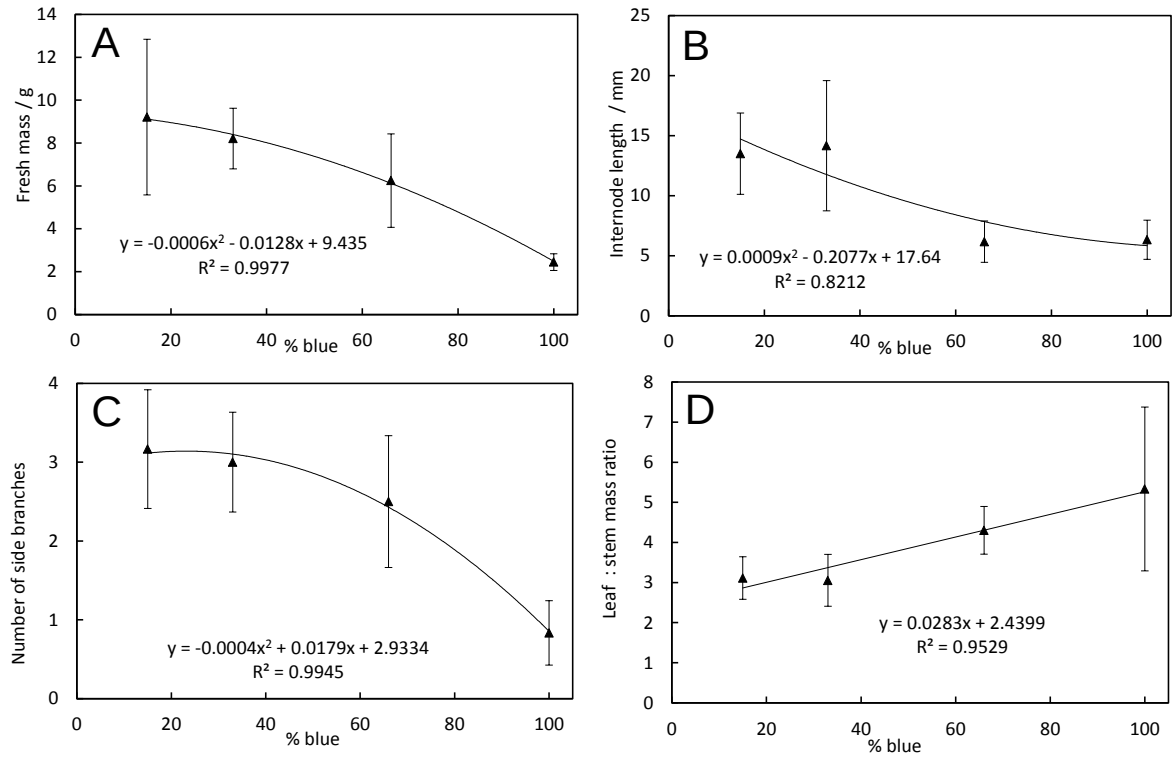


Figure 19. sage fresh mass and morphological parameters at the final harvest on 14th July 2014. The influence of blue percentage on **A)** plant mass, **B)** internode length, **C)** number of side branches formed on the plants and **D)** leaf to stem mass ratio. All error bars indicate standard deviation.

To examine the physiological state of the sage plants, photosynthetic rate was measured in plants grown under five light treatments: four red:blue light treatments (15, 33, 66 and 100% blue) and one control red:white treatment (8% blue). The light curves and other photosynthetic parameters are shown in Figure 20. The maximum photosynthetic rate (P_{max}) and the slope of the light-limited region of the photosynthetic responses curve (alpha) were both found to decrease as blue percentage increased. The maximum photosynthetic rates were observed in the plants grown under 15% blue light and the lowest under the 100% blue light treatments. As with the basil plants, sage respiration rates were found to decrease (become less negative) with increasing blue percentage. The P_{max} and alpha parameters of the leaves grown under the red:white light (data points for 8% blue light) were lower than may have been expected based on the correlation observed with blue percentage for the four other values. This may indicate that the low blue percentage in this light treatment is insufficient to fully activate the photosynthetic machinery in this species.

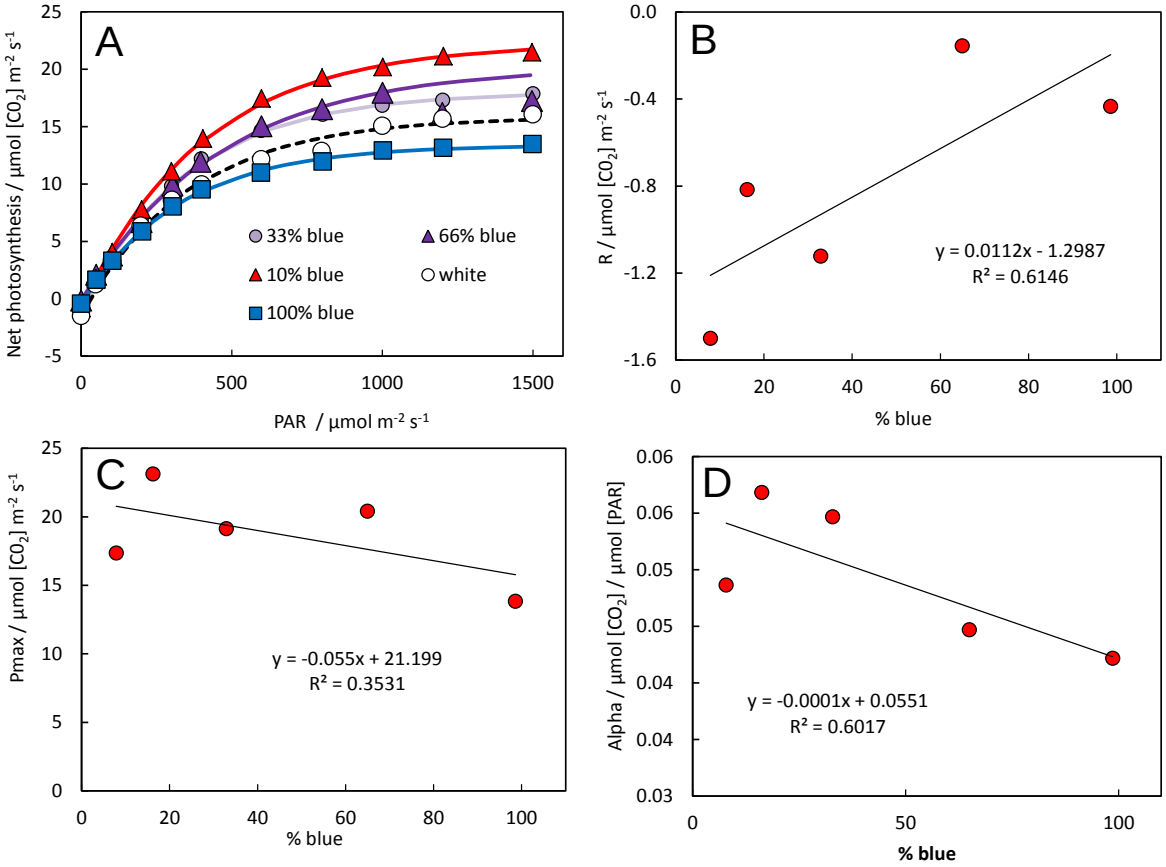
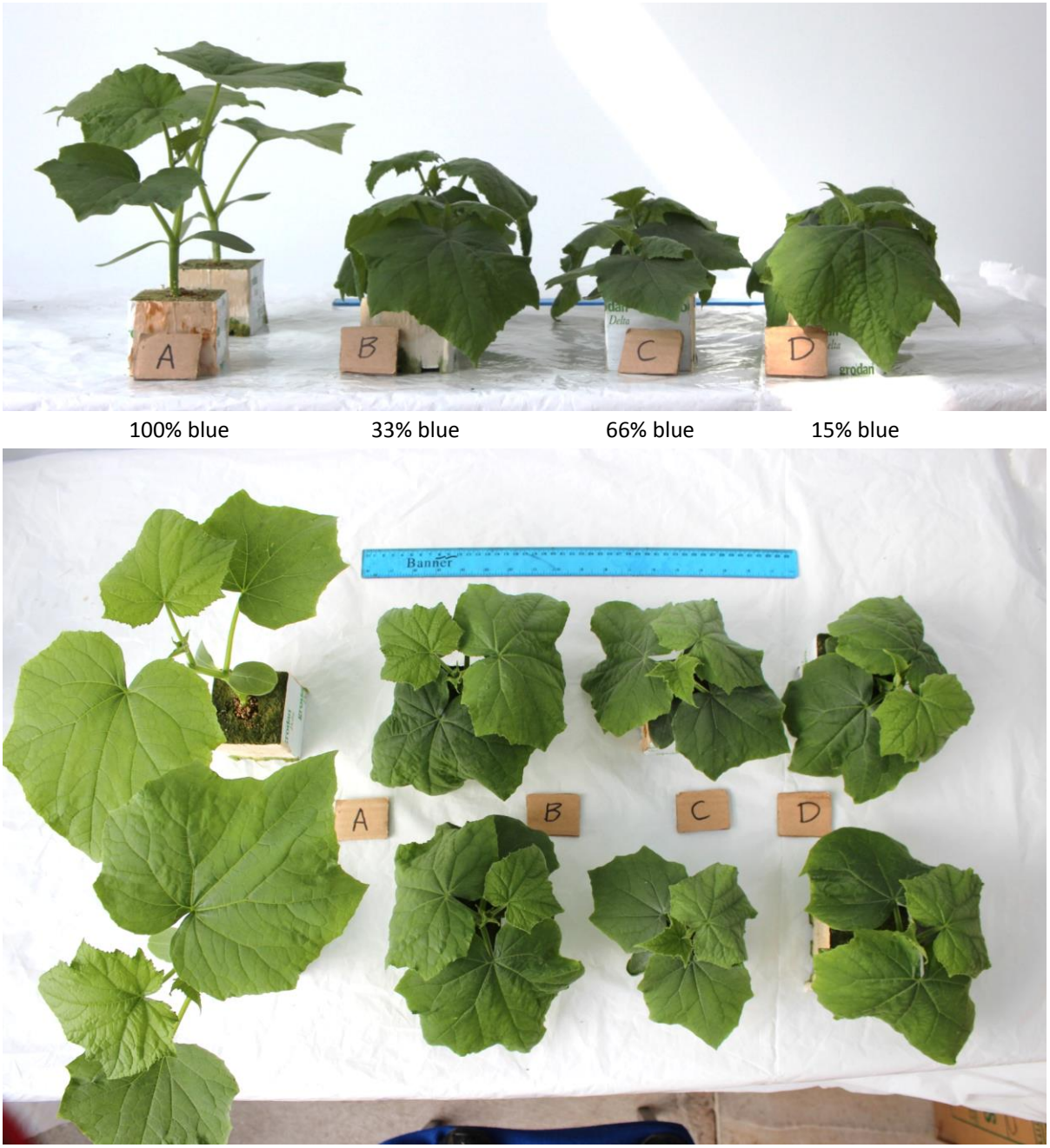


Figure 20. A) Net photosynthetic light response curves of sage plants grown under five different light treatments. The influence of blue percentage (% blue) on **B)** the measured respiration rate in darkness, **C)** maximum gross photosynthetic rate (P_{max}) and **D)** the slope of the net photosynthesis curve in light limiting conditions (Alpha).

Cucumber

The Cucumber plants grew well, producing healthy green leaves with no signs of disease. Plant morphology was highly responsive to light treatments. The most compact plants were observed under 66% blue light and the tallest plants, which were three times taller, were observed under the 100% blue treatment (Figure 21 and Figure 22). The differences in internodes were even more extreme than the differences in plant height, with the 100% blue light treatment plants having internodes 9 times longer than those in 66% blue light treatment. Leaf numbers were lower under the high blue light treatments compared to the low blue light treatments, indicating a reduced rate of development. Leaf size (lengths and widths) were smallest under 66% blue light but were similar for the 100% blue and 15% blue treatments (Figure 22). The overall morphology of the leaves under 100% blue and 15% blue were, however, very different. Leaves developing under 100% blue light were very flat and were held parallel to the floor while those under the lower blue percentages were more epinastic (hanging downward) and curled.



100% blue 33% blue 66% blue 15% blue

Figure 21. Photographs of representative Cucumber plants grown under four different red blue light treatments. The same plants are shown from the side and from above.

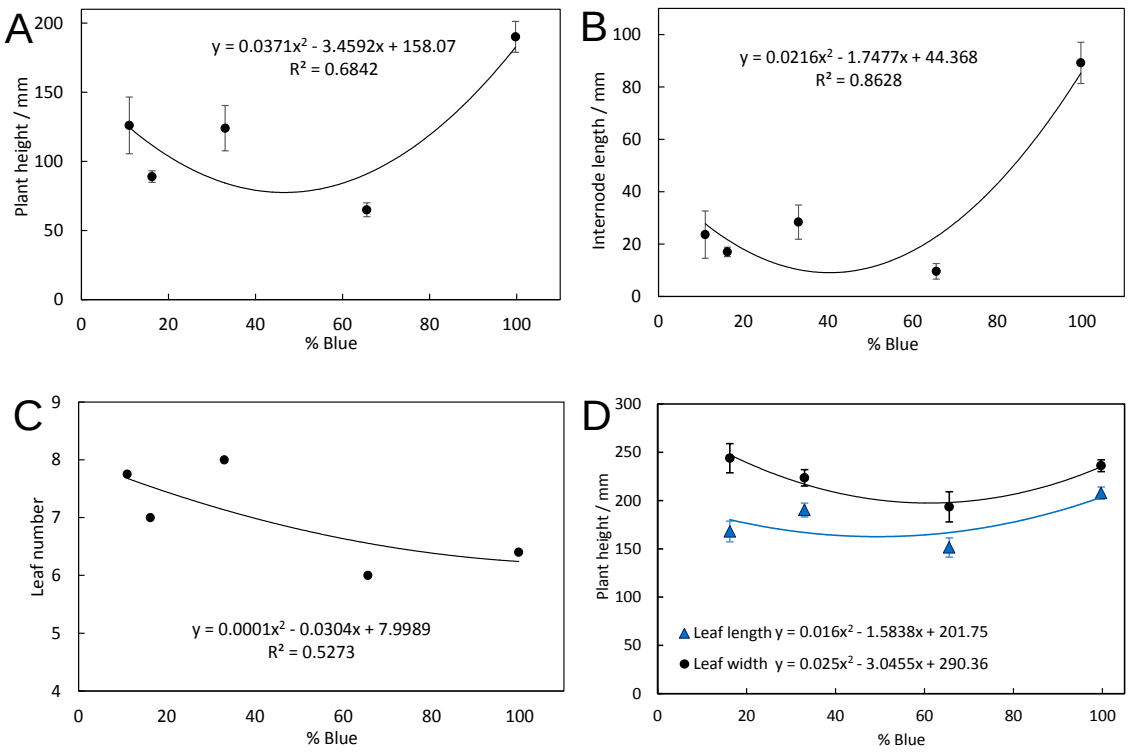


Figure 22. The influence of blue light percentage on **A)** plant height, **B)** internode length, **C)** leaf number and **D)** leaf size in Cucumber plants grown under different red:blue light treatments. Error bars indicate the standard deviation.

Lettuce

The two lettuce varieties grew well under the different red blue light treatments (Figure 23) but the size and morphology differed greatly between the light treatments and between varieties. The mass of both varieties was greatest under the 11% blue light treatment. As blue light percentage increased above 11% blue, the plant mass decreased, though the Amica plants showed a slight increase in biomass between 58 and 100% blue light. Plant mass was also found to decrease considerably between the 11% blue and 0% blue (100% red) treatments (Figure 24). The mass of Alega plants was greater than that of the Amica variety in all treatments. Morphologically, the plants varied dramatically, especially the Alega variety, between the light treatments. The plants under 100% blue light produced the longest leaves (Figure 25) while the shortest leaves were produced under the 58% blue light treatment. The leaf lengths of the two varieties were similar under the 100% red light treatment. Leaf lengths decreased rapidly in the Alega variety as blue percentage increased. This indicated that Alega was more sensitive to blue light than the Amica variety, in which leaf length decreased gradually with increasing blue light. Leaf width was found to decrease between 11% and 58% blue light and increase between 58% and 100%

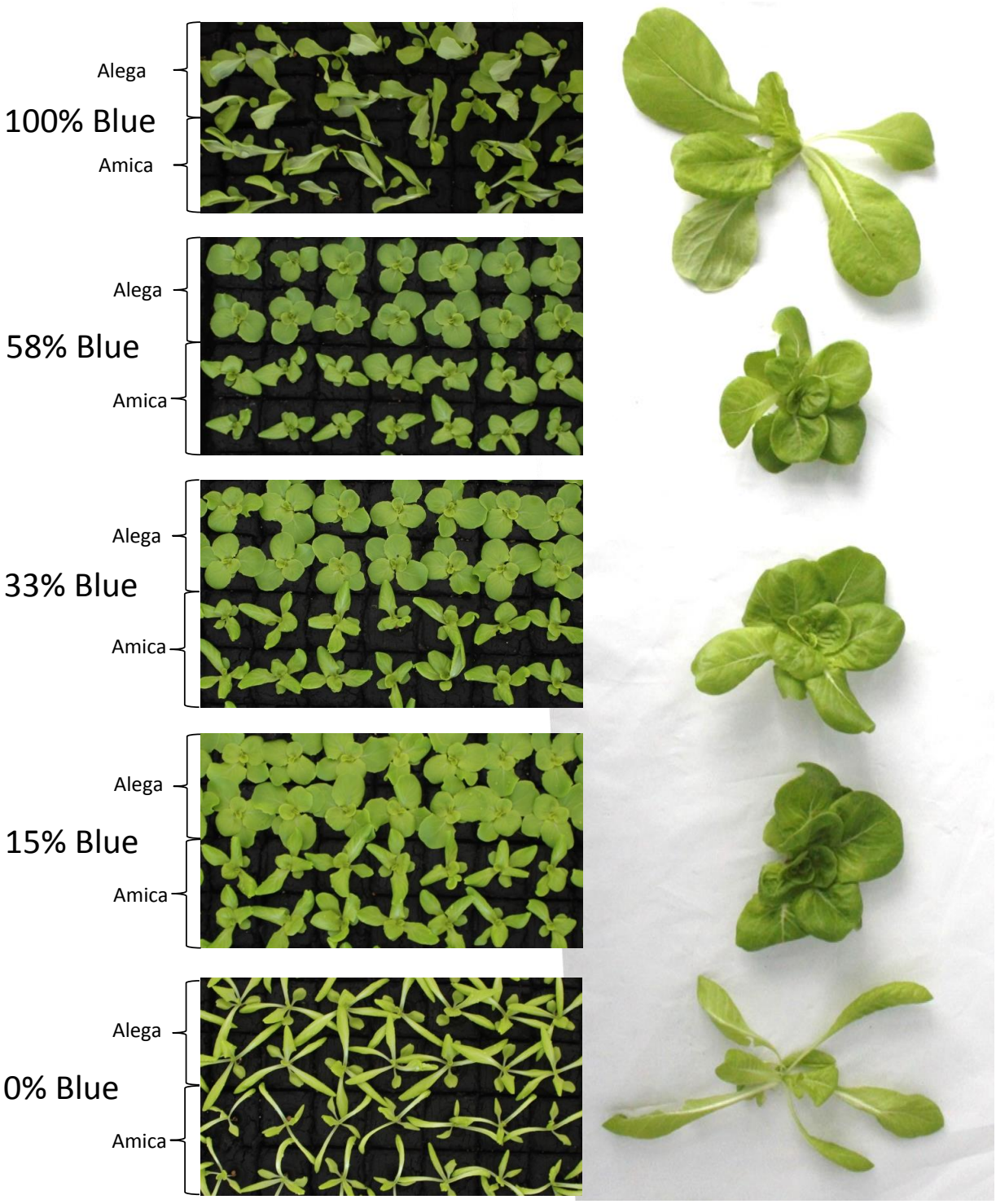


Figure 23. Images of the two lettuce varieties, Alega and Amica, when grown under lights with different red:blue ratios for 19 days. The close-up plant images on the right show representative Alega plants from each light treatment.

blue light. Leaf width decreased, especially in Amica, between 11% and 0% blue light. The leaf curling (assessed as curling index, CI) of the Alega leaves was less than for Amica leaves in all treatments except the 100% red light treatment, where both varieties were heavily curled. In the Alega plants the majority of the curling was removed by the 11% blue light treatment while the curling of the Amica leaves was unresponsive to the blue light levels used in this experiment. This again indicates that Alega plants were more sensitive to blue light than the Amica plants.

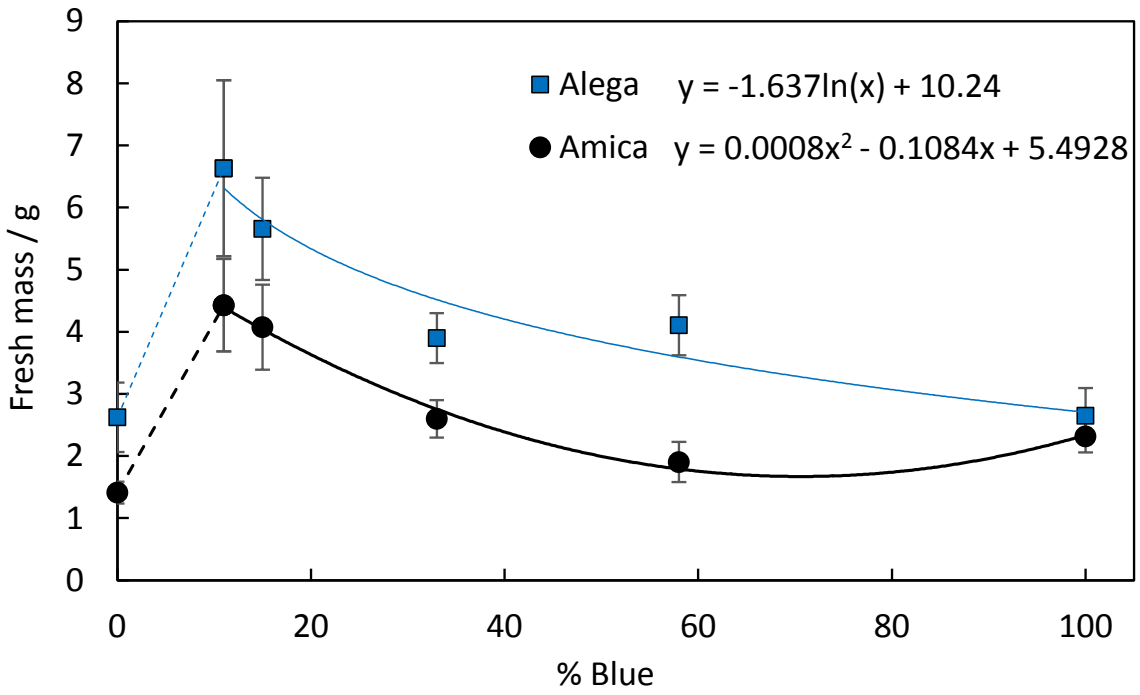


Figure 24. The influence of blue light percentage on the fresh biomass of the two lettuce varieties Alega and Amica. Error bars indicate standard deviation.

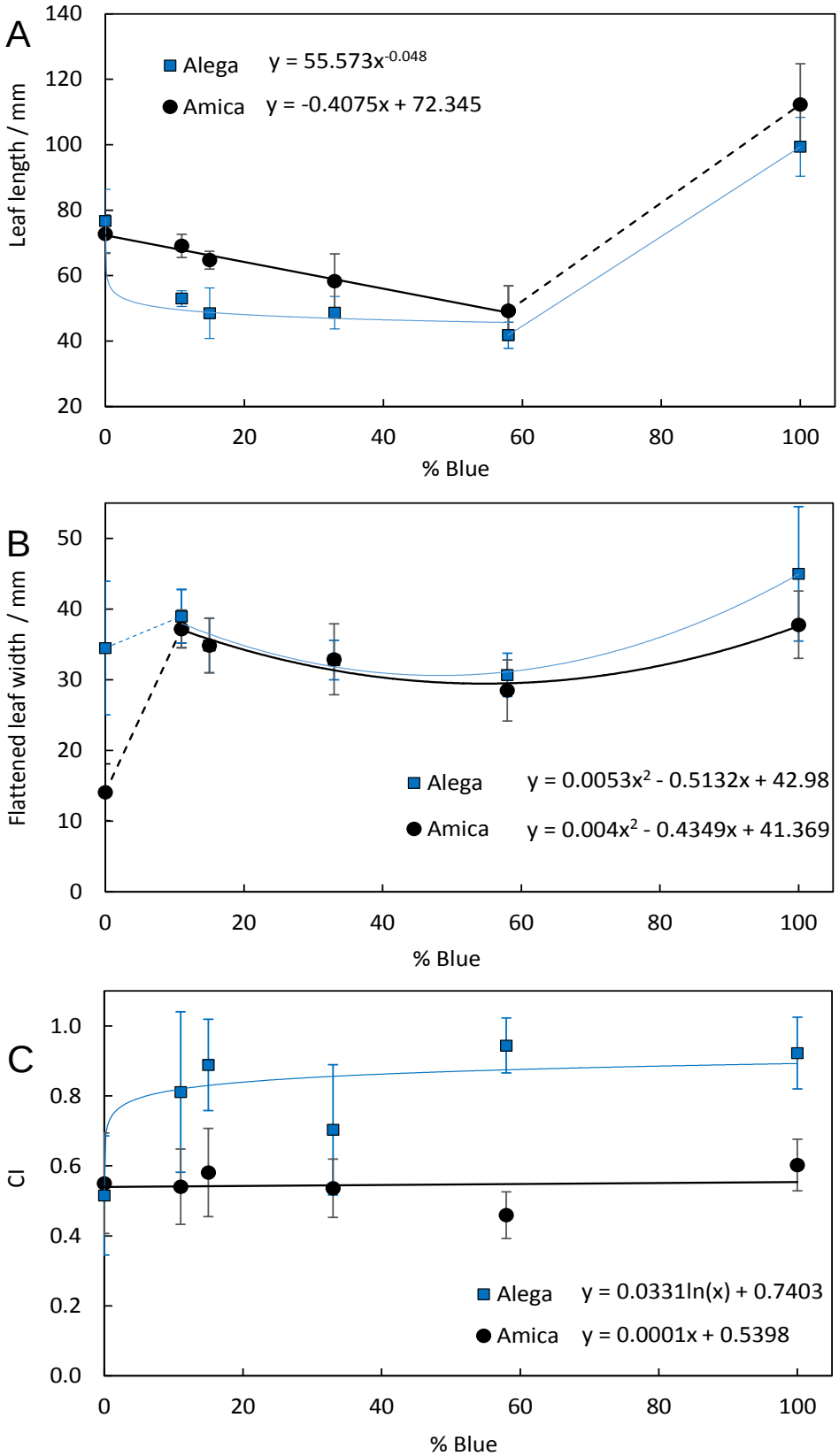


Figure 25. The influence of blue light percentage on **A)** leaf length, **B)** flattened leaf width and **C)** curling index (CI) of the two lettuce varieties Alega and Amica. Error bars indicate standard deviation.

Protected ornamental plants

Petunia

The petunia plants germinated and grew rapidly and produced good quality plug plants 3.5 weeks after sowing (Figure 26). The plug plants produced under the 100% blue light treatment had the largest leaves but, overall, these plants were the lowest quality as they had long petioles. The most compact plants were produced under the 58% light treatment. The fastest growing and best quality plants were produced under the 11 and 15% blue light treatments. The plant size was strongly influenced by light treatment at all stages of growth after potting on (Figure 27). Plants grown under 100% blue light produced larger leaves and consistently longer internodes than those in the lower blue percentage treatments that also contained red light (Figure 28). Total shoot mass was however, lowest for the plants grown under 100% blue and greatest under the 11% blue light. This indicates than the large increase in plant height is associated with significant changes in biomass partitioning. The most compact plants were observed in the 58% blue treatment. Branch number was found to be greatest in the 11% light treatment and correlated with shoot biomass.

The large differences in plant morphology were combined with large differences in flowering rates between the different light treatments. Flowering occurred earliest and most intensely in plants grown under 100% blue light (Figure 29). These plants not only produced the greatest total number of flower buds, but also had a higher rate of flower development, with these plants having the greatest number of flowers between developmental stages 4 and 6 (Figure 29B), as defined by Colquhoun *et al*., 2010, and open flowers (Figure 29C) for the majority of the trial. Plants from the 11% blue light treatments were the second most vigorously flowering and plants from the 58% blue light treatment produced the fewest flowers. Figure 30A shows the relationship between blue percentage and total number of flowers. In order to assess if the differences in flowering could be described by the different growth rates of the plants from the different treatments, the total number of flowers was divided by the total shoot mass (see Figure 30B). For the plants grown under light treatments ranging between 11 and 58% blue light, flowers were produced at a similar rate with one flower occurring for every 0.5-1g of fresh weight. In the 100% blue light treatment, flower production per mass of plant was greatly increased, with greater than 2.5 flowers occurring for every gram of plant tissue. This indicates a large increase in investment towards flowers in plants grown with no red light.

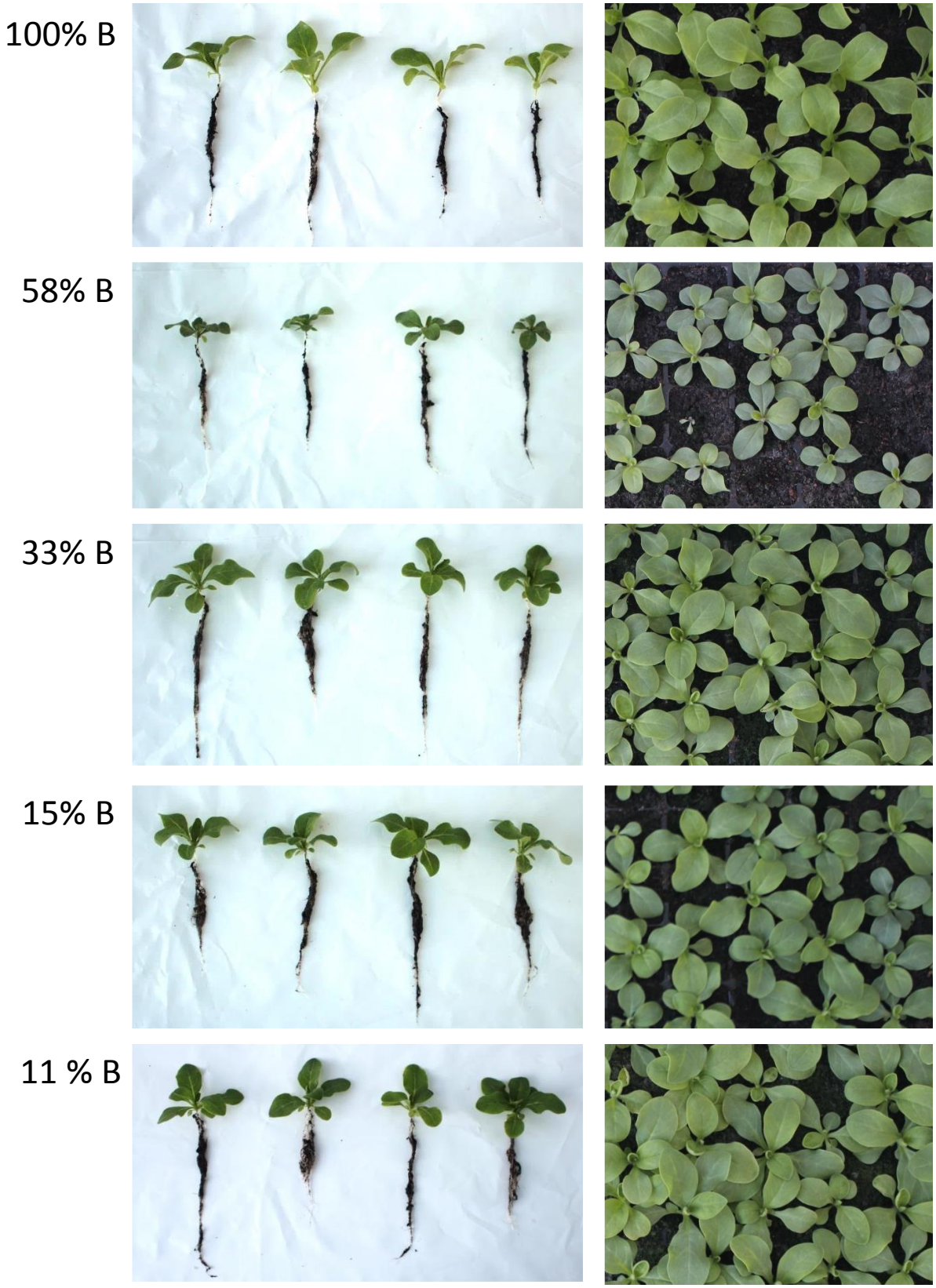


Figure 26. Images of the petunia plug plants grown under the different red:blue light treatments for 25 days.

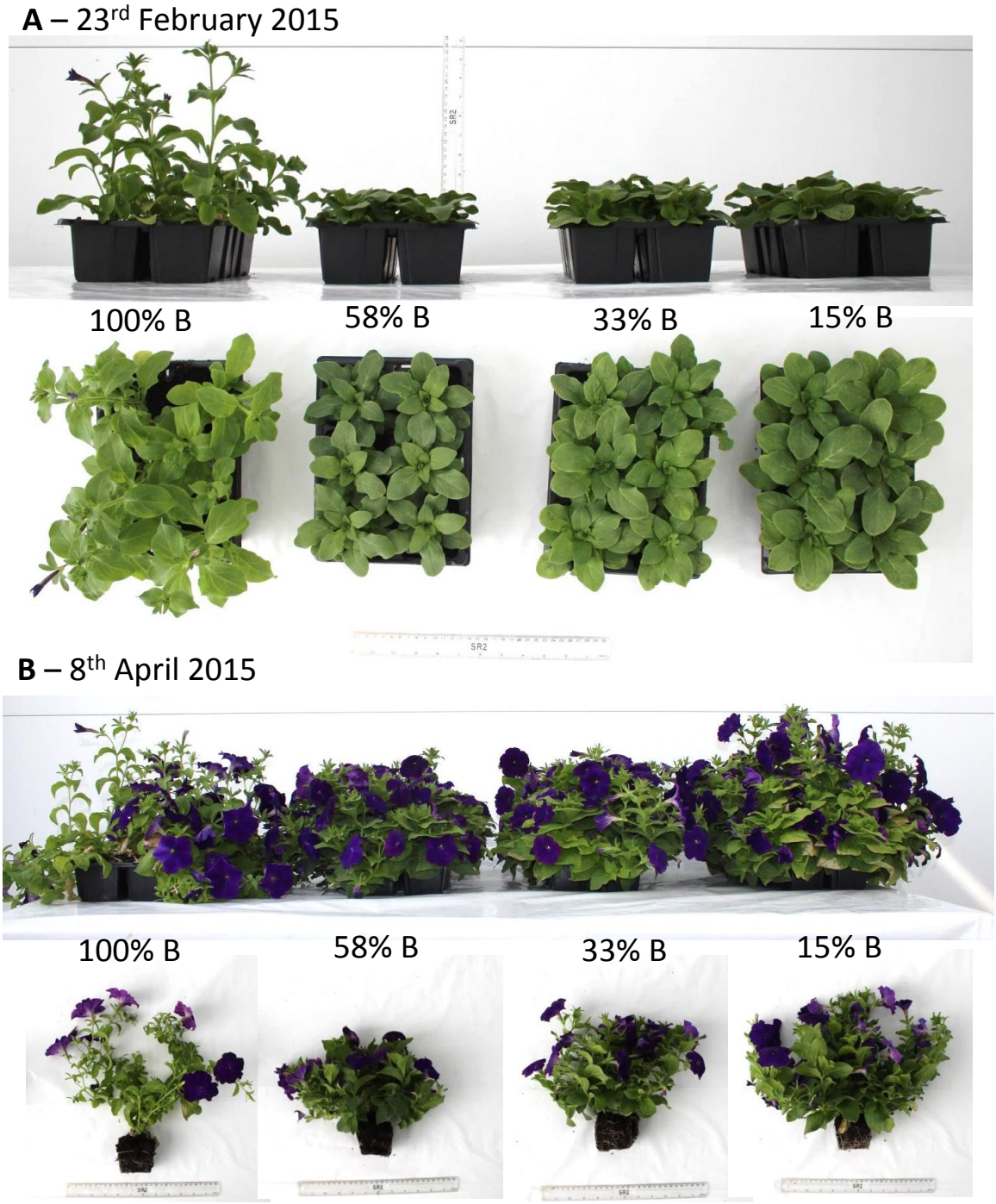


Figure 27 Images of the petunia plants at two stages of growth showing the effect of light quality on vegetative growth at 42 days **(A)** and flowering at 86 days**(B)**.

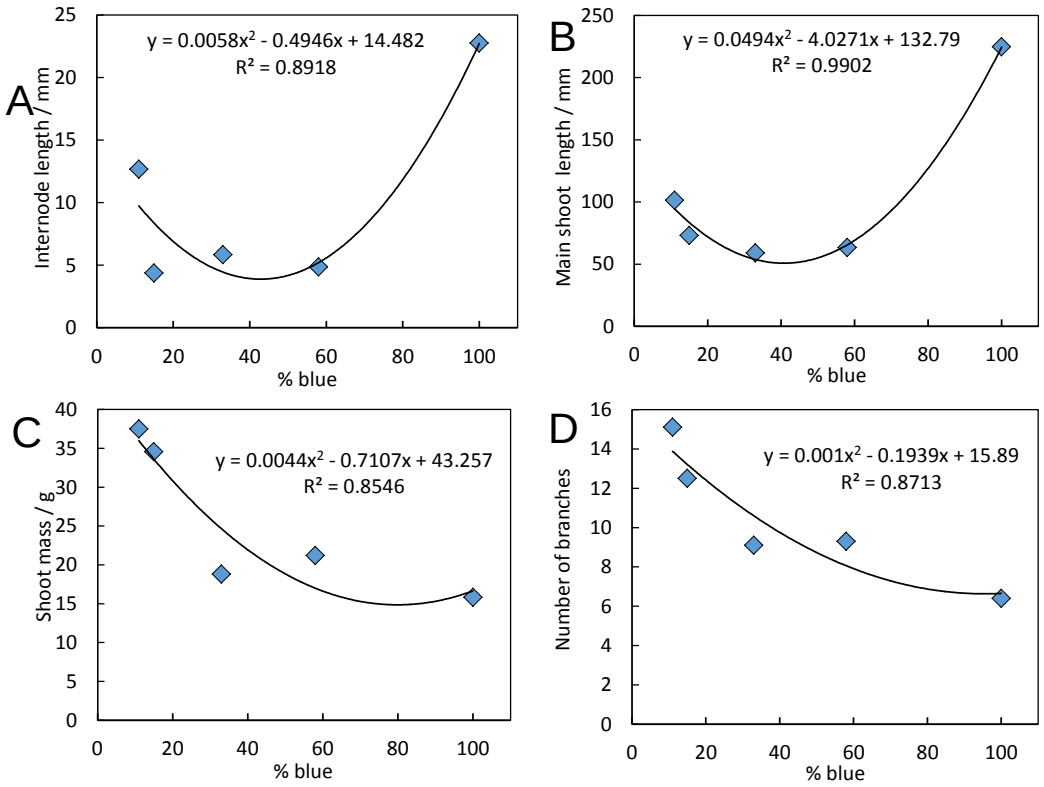
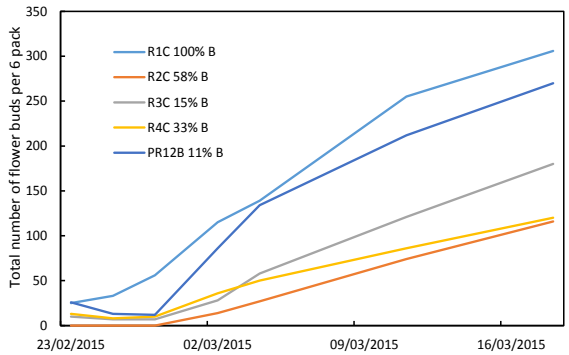
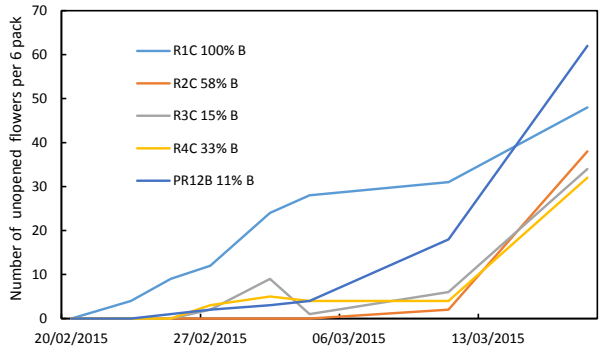


Figure 28. The influence of blue light percentage on the A) internode lengths, B) main shoot length, C) the fresh shoot mass and D) the number of side branches of petunia plants grown under different red blue light treatments.

A



B



C

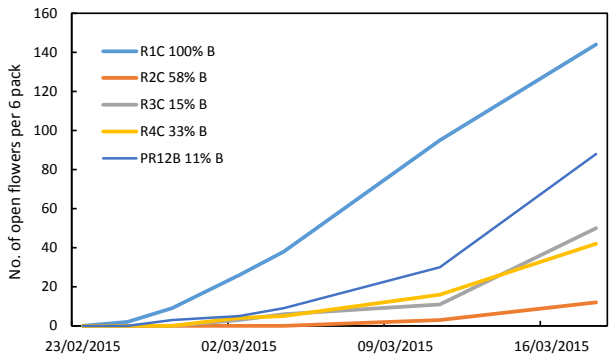


Figure 29. The influence of blue light percentage on time courses of **A)** total numbers of flowers (this includes buds, open flowers and seed heads), **B)** number of flowers between developmental stage 4 and 6, and **C)** number of open flowers of petunia plants.

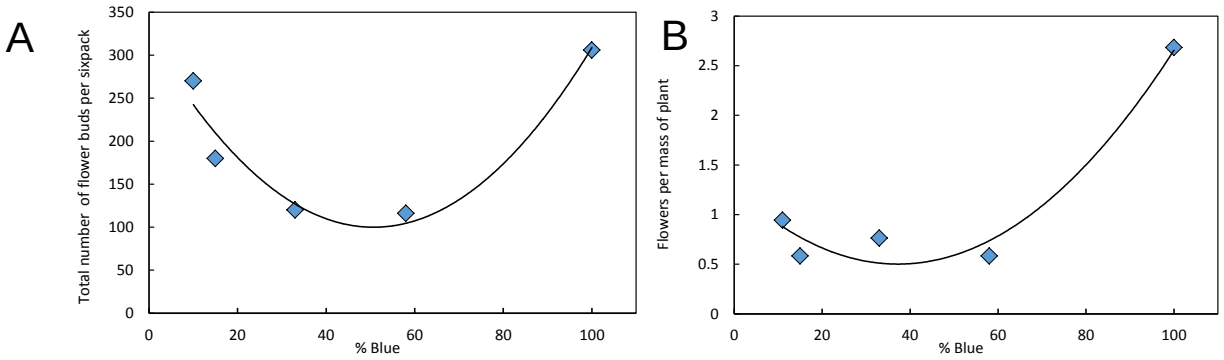


Figure 30. The relationship between blue light percentage and **A)** total numbers of flowers and **B)** number of flowers per gram of fresh weight for petunia plants grown under the different light treatments.

Pansy

The pansy seedlings grew well under all light treatments and produced plug plants after 6 weeks. Plug plant size and quality was greatly influenced by light treatment (Figure 31 and Figure 32). The plant-to-plant differences observed in the pansy plants grown in this experiment were greater than those observed in the other species examined. This was because the pansy seeds were a mixed seed batch rather than a single genotype. However, the differences seen with different light recipes were large enough to identify treatment effects. The lowest quality plants were produced under the 100% blue light treatments, as these plants were etiolated and had the fewest leaves (Figure 32A). The differences in quality between the other treatments were largely associated with total plant size, with the largest fastest growing plants observed under the 11% blue light treatment. The slowest growing and most compact plants were observed under the 58% blue light treatment.

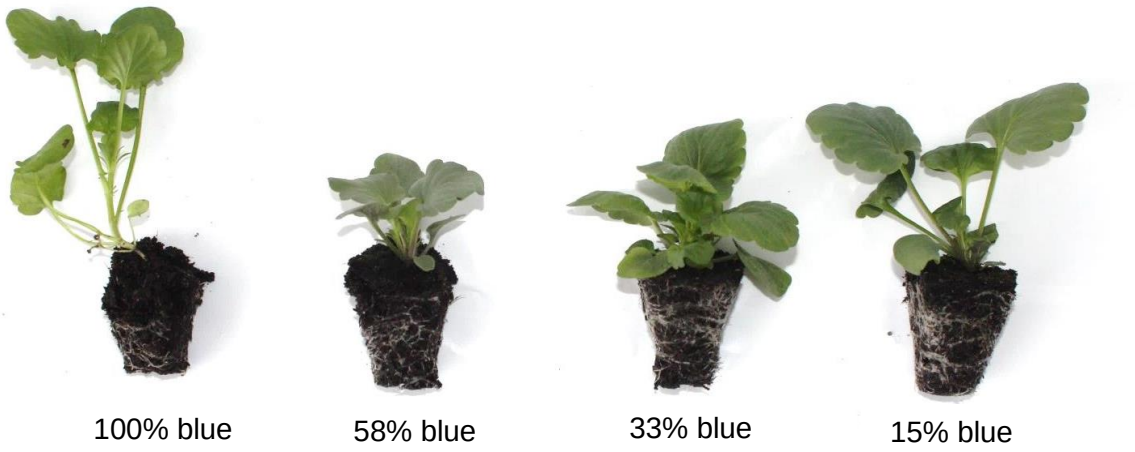


Figure 31. Representative pansy plug plants grown under four different red blue light treatments after 42 days growth.

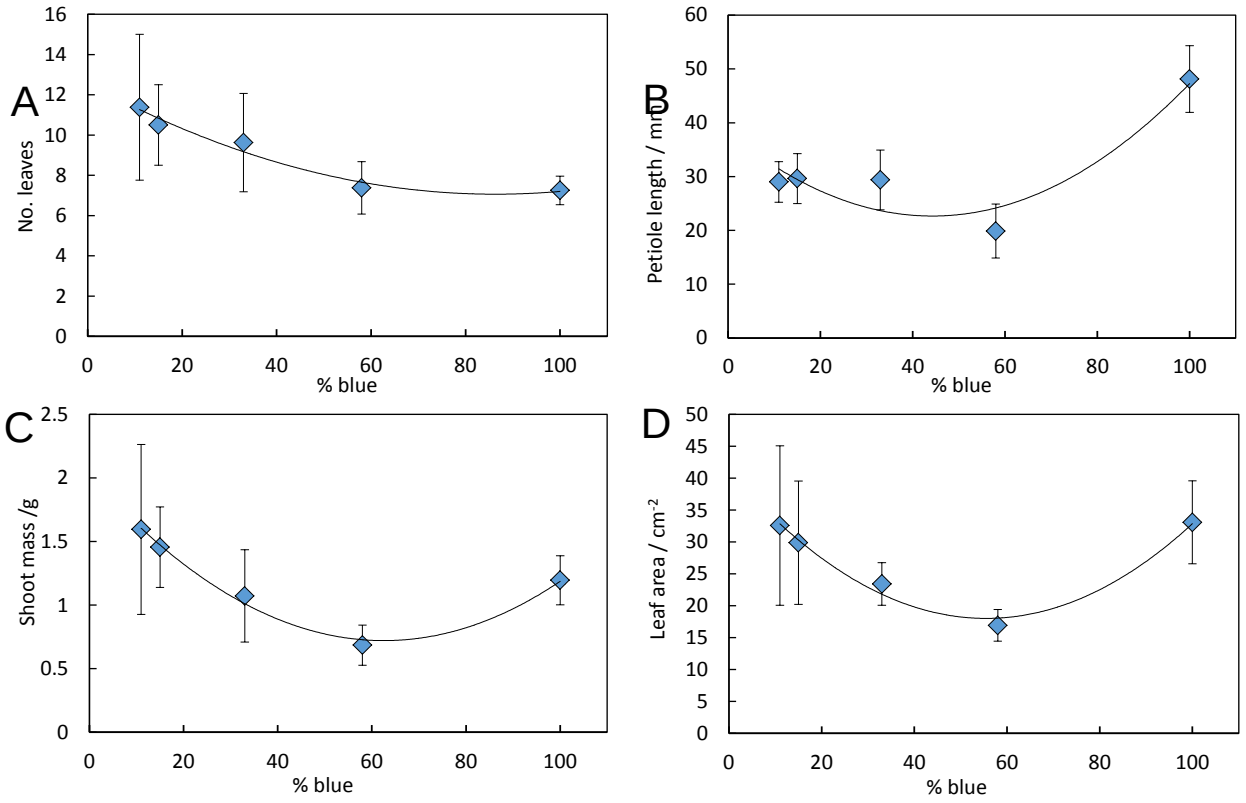


Figure 32. The influence of blue light percentage on **A)** the number of leaves, **B)** the petiole length, **C)** the total shoot mass, and **D)** the total leaf area of pansy plug plants.

After transplanting, the pansies continued to grow well, with the overall differences in plant quality and morphology persisting through the life of the plants (Figure 33). The plants grown under 100% blue light remained etiolated with internodes being almost 10 times greater than the internodes of plants from the other treatments (Figure 34). Stem diameter was observed to increase between 11 and 33% blue light but remained similar at greater blue light percentages. The number of side shoots was least in the 100% blue light treatments and greatest in the 15% blue light treatment. Light treatments also influenced flowering time and intensity. Flowering occurred earliest and most extensively in pansies grown under 100% blue light (Figures 35 and 36). Flower production was similar in the 11 and 15% light treatments and was slowest and similar for the 33 and 58% blue light treatments.

Figure 33. Images of pansy plants from the different red:blue light treatments at two stages of growth showing the influence of light quality on A) vegetative growth after 52 days and B) flowering after 73 days growth.

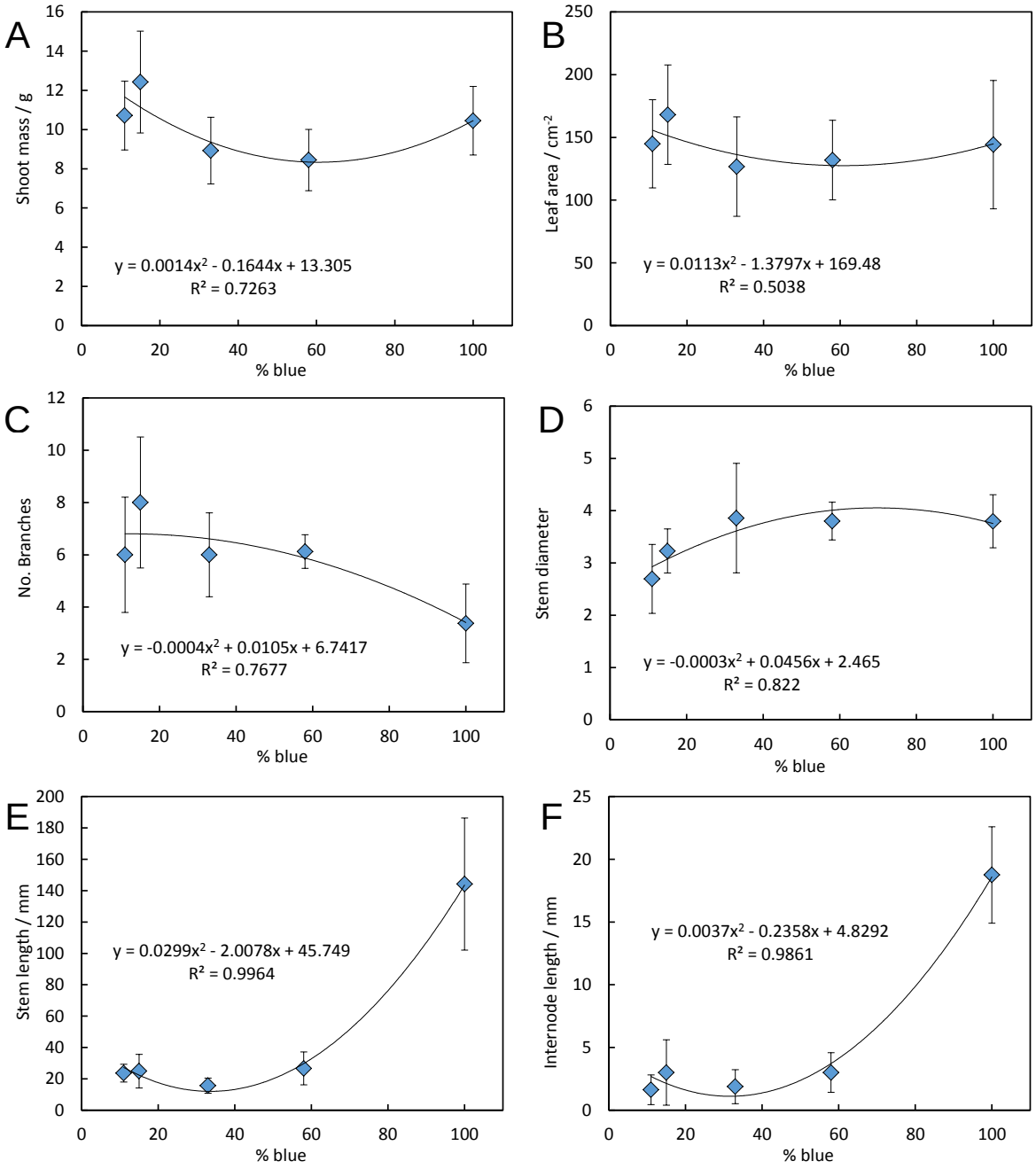


Figure 34. The influence of red:blue light treatments on the A) shoot mass, B) leaf area, C) number of branches, D) stem diameter, E) shoot length, and F) internode lengths of pansy plants at final harvest.

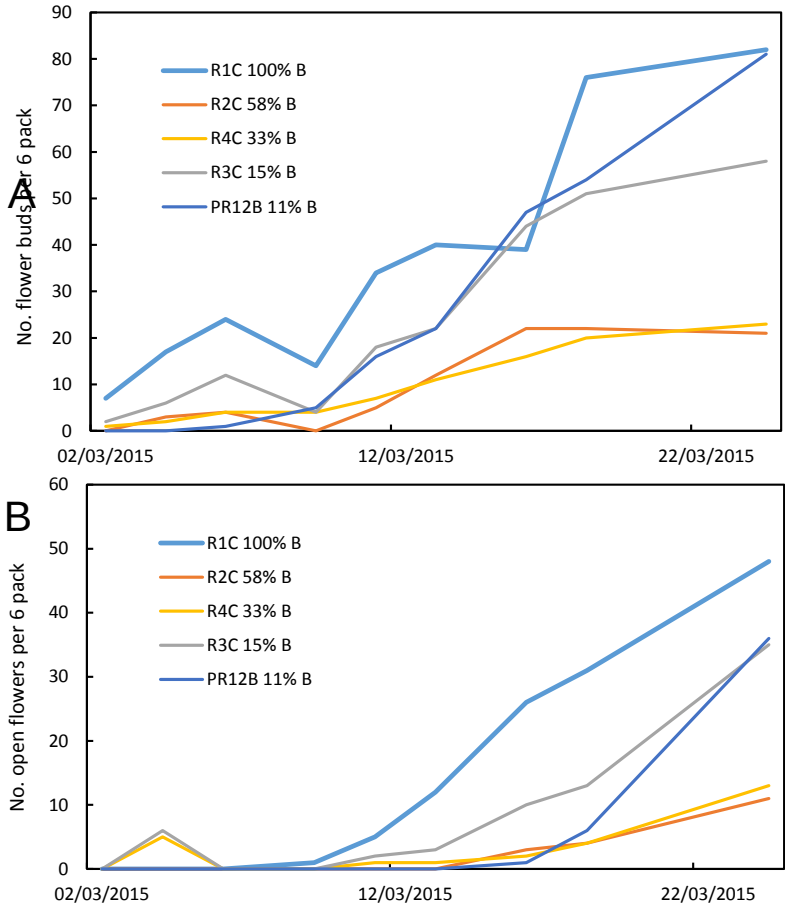


Figure 35. Time courses of production of A) total visible flower buds (including buds, open flowers and seed heads) and B) open flowers by pansy plants grown under the different red blue light treatments

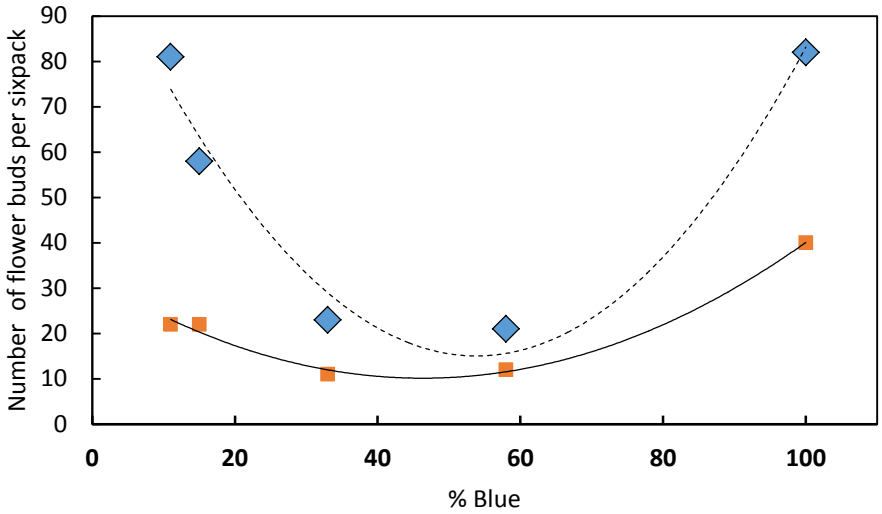


Figure 36. Effect of red blue light treatment on the total numbers of flowers produced by pansies grown under the different blue light percentage treatments on two dates: 13th March 14 (orange symbols) and 24th March 2014 (final harvest; blue symbols).

Begonia

Begonia seedlings grew slowly compared with the petunia and pansy seedlings sown at the same time, but plug plants were of sufficient size for transplanting after 11 weeks (see Figure 37). The smallest plug plants were produced under the 58% blue light treatment and the largest under the 15% blue light treatment. Unlike the other bedding plants, the begonia plug plants grown under the 100% blue light treatments did not become significantly etiolated and overall morphology was similar to the other light treatments.

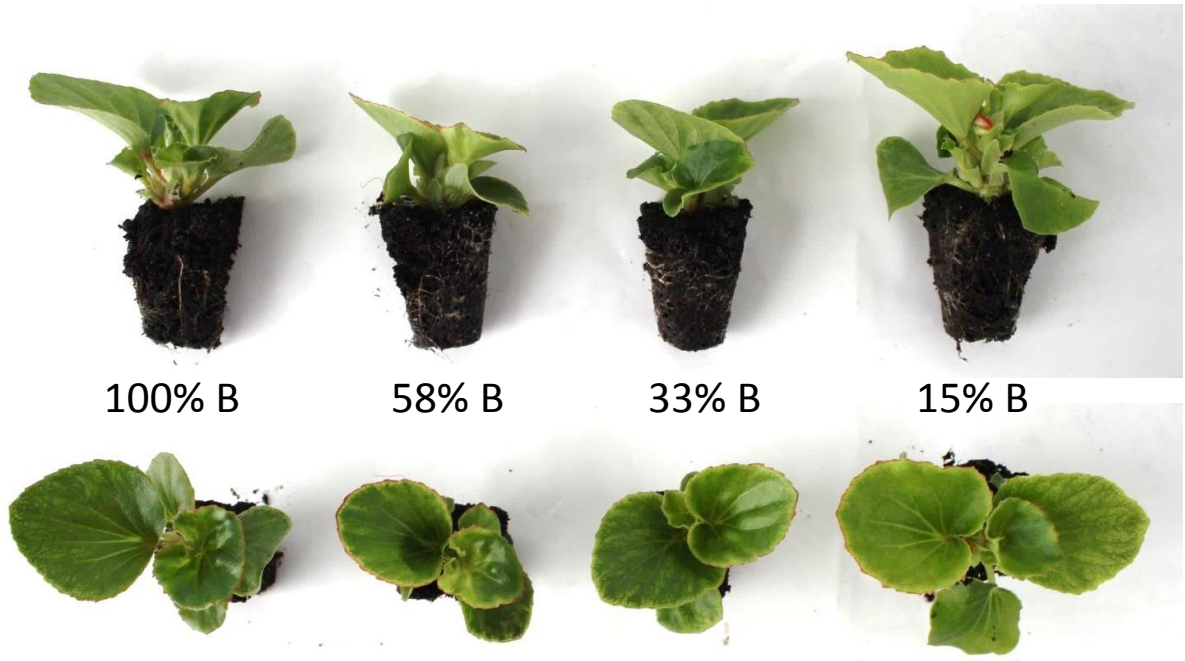


Figure 37. Images of the begonia plug plants from the different red:blue light treatments after 52 days growth.

After potting-up, the plants continued to grow well. The 58% light treatment produced the smallest and most compact plants (Figure 38). The plants from the 100% blue and 15% blue treatments had a similar appearance but, on closer inspection, there were significant differences. Shoot mass and leaf area were found to decrease with an increase in blue light percentage (Figure 39). Neither parameter showed a significant increase between 58 and 100% blue light. Leaf size was unaffected by light treatment (data not shown) but petiole length was found to increase as blue light percentage increased. Internode and petiole lengths were found to increase with an increase in blue light percentage, indicating an increase in etiolation. The fewest branches were observed in the 100% blue light treatment. The primary and secondary stem lengths were shortest in the 33% blue light treatment.

Primary stems were longest in the 100% blue light treatments, but secondary stems were a similar length in the 100% blue and 11% blue light treatments. While the secondary shoots in these two treatments were similar, the 100% blue treatment had fewer leaves per stem. The light treatments also affected flowering in the begonia plants. Flowering occurred earliest and most extensively in the plants grown under the 100% blue light treatment (Figures 41 and 42).

Figure 38. Photographs of the begonia plants showing the influence of red:blue light treatments on A) vegetative growth after 58 days and B) flowering after 86 days growth.

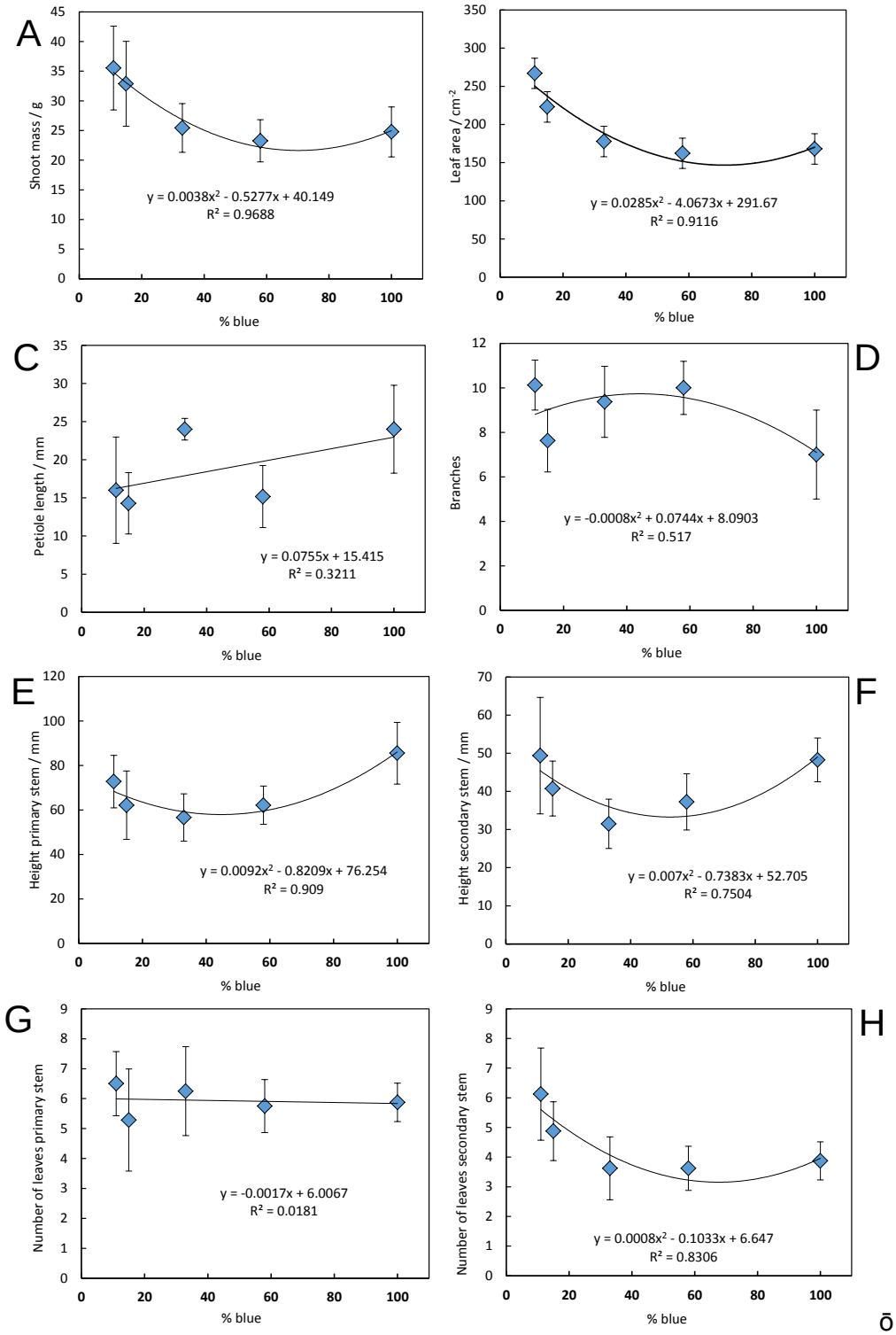


Figure 39. The influence of blue light percentage on **A)** shoot mass, **B)** total leaf area, **C)** petiole length, **D)** number of branches, **E)** length of the primary shoot **F)** the length of the longest secondary shoot, **G)** number of leave of the primary stem, and **H)** the number of leaves of the longest branch in begonia plants grown under the different red:blue light treatments.

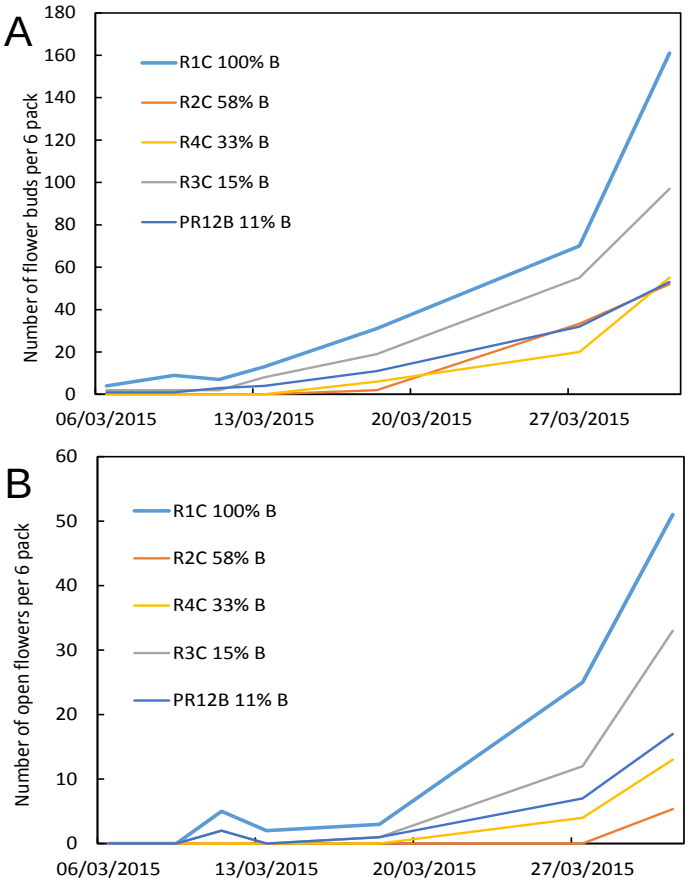


Figure 40. Time courses of begonia flower development under the different red:blue light treatments. A) Total number of flower buds. B) Number of open flowers.

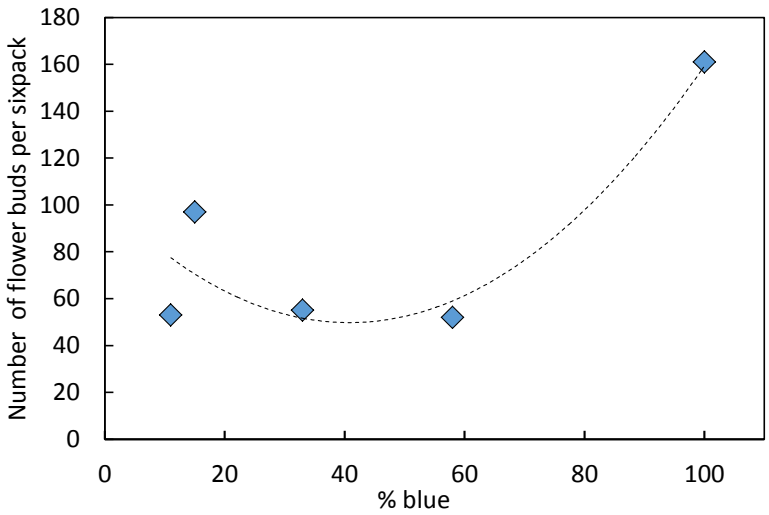


Figure 41. The relationship between blue light percentage and number of flower buds on begonia plants grown under the different light treatments.

Pelargonium

The pelargonium plants grew well and produced healthy flowering plants after 10 weeks (Figure 43). Overall plant appearance was similar for the plants grown under light treatments between 15 and 66% blue light, though the plants were smallest in the 66% treatment and largest in the 15% blue treatment. For the plants grown under the 100% blue light treatments, the petioles were extended and the leaves were cupped upwards when viewed from the side. Some differences in leaf pigmentation were also visible, with the deepest red leaves occurring under the 66% blue light treatment. Plant dry mass was found to decrease as blue light percentage increased to 66% blue, but then remained similar at 100% blue light (Figure 44). Leaf area was observed to decrease with increasing blue light. Internode length was found to decrease as blue percentage increased towards 66% but then increased as blue percentage increased to 100%, with these internodes being similar in length to those observed in the 11% blue light treatment. When the leaf-to-stem dry mass ratio was determined, the greatest relative investment in leaf material was achieved in the 66% blue light treatment while the 11% and 100% blue treatments had a similarly low investment in leaf compared with stem.

Figure 42. Images of pelargonium plants grown under the four red:blue light treatments. Images taken 11 weeks after sowing.

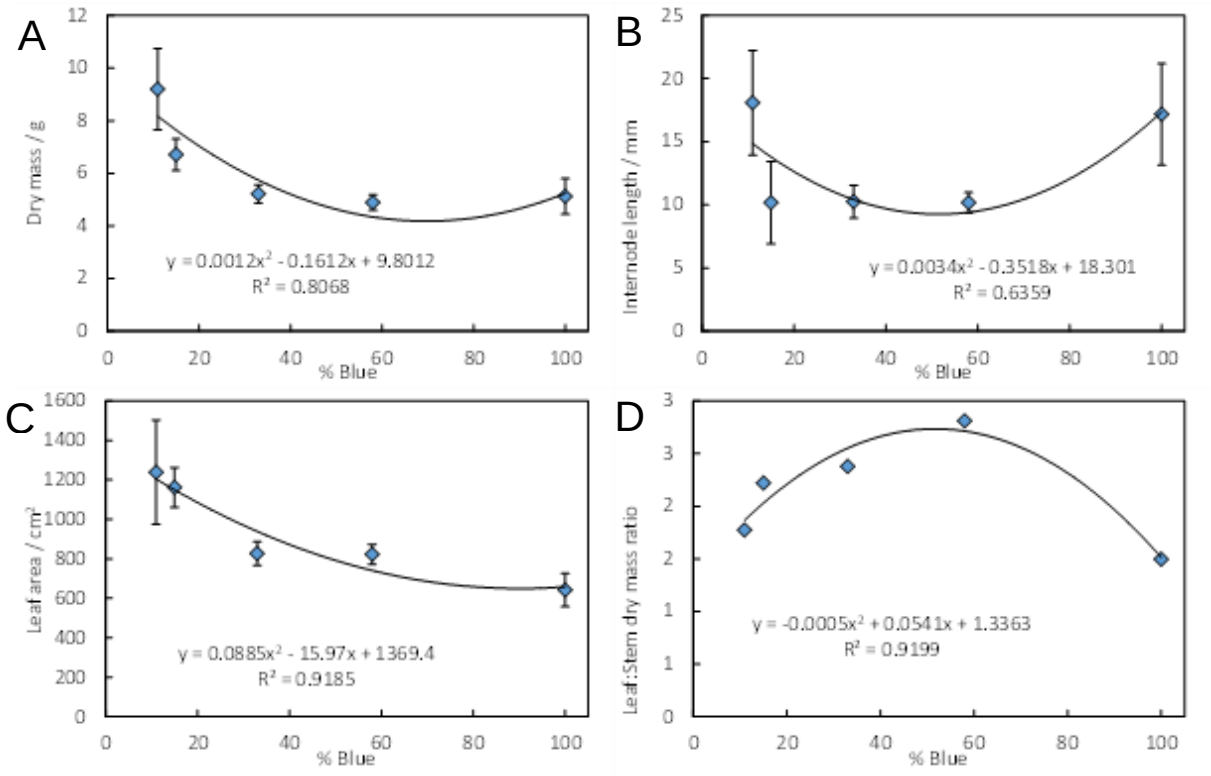


Figure 43. The influence of blue light percentage in red:blue light treatments on the **A)** dry shoot mass, **B)** the internode length, **C)** the leaf area, and **D)** the leaf to stem dry mass ratio of pelargonium plants.

Photosynthesis measurements were performed on the plants grown under the different red:blue ratios. Measurements were performed using the light source contained within the Licor 6400 change head, so any differences in photosynthetic responses are associated with differences in physiological state resulting from growth under the different light treatments rather than from direct influence of the different light treatments. The light response curves of the four different set of plants were very similar (Figure 45), with all treatments achieving a maximum photosynthetic rate at about 600µmol m^{-2} s^{-1}. Maximum photosynthetic rates (P_{max}), light limited photosynthesis (alpha), and respiration rates (R) were found to be unaffected by the light quality under which the plants had been grown.

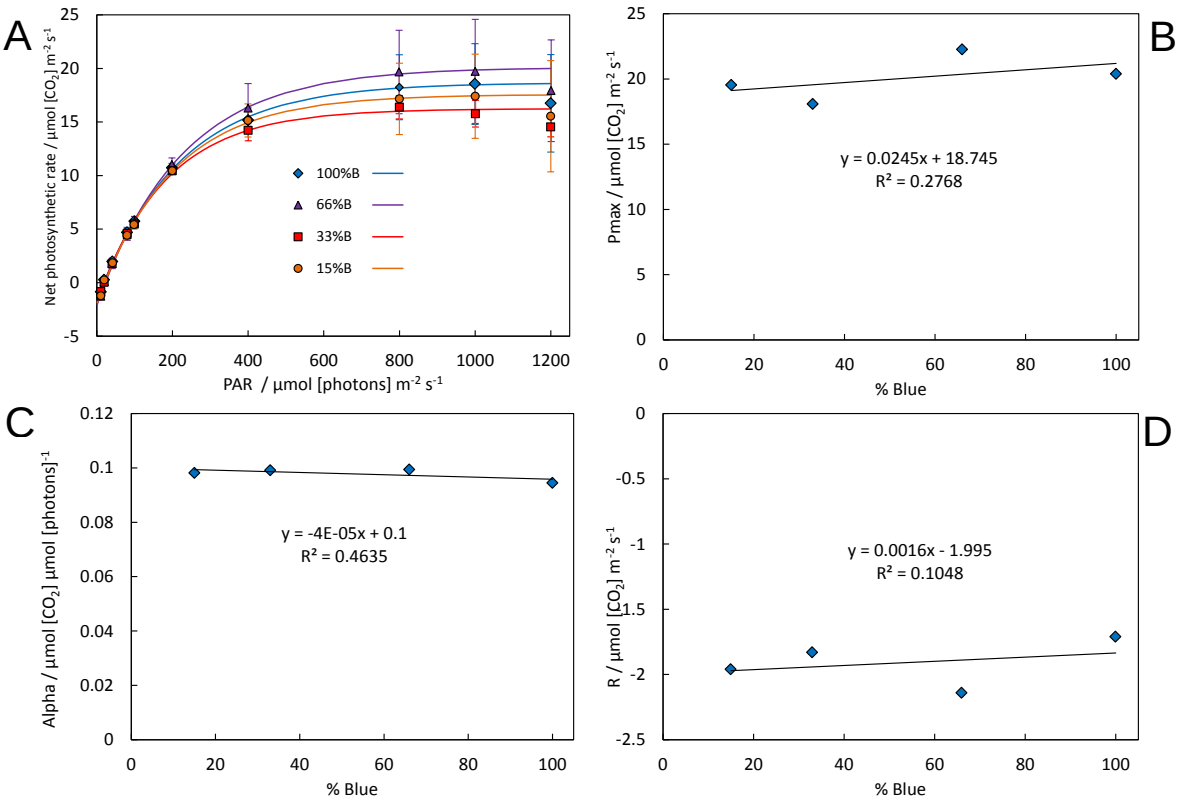


Figure 44. **A)** Net photosynthetic light response curves of pelargonium plants grown under five different light treatments. The influence of blue percentage (% blue) on **B)** maximum gross photosynthetic rate (P_{max}) and **C)** the slope of the net photosynthesis curve in light limiting conditions (Alpha). **D)** The measured respiration rate in darkness.

Discussion WP 2.1b Influence of red / blue ratio on plant growth

The differences in plant mass between the species considered in these experiments were large but the trends in response to light quality were similar. In all cases, the greatest plant masses were observed under the 11% or 15% blue light treatments, and mass was found to decrease as the blue percentage increased to ~60%. This decrease in biomass has two potential causes: 1) lamp photosynthetic efficiency, and 2) blue light induced growth regulation. Plants are able to use red light more efficiently than blue light so the proportion of light that can be converted to biomass decreases as the blue light percentage increases. Blue light also functions to restrict plant growth, resulting in small leaf areas and stem lengths. This sort of growth restriction will reduce light capture and, therefore, photosynthetic activity and growth. Both factors may be functioning simultaneously. There was greater variation between species in the response to 100% blue light treatments. Some species showed further decreases in biomass, some had similar biomass, and others showed an increase in

biomass. This variation provides some insight into the different mechanisms influencing the growth of the different species. In cases where biomass decreases following the transition to 100% blue light, growth rates are likely to be strongly related to the photosynthetic performance under that light regime. In cases where the biomass increased following transition to 100% blue light, there is likely to be some growth regulation/restriction associated with red light and the phytochromes. In fact, the 100% blue light treatment influences the phytochromes in a similar way to the addition of far-red light and causes plant stretching (see morphology data). If this is the case, then it is expected that plants that show a significant increase in biomass under 100% blue light will also exhibit an increase in biomass in response to far-red light. Plants that exhibited little change in mass following the transition to 100% blue light may be influenced equally by both photosynthetic performance changes and loss of phytochrome growth restriction.

Based on the discussions above, the transition from 11% to 0% blue (100% red) may also be expected to result in an increase in biomass because red light drives efficient photosynthesis and there would be reduced blue light growth restriction. This, however, was not the case and biomass production under 100% red light decreased significantly. This is because the blue light regulates several important light responses that improve photosynthetic performance. These include stomatal opening, leaf flattening, leaf positioning, and pigment synthesis, all of which combine to promote light capture and utilisation thus boosting crop growth.

Several morphological parameters were measured in the different species examined. There were differences in the responses between species but also between the different parameters within a species. These differences are thought to be associated with the different factors that regulate growth of different parts of the plants. Some parameters will be associated with photosynthetic carbon gain (and even feedback on photosynthetic carbon gain such as leaf area) while others will be controlled by one type (leaf position – phototropins) or multiple types of photoreceptor (internode length – UVB, blue, and red:far-red photoreceptors). Differences between species and even varieties of the same species may be associated with different sensitives to different regions of the spectrum. This factor is highlighted by the two lettuce varieties. Summer varieties have been selected over many generations for phenotypes that are appropriate for high summer light conditions and this may have led to a lower sensitivity to blue light intensity than in winter varieties. Conversely, winter varieties may have undergone selection processes that may have increased sensitivity to blue light.

Whatever the causes of the differences in growth rate and morphology of plants grown under the different light treatments, the findings demonstrate the potential for using light treatments to replace the use of plant growth regulators. Plant morphology was most compact in plants

grown under ~60% blue light, though growth rates and flowering were delayed in these plants. Crop growth was fastest under the 11-15% blue light, though these plants were less compact and, depending on the species, would potentially require PGR use to maintain sufficient compactness. In most cases, it would be possible to grow good quality plants with light treatments containing somewhere in the region of 11-66% blue light depending on the needs of the production system. One exception to this was Cucumber, where stem elongation of the plants was limited under all the light treatments, resulting in a plant that was perhaps too compact. While the 100% red and blue light treatments provide some interesting insights into crop light responses there are few examples where crops would be of sufficiently high quality if grown solely under these extreme treatments. There is, however, the possibility that adding red or blue light alone could benefit glasshouse production by adding additional growth regulation (blue light) or additional PAR to power growth (red light). The application of these light treatments would, however, need to be restricted to daylight periods when the sun is providing both red and blue light, as loss of control of morphology was observed under those extremes.

The flowering responses of the ornamental plants comprised perhaps the most striking differences seen between treatments. Light quality altered both the timing of flowering and the extent of flowering. 100% blue light treatments were observed to promote flowering, with these treatments producing large numbers of flowers and prompting the beginning of flowering at least one week prior to the other treatments. This promotion of flowering is related to the effect blue light has on phytochromes, which are important at regulating the transition from vegetative to reproductive growth. While the plants flowered early, the morphology of the plants was poor, particularly for petunia and pansy. After the 100% blue treatment, the 11 and 15% blue light treatments were the next to flower, and these also produced large numbers of flowers. The light treatments that produced the most compact plants (33 and 66% blue) were also the slowest to flower and produced the lowest numbers of flowers. The cause of this was not the same for the three species examined. In the petunia the differences in the flowering between the treatments (not including the 100% blue treatment) appeared to be associated with the mass of the shoot (larger plants produce more flowers). For the pansy and begonia plants, the number of flowers was not related to mass of the shoots and was possibly caused by some direct influence of the light treatments on development.

Results WP 2.1c Influence of red /far-red ratio on plant growth.

Protected edible plants

Basil

The basil plants grown under the four far-red light treatments (0, 15, 30 and 45 µmol m^{-2} s^{-1} of far-red) grew at a similar speed and had similar morphology. Far-red had very little

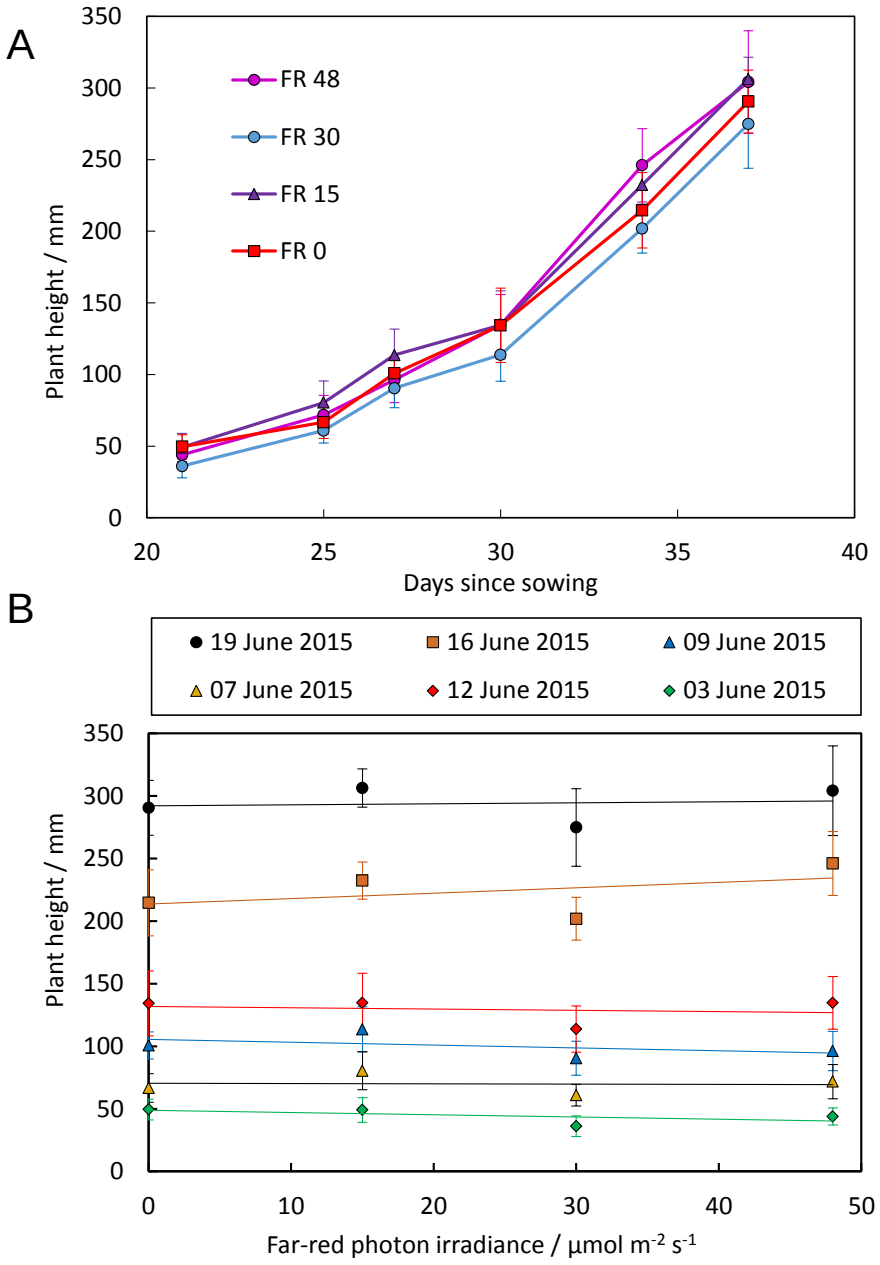


Figure 45. **A)** Time course of basil plant height measurements for plants grown under different far-red light treatments. **B)** The influence of far-red light intensity on plant height at the different sampling dates

influence on plant height at any stage of growth during this trial (Figure 46). Internode length and plant mass were unaffected by the light treatments (data not shown). The leaf-to-stem partitioning was slightly affected by the far-red treatments, with the greatest investment into leaves occurring in the 15 μmol m^{-2} s^{-1} far-red treatment (Figure 47). The lowest investment in leaves and greatest investment in stem was observed in the 45 μmol m^{-2} s^{-1} far-red treatment.

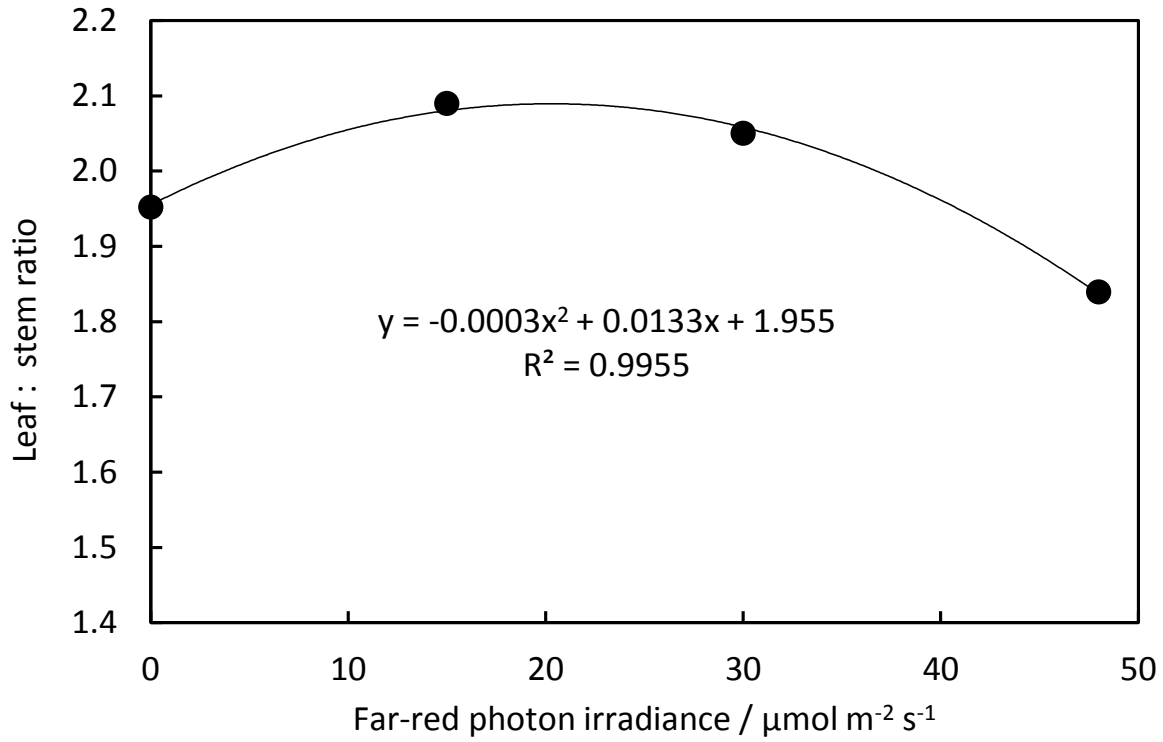


Figure 46. The influence of far-red light on the leaf to stem biomass partitioning of basil plants.

Sage

The sage plants were found to have a weak response to the addition of far-red light. The plants grown under no far-red were the shortest plants throughout the experiment (Figure 48). While the presence of far-red light resulted in an increase in plant height, the growth stimulus was not observed to be dose dependent: *i.e.*, increasing the far-red intensity from 15 to 48 μmol m^{-2} s^{-1} resulted in no additional growth, indicating that the far-red effect is saturated below 15 μmol m^{-2} s^{-1} in this species.

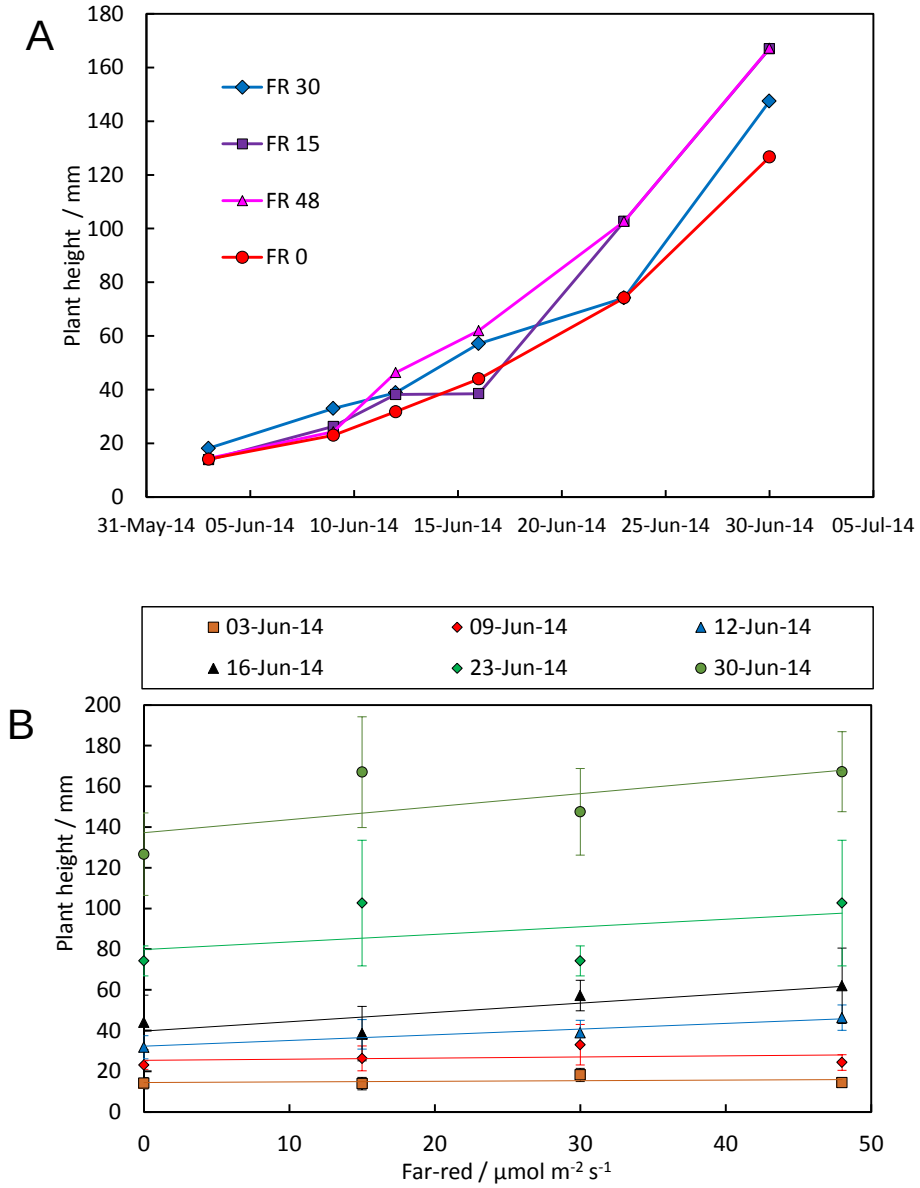


Figure 47. A) Time course of sage height measurements of plants grown under different red:far-red treatments. **B)** The influence of far-red intensity on crop height on the different sampling dates.

Cucumber

In contrast to the two herb species, Cucumber plants were very responsive to the far-red light treatments (Figure 48). Plant height was found to increase with far-red treatment, though plant size was found to be similar for the two highest far-red treatments (Figure 49A). The maximum size of the largest plants at the end of this experiment may have been slightly restricted because they used water very rapidly and suffered from mild water deficits. The mean lengths of internodes 3-5 were found to correlate linearly with the amount of far-red light present (Figure 49B). These internodes would have been produced prior to the plants

suffering from water deficits. Leaf size was also found to be larger in light treatments with a greater intensity of far-red light (Figure 49C).

FR = 30 FR = 15 FR = 0 FR = 48

Figure 48. Images of the Cucumber plants grown under different far-red treatments.

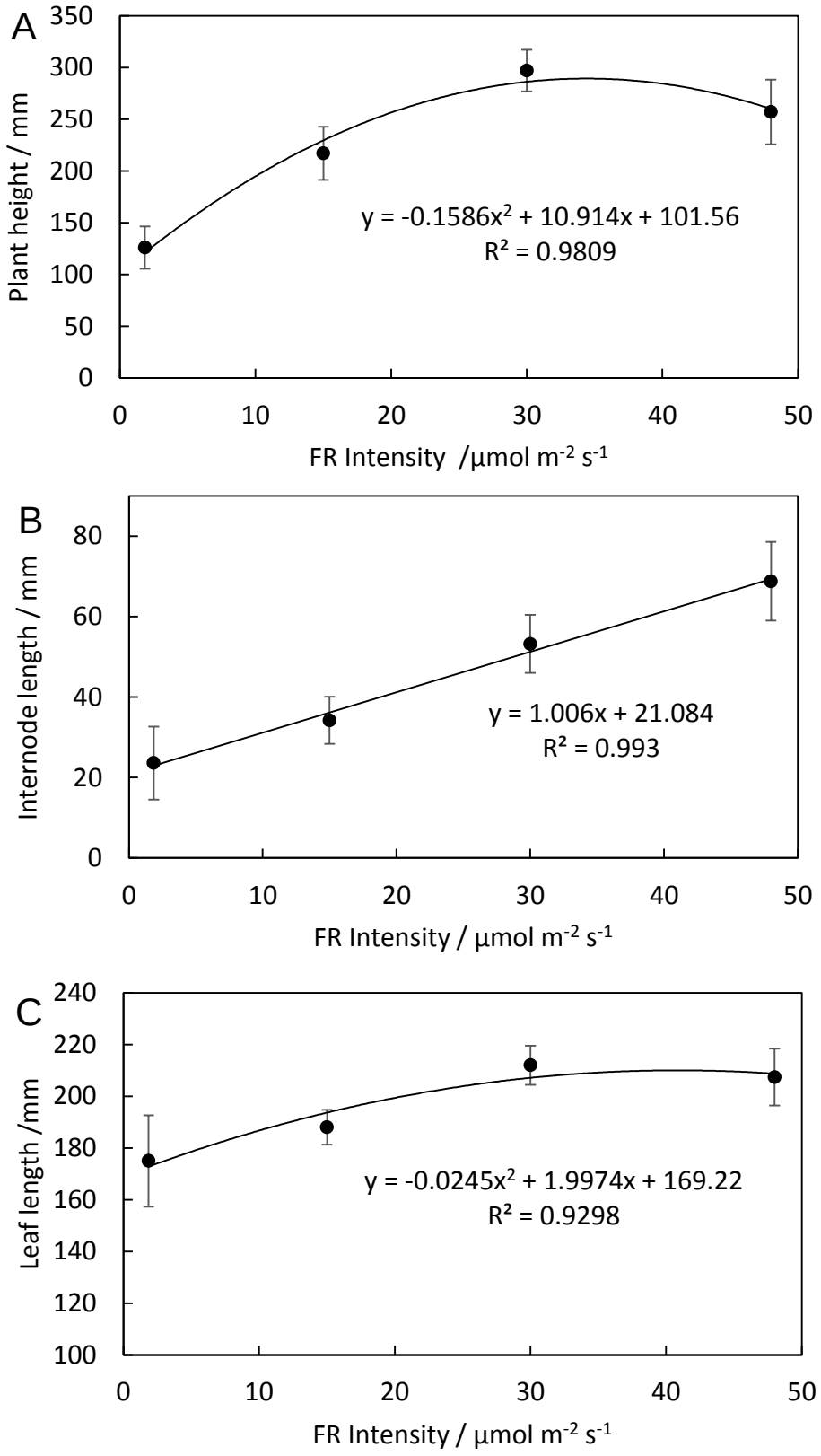


Figure 49. The influence of far-red light intensity on the **A)** plant height, **B)** internode length, and **C)** leaf size of Cucumber plants. Error bars indicate standard deviation.

Lettuce

The two lettuce varieties Amica and Alega were found to have different responses to the far-red treatments (Figure 50). The Amica leaves were found to have a small increase in leaf length as far-red levels increased while the Alega leaves were found to increase substantially as the far-red light intensity increased (Figure 51). Flattened leaf width of the Alega leaves, however, was found to be similar in all the far-red light treatments, while flattened leaf width in the Amica leaves increased slightly. The leaves of the Amica variety remained highly curled in all treatments and this response changed little with far-red treatments. Alega leaves were observed to be relatively flat in all treatments, though leaves were observed to be slightly flatter under the higher far-red treatments. While far-red intensity influenced morphology in these lettuce varieties, there was no influence on plant biomass accumulation (Figure 52). The Alega plants were almost twice the mass of the Amica plants in all light treatments.

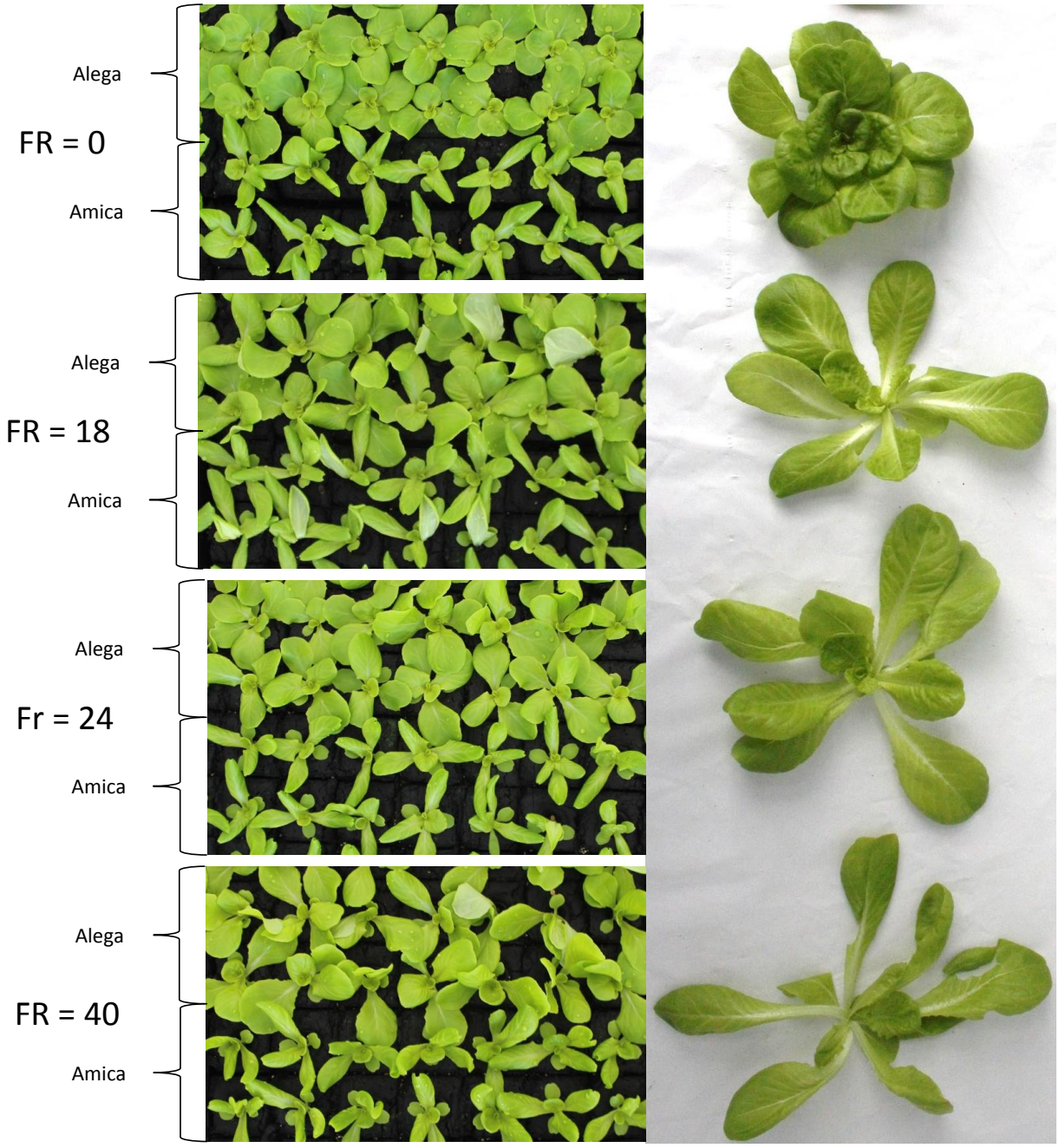


Figure 50. Images of the two lettuce varieties Alega and Amica when grown under lights with different amounts of far-red light. The close up plant images on the right show representative Alega plants from each light treatment.

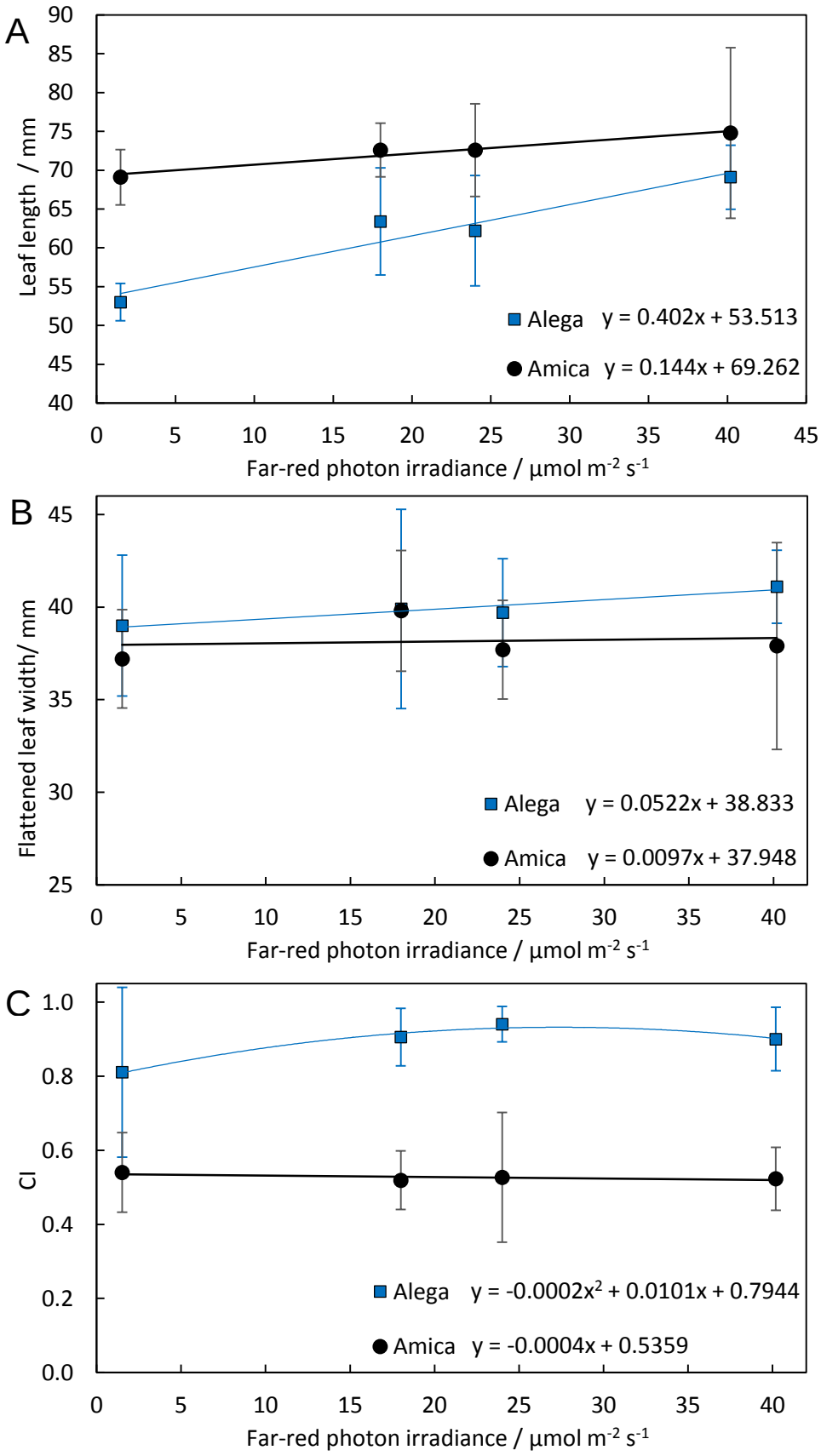


Figure 51. The influence of far-red light intensity on **A)** leaf length, **B)** flattened leaf width, and **C)** curling index (CI) in the two lettuce varieties Alega and Amica.

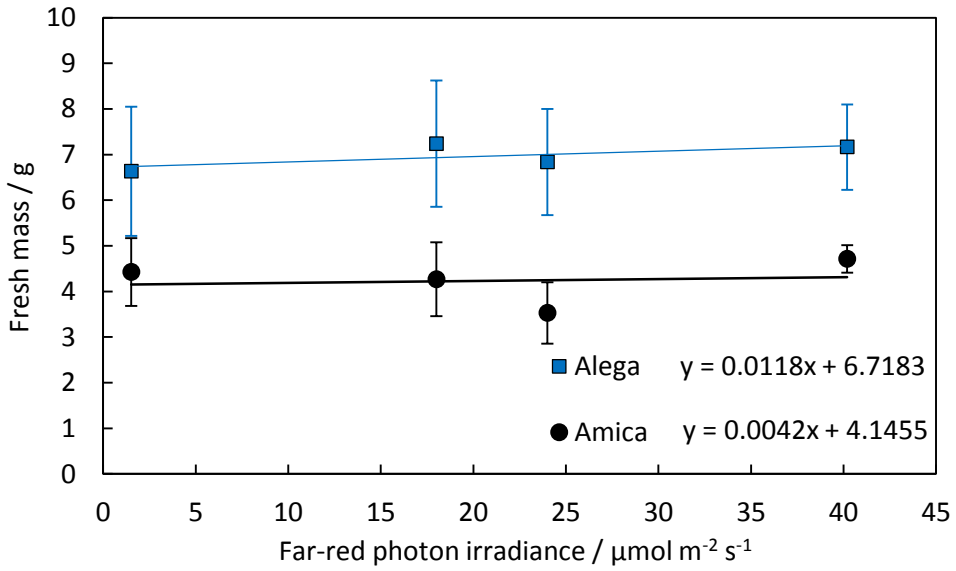


Figure 52. The influence of far-red light intensity on the biomass of the two lettuce varieties Alega and Amica. Error bars indicate standard deviation.

Protected ornamental plants

Petunia

The petunia plug plants (Figure 53) were similar in size in the four far-red treatments, though the plants in the no far-red treatment had shorter petioles and the leaves were held nearer to the substrate. The plants in the highest far-red treatment were slightly weaker plants than those in the other treatments. Once potted up, the differences between the treatments increased as the plants grew (Figure 54). Internode and main stem lengths increased linearly with increasing far-red intensity (Figure 55). As with the lettuce plants, far-red intensity had little influence on shoot mass. The number of side branches decreased rapidly in response to increasing far-red treatments, resulting in a leggy appearance. The plants in the no far-red treatment remained compact and produced many branches, but flowering was delayed by two weeks in comparison to the other treatments (Figure 56). In the far-red light treatment plants, total flower bud production occurred earlier and more intensely but the transition of bud to flowers was also promoted. In contrast to the influence of far-red on internode lengths, flowering was not observed to increase linearly in response to far-red light. Instead, far-red intensities of 15 µmol m^{-2} s^{-1} were sufficient to induce a maximum number of flowers (Figure 57). However, when the number of flowers produced per fresh mass of plant was determined, flower number was found to increase linearly with far-red intensity.

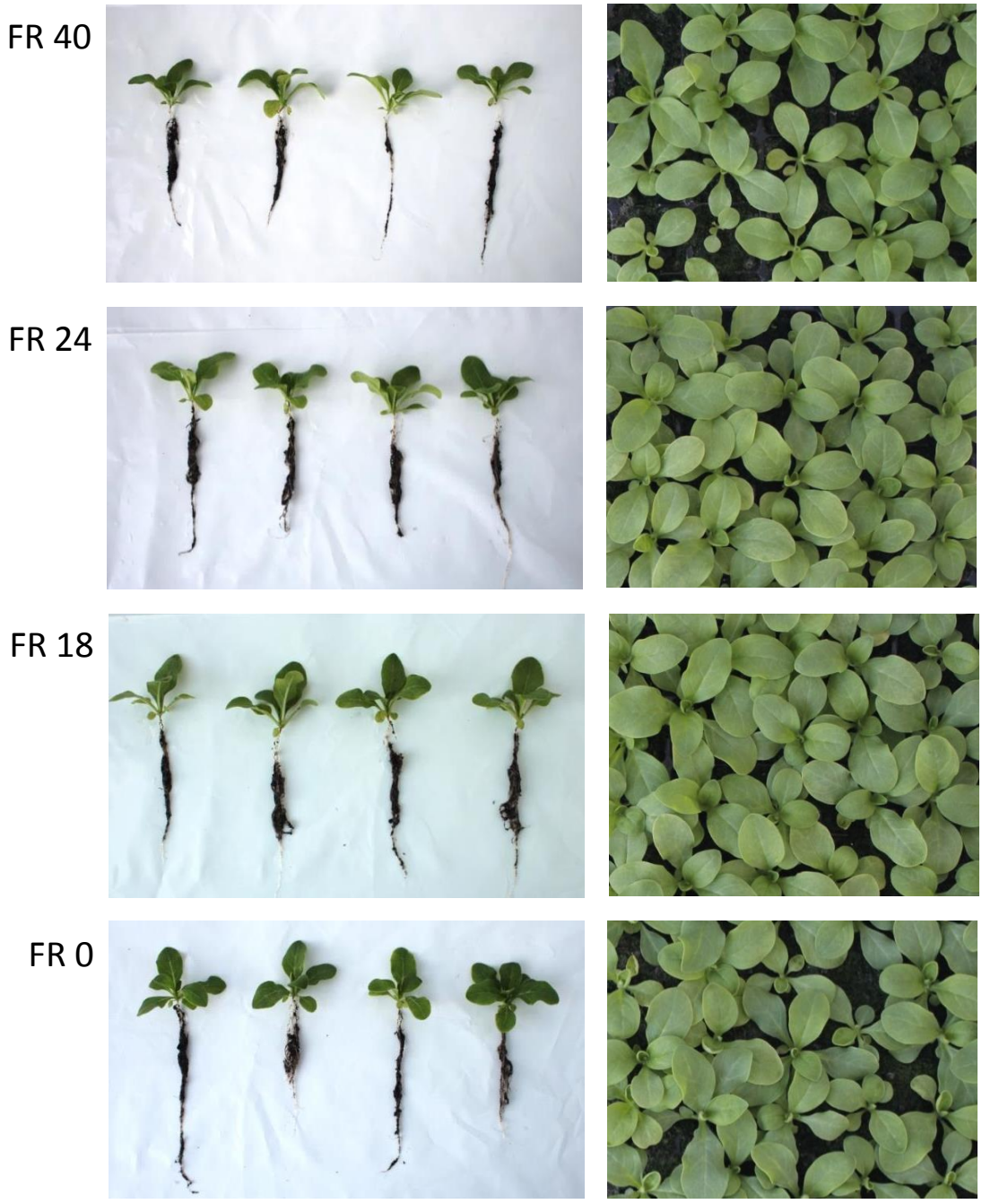


Figure 53. Images of petunia plug plants grown under light treatments containing different amounts of far-red (FR) light after 25 days growth.

Figure 54. Images of petunia plants at two stages of growth showing **A)** the influence of far-red light on vegetative growth after 42 days growths and **B)** the influence of far-red light on flowering after 52 days growth.

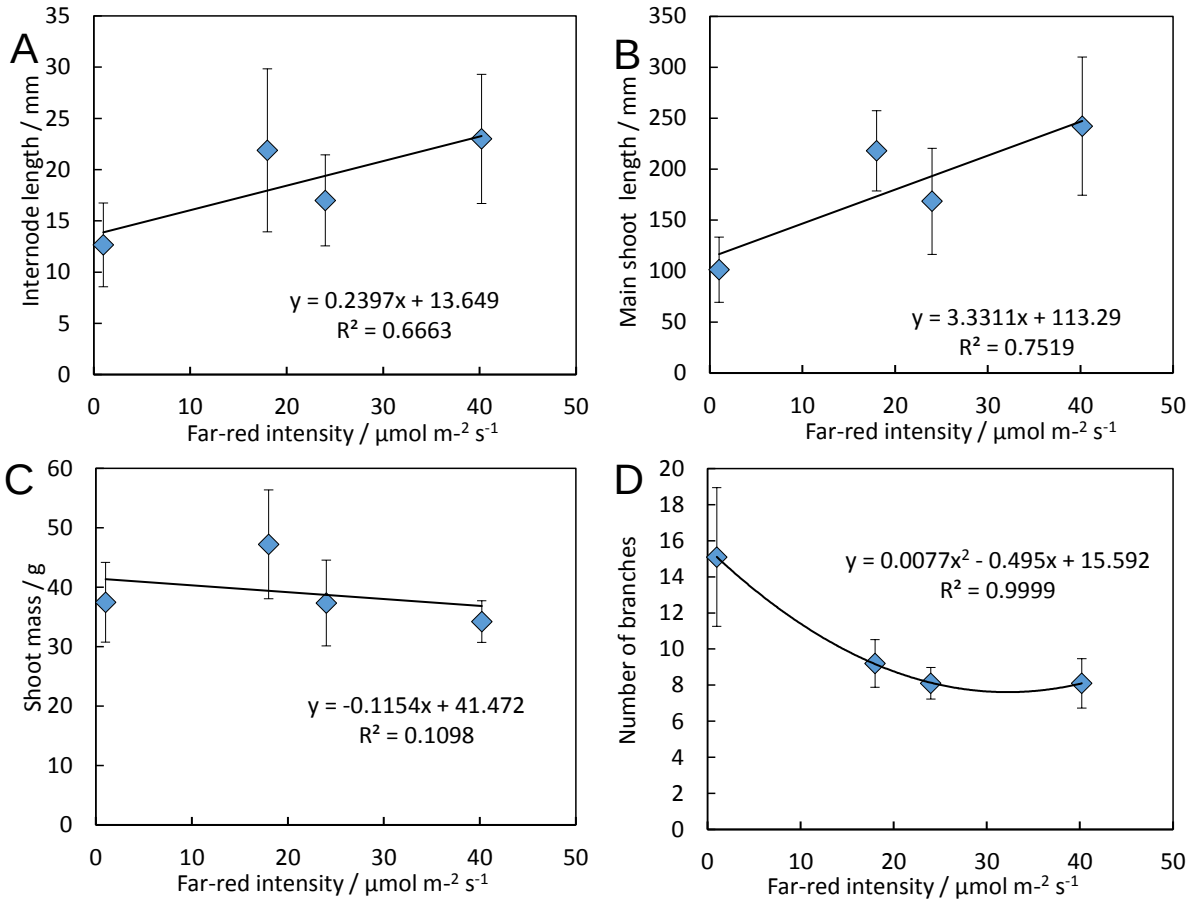


Figure 55. The influence of far-red light on the morphology of petunia plants. **A)** Internode length, **B)** length on primary shoot, **C)** total shoot mass, and **D)** the number of side branches per plant.

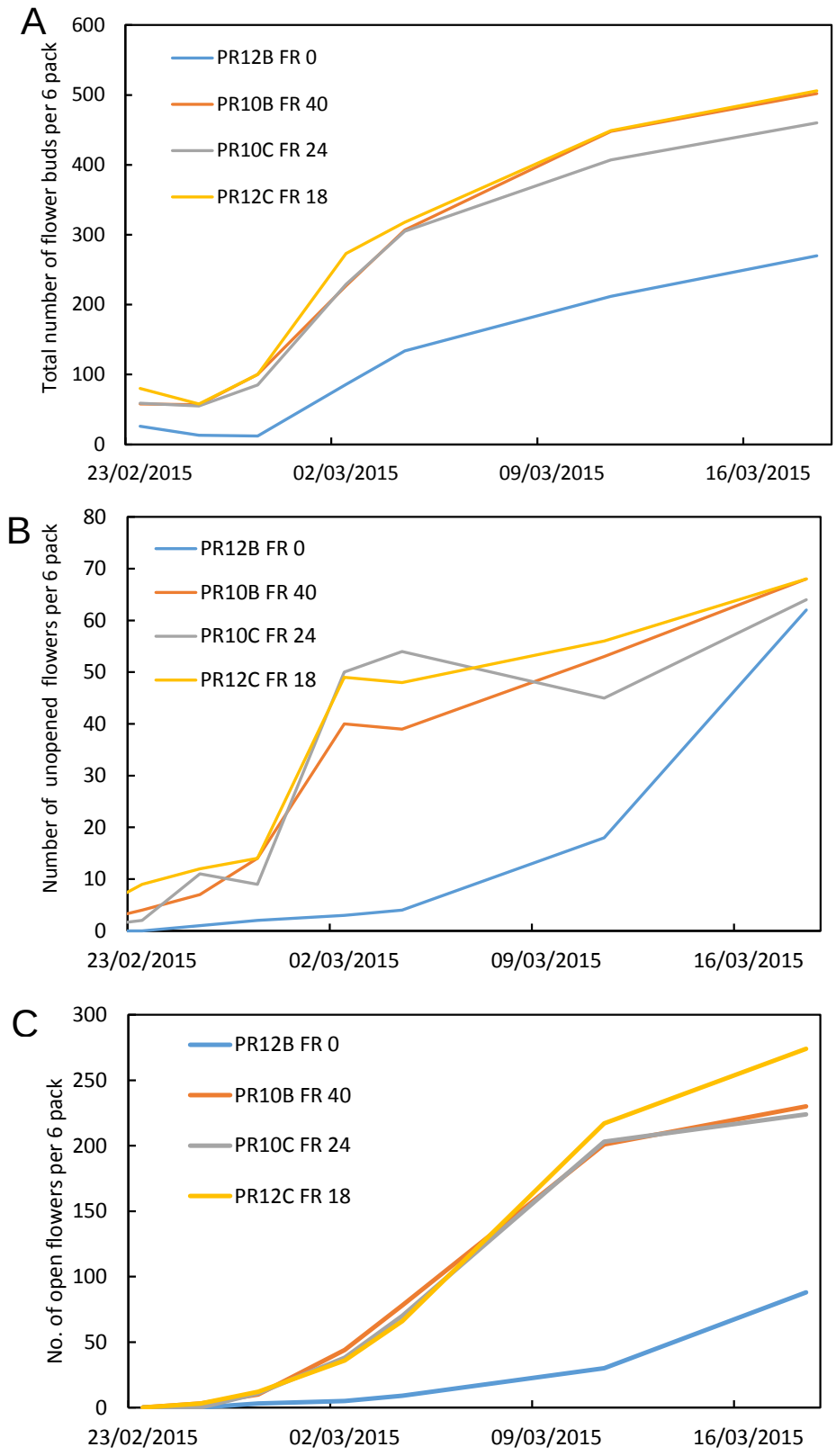


Figure 56. Time course of flowering of petunia plants grown under in the different far-red treatments. A) Total numbers of flower buds visible on the plants (this includes buds, open flowers and seed heads). B) Number of flowers between stages 4 and 6, see text for more detail. C) Number of open flowers.

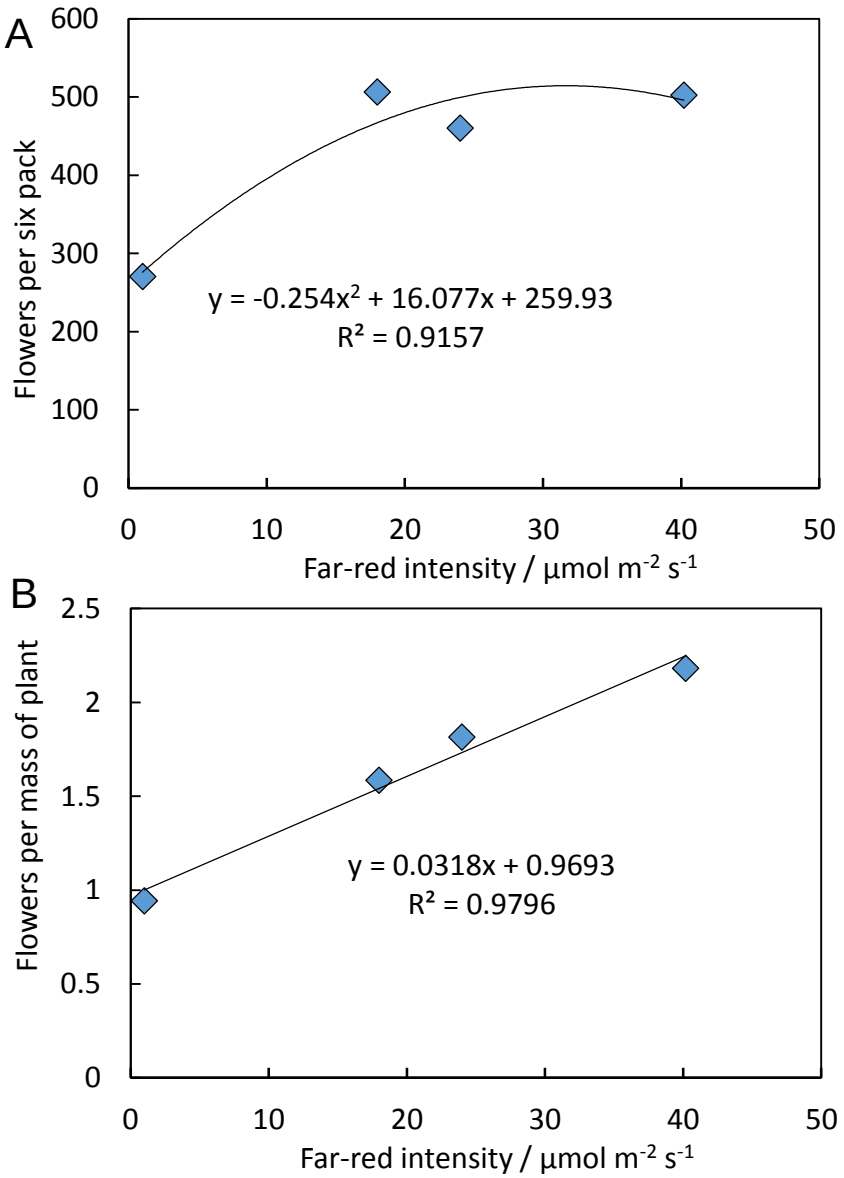


Figure 57. The relationships between far-red intensity and **A)** number of flowers per six pack of petunias and **B)** the number of flowers per mass of plant.

Pansy

Pansy plug plants were found to respond to increases in far-red light intensity by growing taller and producing less compact plants (Figure 58). Plug plants had a more robust appearance and structure when grown in the absence of far-red light. While the plants were taller and appeared larger when grown under the far-red light treatments, the number of leaves per plant was not influenced by far-red light (Figure 58). Petiole lengths were found to correlate linearly with amount of far-red light provided. Leaf area and shoot mass were found to increase as far-red increased, though these responses were saturated at far-red intensities of about 30 μmol m^{-2} s^{-1} (Figure 58).

After potting-on, the treatment differences were observed to persist and increase as the plants grew (Figure 59). The plants remained very compact when grown without far-red light and they remained compact even after flowering had commenced. At the end of the study, all morphological parameters (Figure 60) except the number of branches were observed to increase with far-red light intensity up to about 30 μmol m^{-2} s^{-1} but showed no change with further increases in far-red. Number of branches was not affected by far-red intensity.

Pansy flowering was greatly advanced by the addition of far-red light (Figure 61). In the presence of far-red light, flower buds were observed one week before they were observed on plants grown without far-red light. Open flowers were observed two weeks later on plants grown without far-red light. There was little increase in flowering as far-red increased from 18 48 μmol m^{-2} s^{-1} indicating that the flowering responses was far-red saturated. It is expected that smaller amounts of far-red would promote flowering and that these treatments would have less impact on plant morphology.

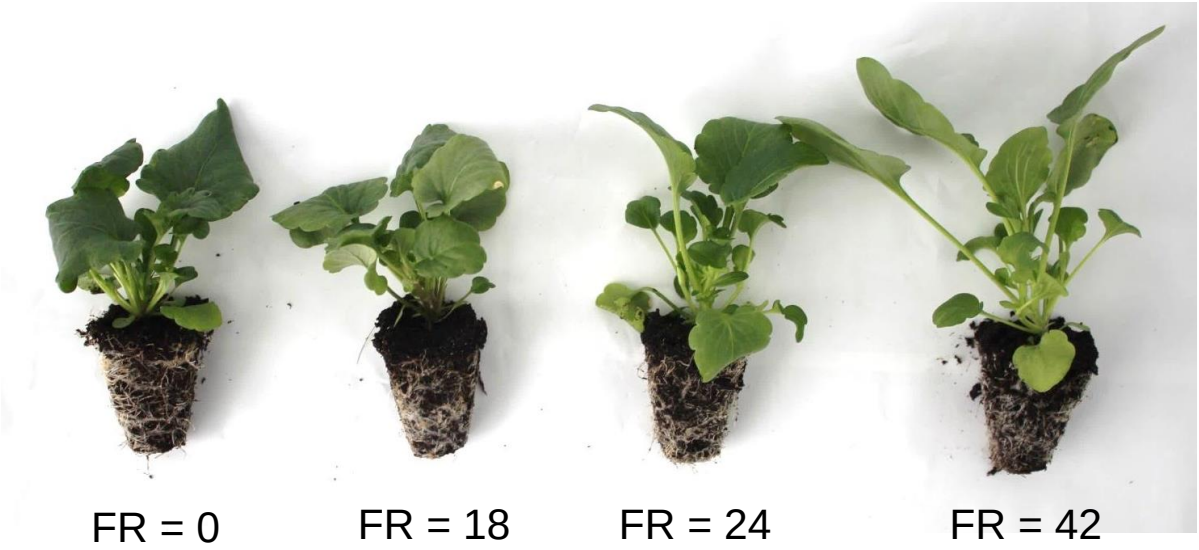


Figure 58. Images of pansy plug plants grown under different amounts of far-red light after 42 days growth.

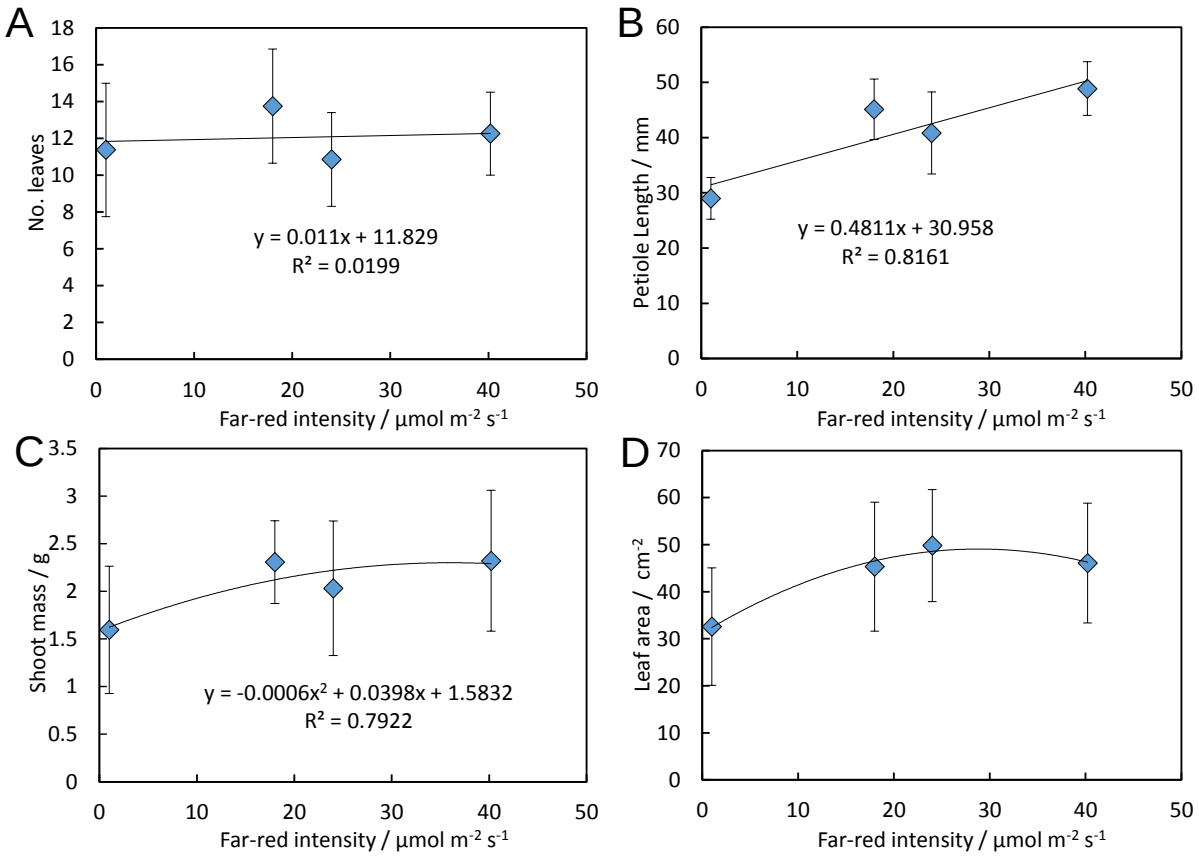


Figure 59. The influence of far-red intensity on pansy plug plant morphology **A)** number of leaves, **B)** petiole length, **C)** total shoot mass, and **D)** leaf area.

Figure 60. Images of pansy plants at two stages of growth showing the influence of far-red light on **A)** vegetative growth after 52 days and **B)** flowering after 73 days growth.

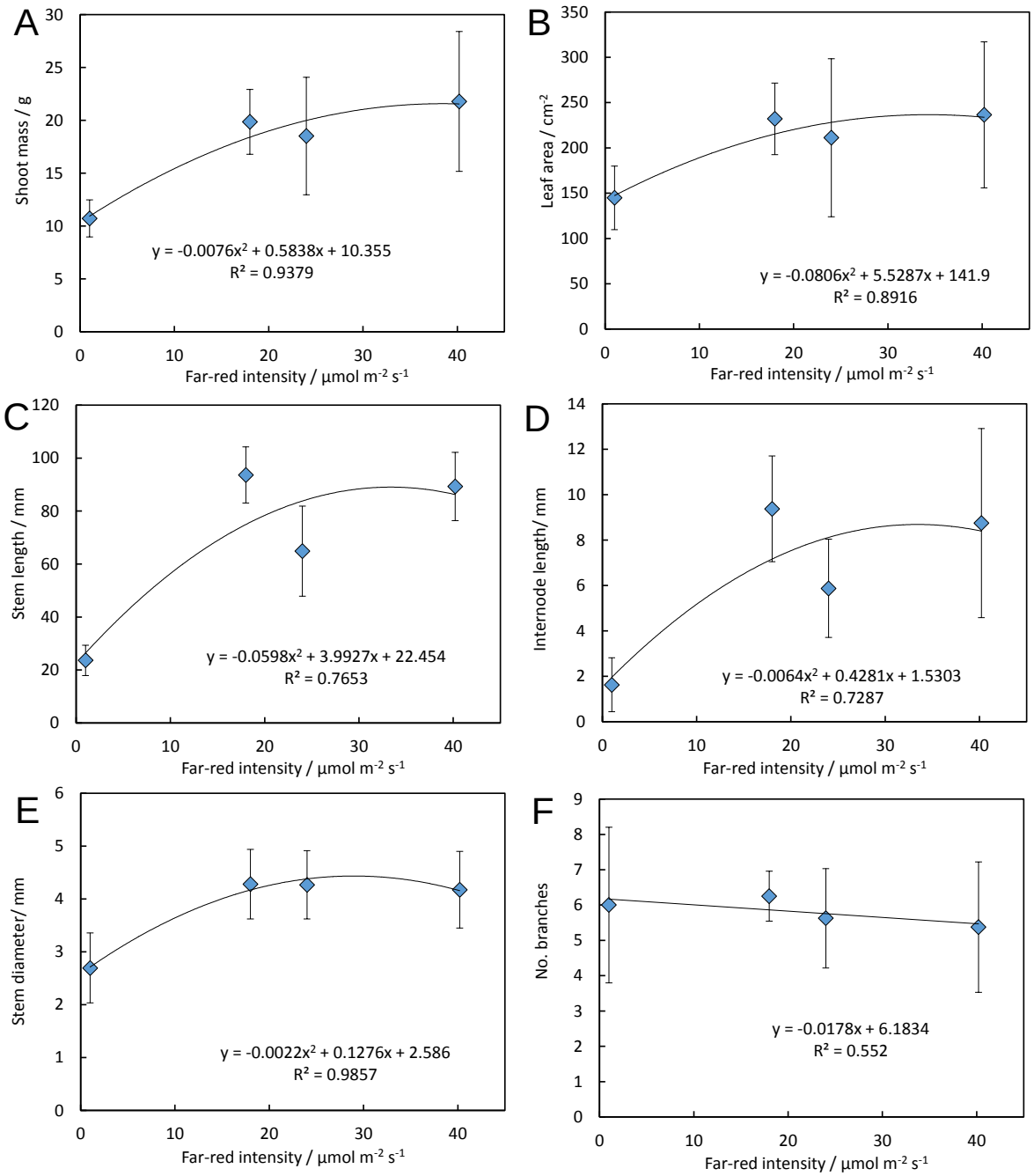


Figure 61. The influence of far-red light on the morphology of pansy plants at final harvest. **A)** Total shoot fresh mass, **B)** leaf area per plants, **C)** length of the primary stem, **D)** internode length, **E)** stem diameter, and **F)** number of branches.

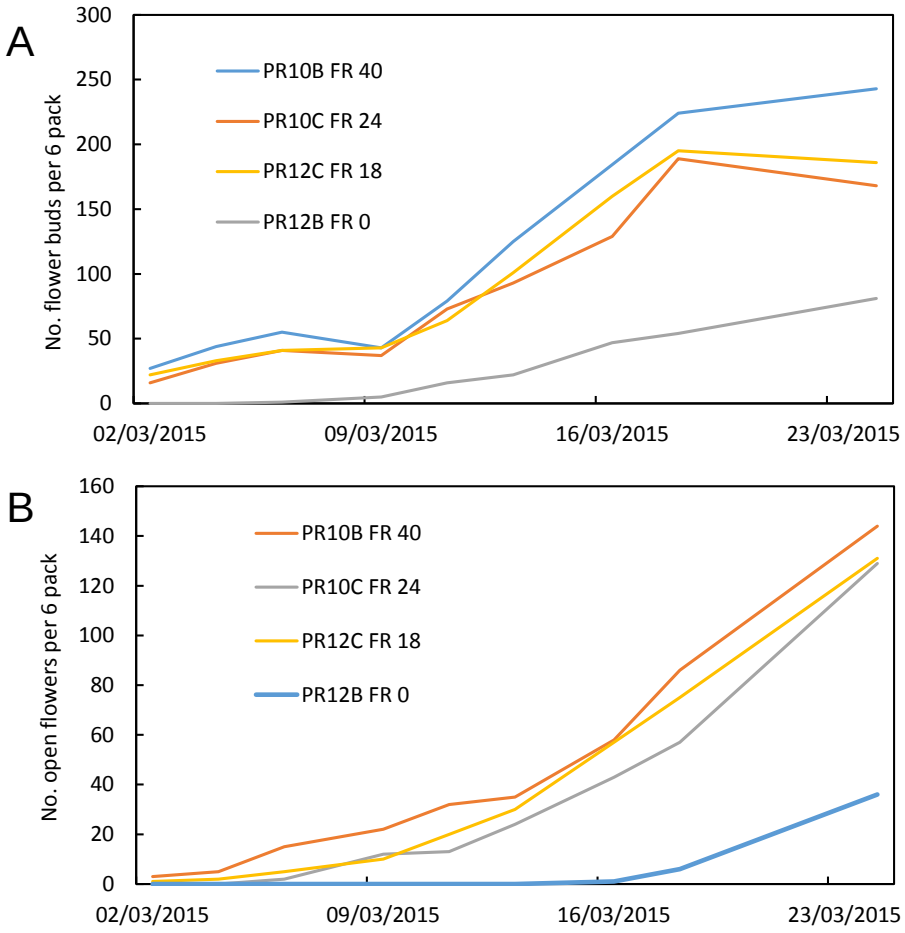


Figure 62. Time course of pansy flowering in plants grown under different far-red light treatments. **A)** Total number of visible buds and **B)** number of open flowers.

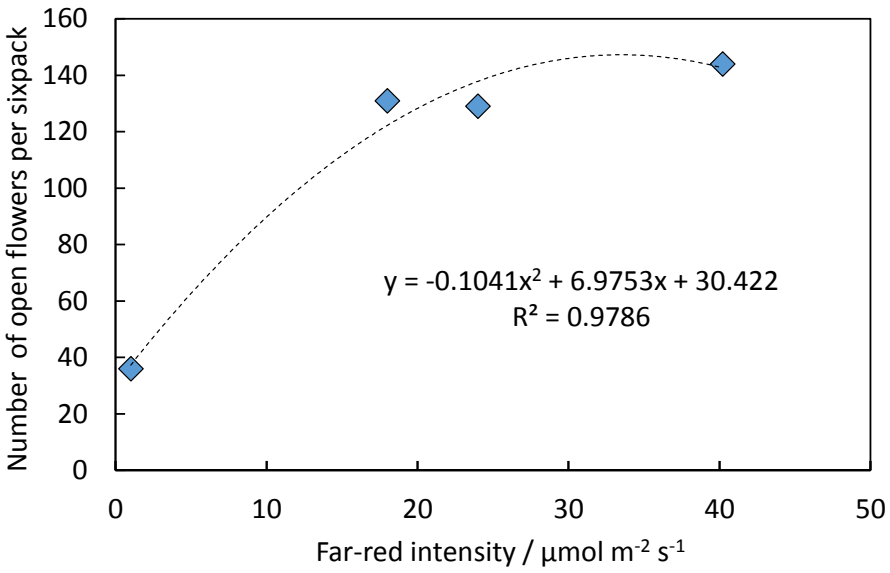


Figure 63. The relationship between far-red light intensity and number of flowers produced by pansies.

Begonia

The begonia plug plants were observed to grow slightly larger in the presence of far-red light (Figure 64), though these differences were small compared to those observed in petunia and pansy. Following potting-on, the plants grew more rapidly and treatment effects if anything reduced slightly (Figure 64). At the final harvest, the shoot mass was observed to decrease slightly as far-red intensity increased. In contrast to the other species examined, leaf area and leaf length were observed to decrease as far-red intensity increased (Figure 65). Under far-red intensities >30 μmol m- s^{-1}, petiole and internode lengths were observed to increase. Flowering was observed to commence at a similar stage in all the light treatments (Figure 66). However, two weeks after the first flowers were observed, flower number increased more rapidly in the light treatments containing far-red light. At the end of the trial, the no far-red treatments were approximately one week behind the other far-red treatments. The number of flowers was not observed to increase with far-red intensities between 18 and 40 μmol m^{-2} s^{-1}, indicating that the flowering response was saturated at a lower light intensity.

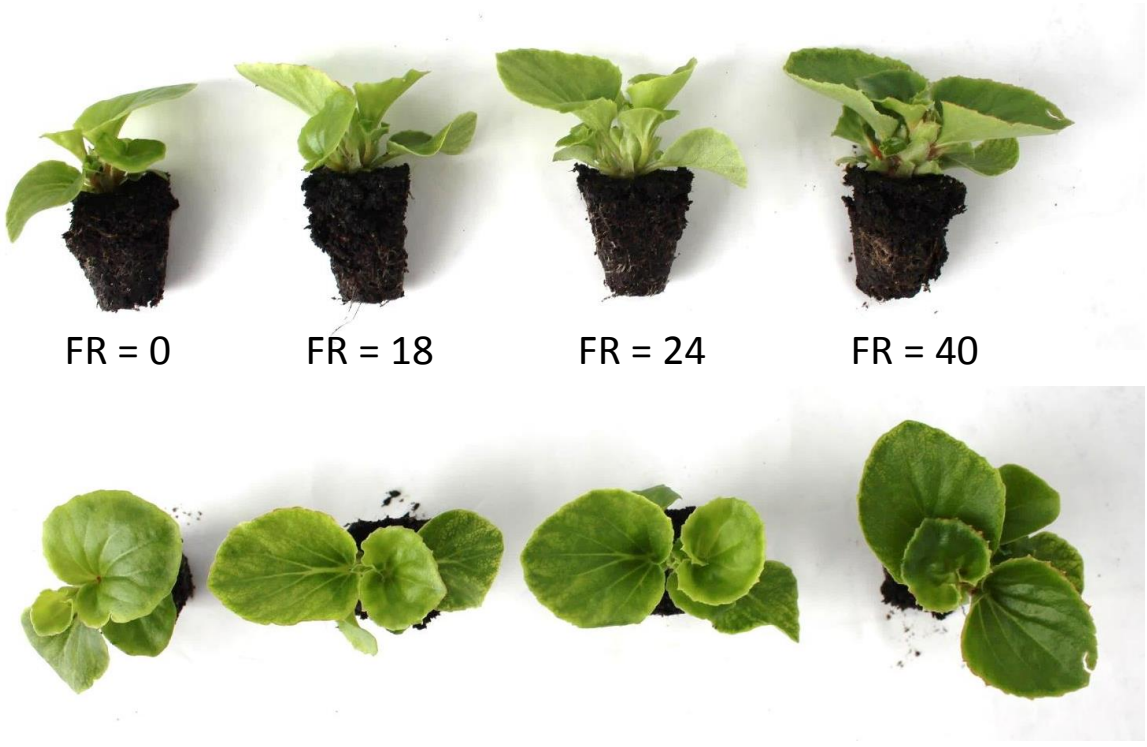


Figure 64. Images of begonia plug plants grown under different far-red light treatments after 52 days of growth.

Figure 65. Images of begonia plants grown under different far-red light treatments. Plants are shown at two growth stages to demonstrate the influence of far-red on **A)** after 58 days and **B)** flowering after 86 days growth.

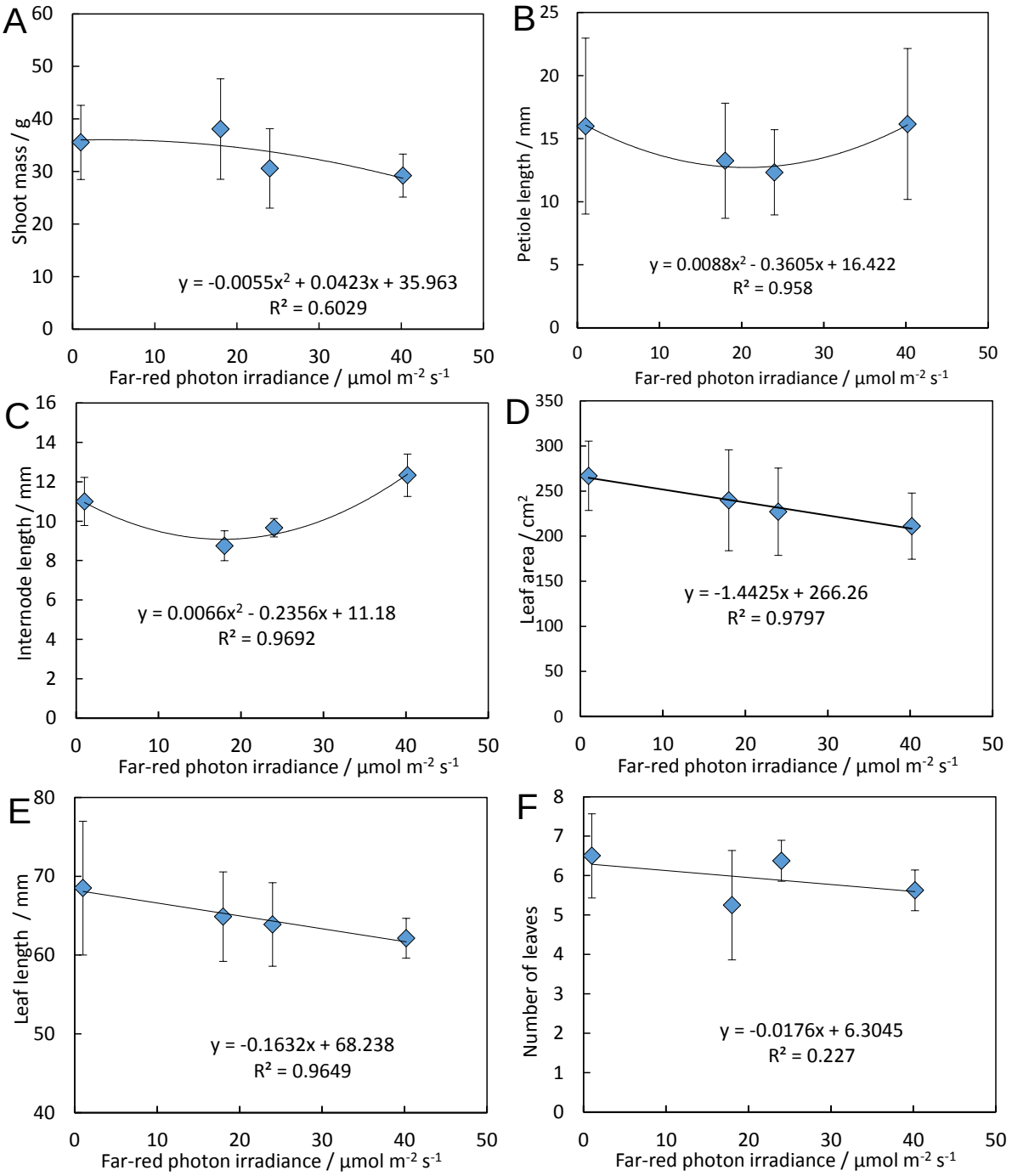


Figure 66. The influence of far-red light on **A)** shoot fresh mass, **B)** petiole length, **C)** internode length, **D)** total plant leaf area, **E)** mean leaf length, and **F)** number of leaves per begonia plant.

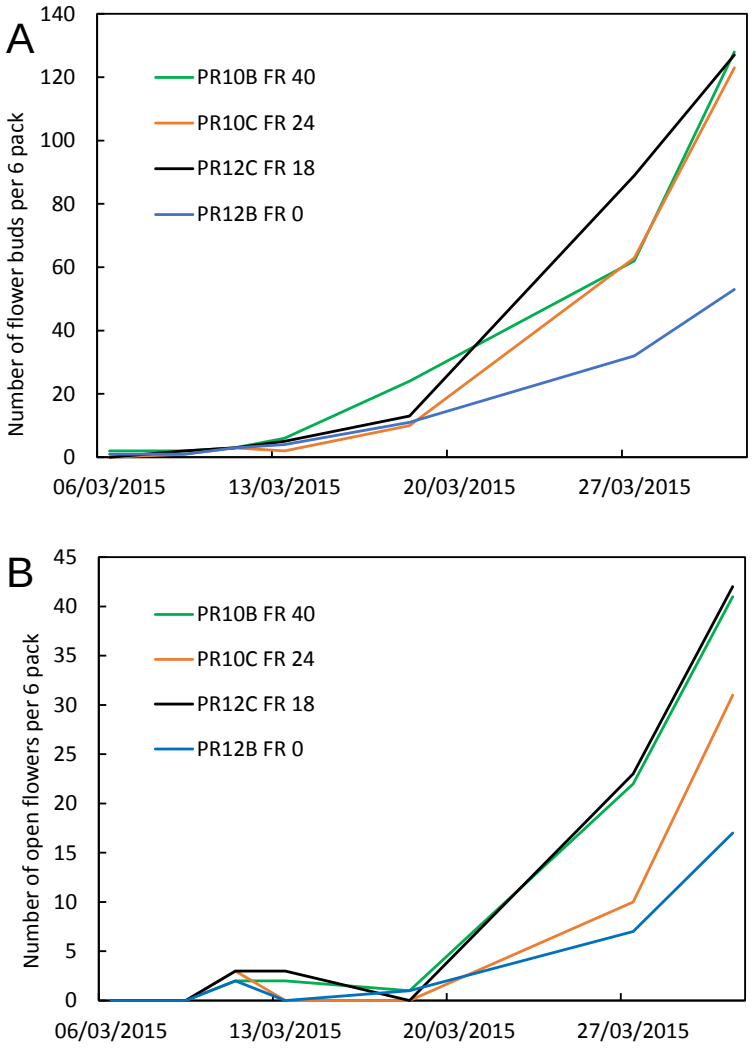


Figure 67. The time course of **A)** visible flower buds (includes developing buds and open flowers) and **B)** open flowers of begonia plants exposed to different far-red treatments.

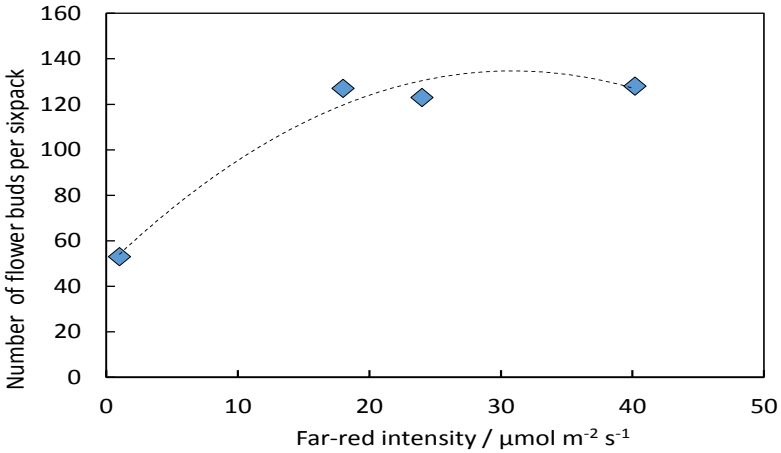


Figure 68. The influence of far-red light on total number of visible begonia flower buds.

Pelargonium

The pelargonium plants were slightly more compact in appearance when grown under the no-far-red treatment. This was most apparent when comparing the leaves near the top of the plant, where petiole extension was apparent in the high far-red treatments (Figure 69). Flowering occurred slightly earlier in the higher far-red treatments, and the flower stems were taller. The far-red treated plants were taller with longer internodes (Figure 70) and plant dry mass was also slightly greater.

Figure 69. Images of pelargonium plants grown under different far-red light treatments after 7 weeks growth.

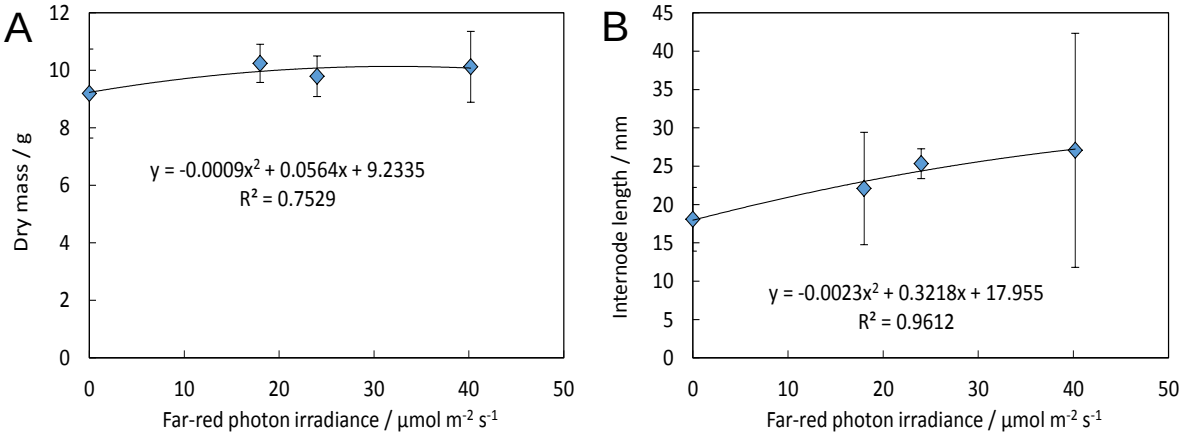


Figure 70. The influence of far-red light on A) the dry mass and B) the internode lengths of pelargoniums grown under different far-red light treatments for seven weeks.

Discussion WP 2.1.c Influence of red /far-red ratio on plant growth.

Far-red responses are mediated by phytochrome photoreceptors and are associated with shade avoidance syndrome and flowering initiation. There was considerable variation in the ways different plant species responded to the different far-red treatments. Some plants, such as basil, showed very little response to far-red while the others such as petunia and pansy showed extreme increases in stem elongation and enhanced flowering. The species-to-species differences observed in the far-red responses were similar to those seen in responses to 100% blue light treatments (see WP2.1b). Plants that showed enhanced far-red responses also showed exaggerated responses to 100% blue light treatments. This provides evidence that the responses observed under 100% blue light are associated with phytochrome signalling rather than a blue-specific response. This also provides the opportunity to identify which photoreceptors are imposing the greatest level of influence in the different species in these experiments.

These results not only provide useful information regarding the scientific basis for differences between plant species but also provide a better idea of which light treatments are likely to provide the best route for manipulating the responses of the different species. For example, removing far-red light from a basil production facility is unlikely to provide the same benefit as providing additional blue light. In contrast, removing far-red light from a petunia or pansy production facility is likely to reduce stretching but may delay flowering.

There were large differences in the sensitivity to far-red, both between species and also between the different responses observed on a given plant. For example, in petunia the number of flowers produced per gram of shoot biomass was observed to increase linearly with increasing far-red intensity. However, the number of side branches and total shoot biomass was observed to decrease as far red-intensity increased. In this case, selecting a far-red light intensity that promotes flowering sufficiently while also keeping the stem extension and number of branches within desirable limits will be necessary to allow successful plant production. Selecting the optimal light treatment can be easier in cases where desirable responses are observed to saturate at low intensities and in which undesirable characteristics were correlated linearly with far-red intensity. If we use begonia as an example, flowering was saturated at less than 15 $\mu mol\ m^{-2}\ s^{-1}$ of far-red but leaf area was found to decrease progressively as far-red intensity was increased. In this case, providing too much far-red would lower the crop growth rates and quality, promote no additional flowers, and cost more to install and operate the lamps. In cases where saturation of a response was observed at the lowest intensity, further studies will be required to evaluate the optimal far-red light treatments for each species. Fully optimising crop light responses is

likely to require treatments that combine the results of red:blue and red:far-red experiments. If high-blue is combined with far-red treatments, it may be possible to produce compact plants with extensive flower production without the need for PGRs (this will be examined in a work package performed at a later stage of the project).

Results WP 2.3 Improving HNS Propagation

Influence of red:blue ratio.

Cuttings of three HNS species (elaeagnus, photinia, and phododendron) were placed under five different red:blue light treatments ranging from 100% blue to 100% red light. Blue intensity was found to be a significant factor in cutting survival during this experiment (Figure 71A). Survival of all three species was very low (less than 10%) under 100% blue light. Survival was greatest under light treatments with less than 40% blue light. The best light treatment for survival varied between the species but 100% red light treatments were observed to have lower survival rates (especially in rhododendron) than treatments containing some blue light. The reason for the low survival under high blue conditions is thought to be caused by cutting dehydration. Blue light induces stomatal opening thus dehydrating the cuttings. For the elaeagnus cuttings, wilting was observed early in the experiment and this was found to correlate with blue light percentage (Figure 71), consistent with the influence of blue light on stomatal conductance. The high mortality of elaeagnus cuttings occurred within the first few weeks of trial. Plants in the 100% blue treatment shed their leaves rapidly in the first and second weeks. Overall, the percentage of cuttings that rooted was low in this experiment (Figure 70B), a factor that was partially caused by low cutting survival in high blue treatments. When percentage rooting is corrected for the number of cuttings that died (Figure 71C) some interesting observations were made. Elaeagnus rooting percentage was unaffected by light quality, though overall percentage rooting was still low. As none of the rhododendron of photinia cuttings survived at high blue treatments, it was not possible to assess whether higher blue light treatments actually affected rooting, but for most treatments percentage rooting was still less than 40%. The one exception was rhododendron propagated under 33% blue light in which rooting was >90%. While the percentage of rooting was low in the photinia cuttings, there were large differences in the amount and rate of callus produced. Callus production was greatest in the light treatments with higher amounts of red light. Callus was observed to continue to grow throughout the experiment with fresh callus observed even after three months. It is clear that some environmental factor in this experiment was not optimal for inducing the transition to rooting. Of the cuttings that rooted, the rate of root production was determined (Figure 71D). In elaeagnus, a greater number of roots were produced in light treatments with between 30 and 70 μmol m^{-2} s^{-1} of blue light. This indicates that, while high blue light can reduce survival during the early stages of propagation, blue light can help promote root development. Root numbers for the other two species were low in all treatments, again suggesting the conditions for rooting were suboptimal in this trial.

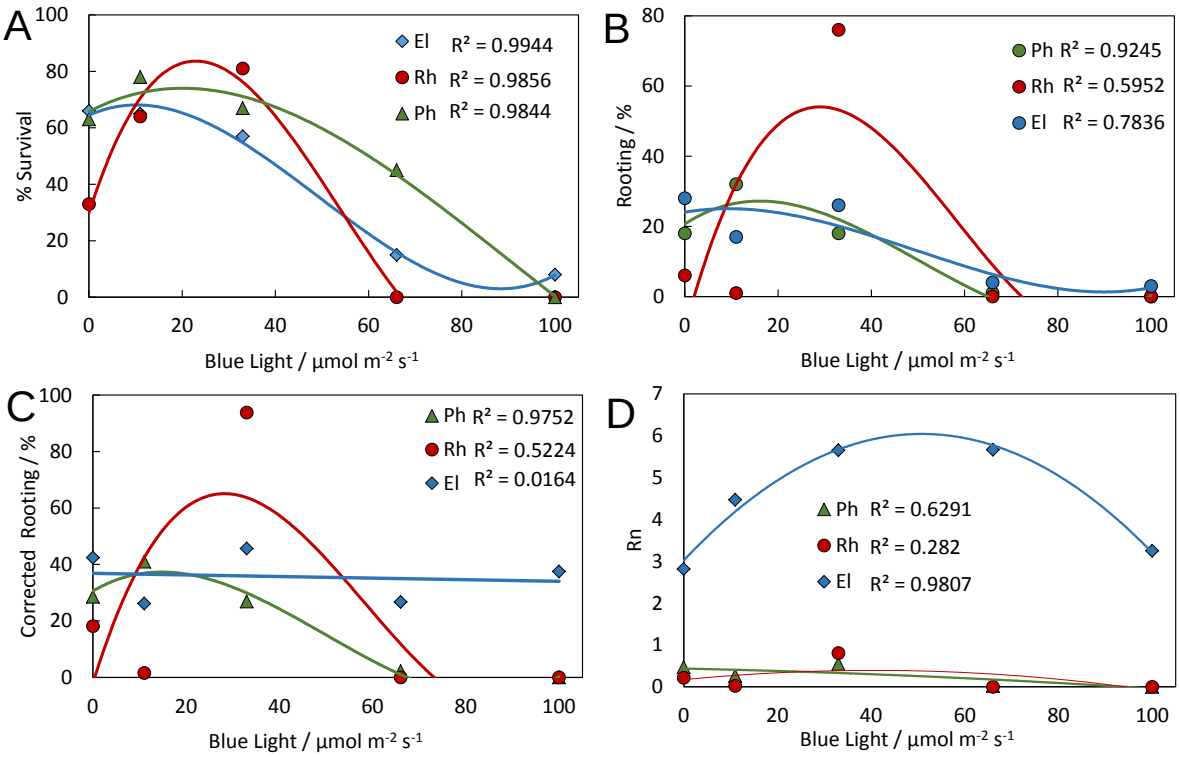


Figure 71. The influence of blue light intensity on **A)** cutting survival, **B)** percentage of cuttings rooted, **C)** the corrected percentage of cuttings rooted, and **D)** the number of roots produced per day (Rn) by cuttings of elaeagnus (El), photinia (Ph) and rhododendron (Rh) propagated under different red:blue light mixtures.

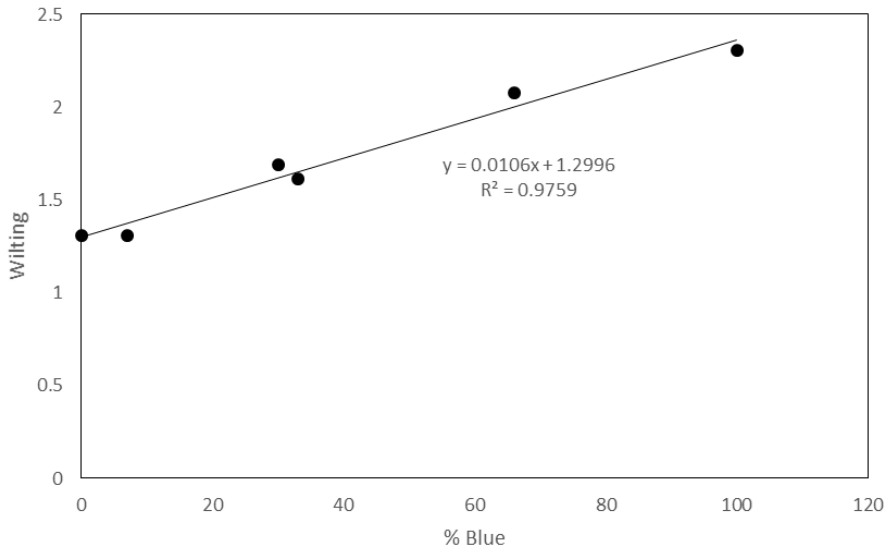


Figure 72. The influence of blue light percentage on the observed wilting of elaeagnus cuttings that occurred during the first week of the trial prior to high levels of cutting mortality.

Influence of far-red light.

In addition to the red:blue ratio experiments, the influence of far-red light on propagation success of the three species was also examined. As far-red light intensity was increased, percentage survival was observed to decrease. This was especially pronounced in the elaeagnus cuttings, where survival dropped from greater than 60% to less than 20% as far-red increased from 0 to 48 µmol m^{-2} s^{-1} (Figure 73A). The rooting percentage was also found to change with far-red intensity. For photinia and elaeagnus, rooting percentage decreased with increasing far-red up to 30 µmol m^{-2} s^{-1} of far-red light before increasing slightly at higher intensities (Figure 73B). In contrast, rhododendron was observed to have an increase in rooting percentage from 0 to 30 µmol m^{-2} s^{-1} of far-red light, though no rooting was observed at the highest far-red treatment. Correcting the rooting percentage for percentage survival had less effect on the rooting estimates for the far-red treatments than the red:blue treatments due to higher overall survival rates, and the trends were broadly similar (Figure 73C). Far-red light reduced root number in elaeagnus (Figure 73D) but had little influence in the other species.

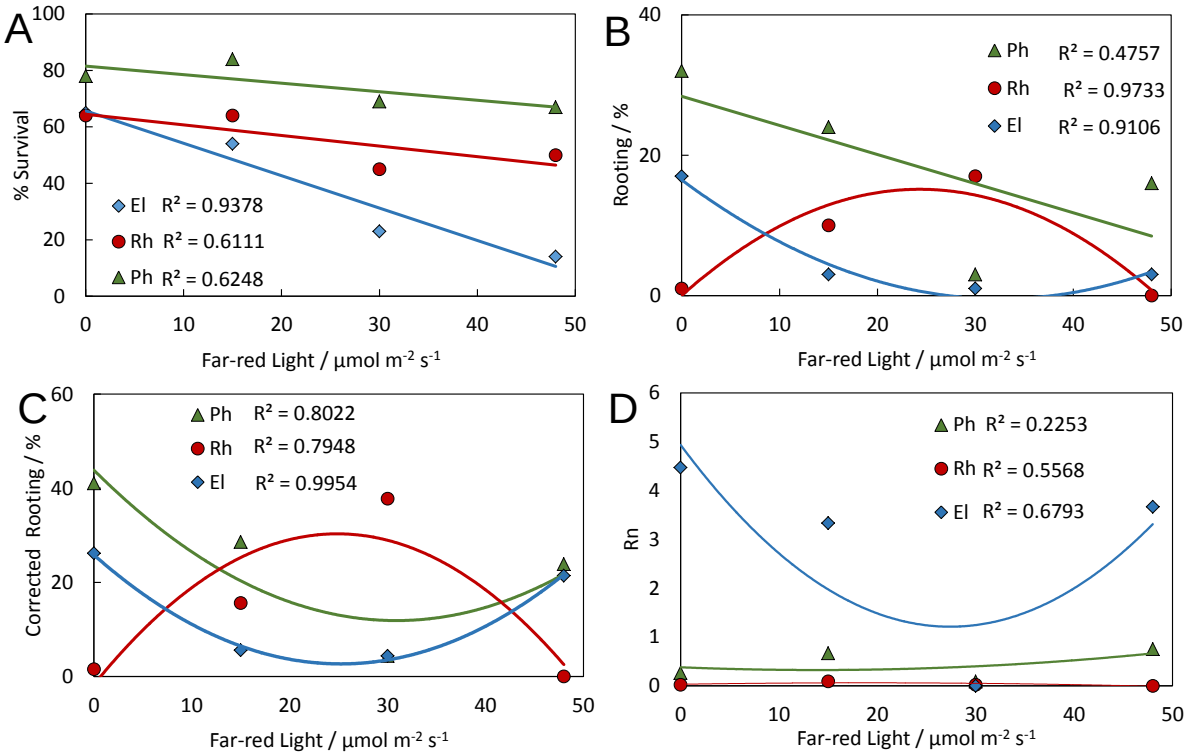


Figure 73. The influence of far-red light intensity on the **A)** survival, **B)** percentage of cuttings rooted, **C)** the corrected percentage of cutting rooted and **D)** the number of roots produced per day (Rn) by cuttings of elaeagnus (El), photinia (Ph) and rhododendron (Rh) propagated under different a red:blue light recipe containing11% blue light and different far-red doses.

Discussion WP 2.3. Improving HNS Propagation

Cutting survival

While recognising that maintenance of other environmental conditions is important, spectral quality has the potential to improve cutting success. Cutting survival was negatively impacted by the amount of both blue and far-red light. Higher amounts of blue light will promote stomatal opening, driving the dehydration of cuttings. In the elaeagnus cuttings in this experiment, blue-light-induced dehydration drove the wilting and loss of leaves even though cuttings were kept in high humidity conditions. While the other two species retained their leaves throughout the trial, there were other signs that dehydration contributed to reduced survival (browning of leaf tips and stem shrinkage). Preventing exposure of cuttings to high levels of blue light will help reduce cutting dehydration, especially at early stages of rooting. The negative impact of far-red on survival was most pronounced in the elaeagnus species, but there was also a weak response in the other two species. Far-red is not generally expected to cause stomatal opening, but it may have an influence on the synthesis of hormones such as ABA that are involved in stomatal closure and may therefore have had some impact on cutting survival via dehydration.

Cutting rooting

Overall rooting success in this experiment was low. This was thought to be caused by two major factors. 1) In an attempt to assess identify differences in the rate of rooting, cuttings were disturbed. This may have damaged small roots and altered the substrate structure. 2) Cuttings were irrigated with an ebb and flood system rather than from above with water. This potentially led to localised soil saturation leading to a poor substrate environment for rooting.

Previous studies have shown that 100% red light conditions can promote cutting rooting (Wu & Lin 2012). In our experiments, 100% red light did not produce maximal rooting. Once differences in survival were accounted for, rooting success of elaeagnus was found to be independent of red:blue ratio. For photinia, rooting was greatest in 15% blue light and deteriorated rapidly above 30% blue. While the rooting percentage of photinia was low, callus production was extensive and was actively growing (fresh white callus was observed at the end of the study) throughout the trial. Callus production was most rapid and extensive in treatments with lower blue light percentages. Given time, these cuttings would presumably have rooted, and the cuttings were healthy enough to have survived re-sticking.

For rhododendron, rooting was poor in all treatments accept the 30% blue treatment, where rooting was observed in over 90% of the surviving cuttings. Determining whether the high

success rate at 30% was a true ‘light response’ or was due to a subtle difference in climate would require further investigation.

For the far-red light treatments, the rhododendron rooting response differed to that of photinia and eleaegnus. Intermediate far-red light promoted rooting in rhododendron but inhibited rooting in the other two species. This may relate to the different hormonal requirements of the induction of rooting in the different species. Small changes in light quality may have large influences on the production of hormones or even alter the ratio of different hormones.

Work package 3 Light quality and its influence on pests

Introduction WP3.1 Insect monitoring

Production of high quality plants requires an understanding of pest and beneficial insect species in order to enable efficient monitoring and control of populations before they can cause damage to crops. As with plants, insects are sensitive to light and many pest responses are mediated by light. Light controls insect circadian rhythms but also influences innate and learned behaviours that are mediated via visual cues sensed through their compound eyes and ocelli. Insect vision systems are diverse and spectral sensitivity differs between species. Some insect vision systems, such as those of bees, are sensitive to three colours (UV, Blue and Green) as well as to the polarization of light. In contrast, *Caliothips phaseoli* are only capable of seeing UV wavelengths (Mazza *et al*., 2010). Insect vision influences many insect decisions, such as flight take-off and landing, direction of migration, and feeding rates. In addition to colour, insects are responding to areas of contrast and intensity of light. Within a species, the different sexes may also have different responses. Male and female western flower thrips have similar visual sensitivities but the two sexes have different swarming behaviours and males are more likely to gather on flowers than females (Matterson *et al*., 1992).

Early identification of the presence of pests is key to successful control and insect populations are often monitored using coloured sticky traps as they are low cost and easy to use. Sticky traps are commonly yellow or blue, with different species having preferences for different colours. Sticky traps are only effective if they attract the pest species thus allowing identification prior to the development of significant problems. In most cases, the spectral sensitivity of insect vision is not known and so designing insect traps is largely trial and error. Trap effectiveness has been evaluated in naturally illuminated systems (with supplemental HPS lighting). The benefits of adding green LEDs to traps has also been assessed and found to enhance capture of certain species but not all. In enclosed structures illuminated with red and blue LEDs colour perception is greatly altered. Any species that show preferences for yellow sticky traps or increased attraction to green LED enhanced traps are expected to be less likely to be caught on traps under red:blue illumination. The experiments reported here outline the sticky trap pest monitoring program performed in the LED4CROPS facility. This monitoring assessed the effectiveness of different coloured sticky traps under LED lighting and initiated the first steps in improving sticky trap effectiveness.

Materials and methods WP3.1 Insect monitoring

Insect species

The insect species present in the LED4CROPS facility were qualitatively assessed to determine which species were present and which were attracted to the sticky traps. No quantitative assessments of insect populations were made. No insects were introduced deliberately into the facility so assessments are based only on species that entered the facility on soil and plants. Pest species were actively discouraged through altered management, introduction of biocontrol agents and, when necessary, spraying of the plant material.

Insect monitoring

Standard yellow and blue sticky traps were placed side by side, flat, on an upturned tray to keep them out of the irrigation solution, at the centre of each LED bench between the experimental plants. The traps were placed flat rather than hung to ensure even illumination of the traps (when hung vertically the traps were illuminated unevenly (both colour and intensity) and this was expected to influence the results). At regular intervals the numbers of insects on each trap were counted. The numbers of each species of insect identified on each trap were recorded. After each count, fresh traps were placed out. Traps were located on light benches illuminated with red:blue mixtures of light as well as a red:white mix that acted as the control in this experiment.

Improving sticky trap effectiveness

In order to examine if sticky trap effectiveness could be enhanced in red:blue light conditions, we assessed the use of fluorescent coloured card to make sticky traps that appeared different colours even when viewed under the red:blue light mixtures (Figure 74). The fluorescent pigments contained in the card function by absorbing blue light and re-emitting (fluorescing) the energy as light with a longer wavelength (yellow, green, or pink). The spectrum of the emitted light was determined by measuring the reflectance spectrum of the traps when illuminated with blue light only. Reflectance spectra were measured using a Jaz spectroradiometer (Ocean optics Inc., 830 Douglas Av., Dunedin FL 34698, USA) with the sensor head mounted 5 cm above the trap at 45°, so the sensor did not shade the trap.

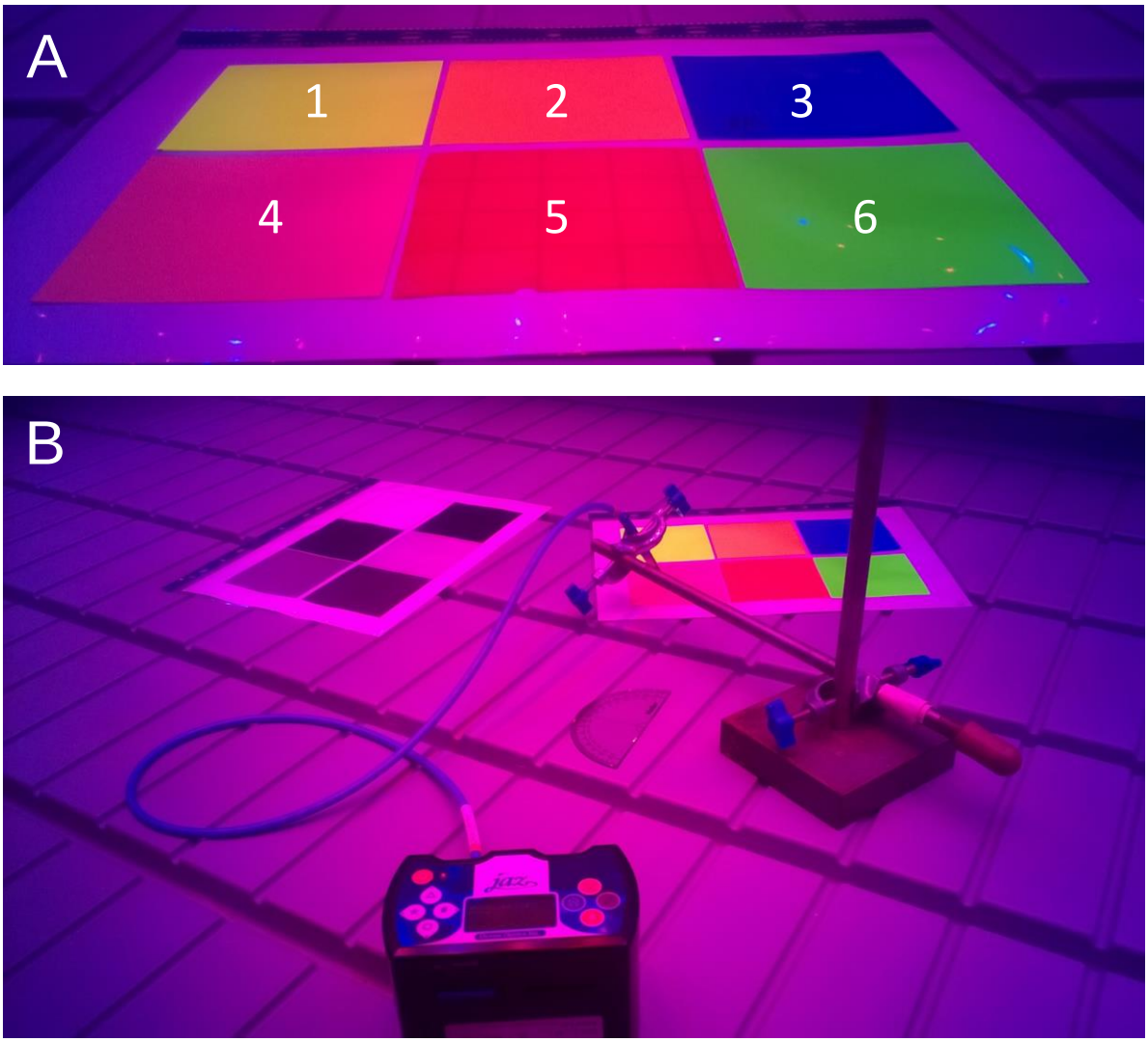


Figure 74. A) Coloured sticky traps viewed under red blue light: 1 -Fluorescent yellow card; 2 - Fluorescent orange card; **3 - Standard blue sticky trap**, 4 – pink fluorescent card; **5 – standard yellow sticky trap**; 6 – green fluorescent card. **B)** Measurement of reflectance spectra from the different coloured traps.

Results WP3.1 Insect monitoring

Qualitative assessment of insects present in the facility.

During these experiments, several pest species were observed in the facility, including Shore flies (*Scatella stagnalis*), fungus gnats (*Bradysia spp*.), Aphids (*Myzus persicae*), Onion thrips (*Frankliniella occidentalis*), Spider mites (*Tetranychus urticae*), Owl midges (family *Psychodidae*), and Leafhoppers (family *Cicadellidae*). Fungus gnats and shore flies were the most numerous species and numbers correlated with the transient changes in the area of exposed soil within the facility. Once introduced into the facility, fungus gnat and shore fly populations could be sustained by algal growth occurring on the trays or on rock wool growing media. Adjustments to soil water content through changes in management of the irrigation system were partially successful in reducing numbers but did not eradicate these species. Treatment of the soil with nematodes (Nemasys - *Steinernema feltiae*) was successful at reducing fungus gnat populations but did not influence shore fly numbers. Aphid and thrip populations were observed occasionally within the facility. When observed, the number of these species were found to be high but to have very localised spatial distributions. Thrip populations were more persistent in the facility than aphids. Leafhopper nymphs were observed on the elaeagnus cuttings during the propagation trials (WP2.3). No adults were observed/trapped before crop damage would have occurred.

Table 7. Total numbers of each insect species observed on sticky traps under the red:blue light treatments during between May and August 2014, and whether plant damage occurred prior to identification on traps. NP = not present during this period or under the red:blue treatments. NO = pest never observed on sticky traps.

Species	Number caught between May and August 2014	Plant damage observed before presence on traps
Shore fly	2715	No
Fungus gnat	5071	No
Owl midge	102	No
Onion Thrip	92	Yes
Leafhopper	NP	Yes
White fly	NP	No
Aphids	NO	Yes

Trap data – insects detected.

Both fungus gnats and shore flies were regularly observed on the sticky traps and variations in numbers were consistent with changes in observed populations (Figure 75). The presence of owl midges on traps was the first indication of their presence in the facility, possibly due to the difficulty of distinguishing between flying insects under the red:blue light conditions. Onion thrips were observed on the sticky traps but in low numbers and only in locations in the facility where populations were very high and significant plant damage had already occurred. Plant damage was the first sign of these pests. Whitefly were observed on the sticky traps but these pests were only observed in the facility on plants grown under the white light treatments, so no information regarding trap effectiveness under the red:blue LEDs was gathered. Leafhopper adults were observed on the sticky traps, but this was long after nymphs had been observed and damage to plants had occurred.

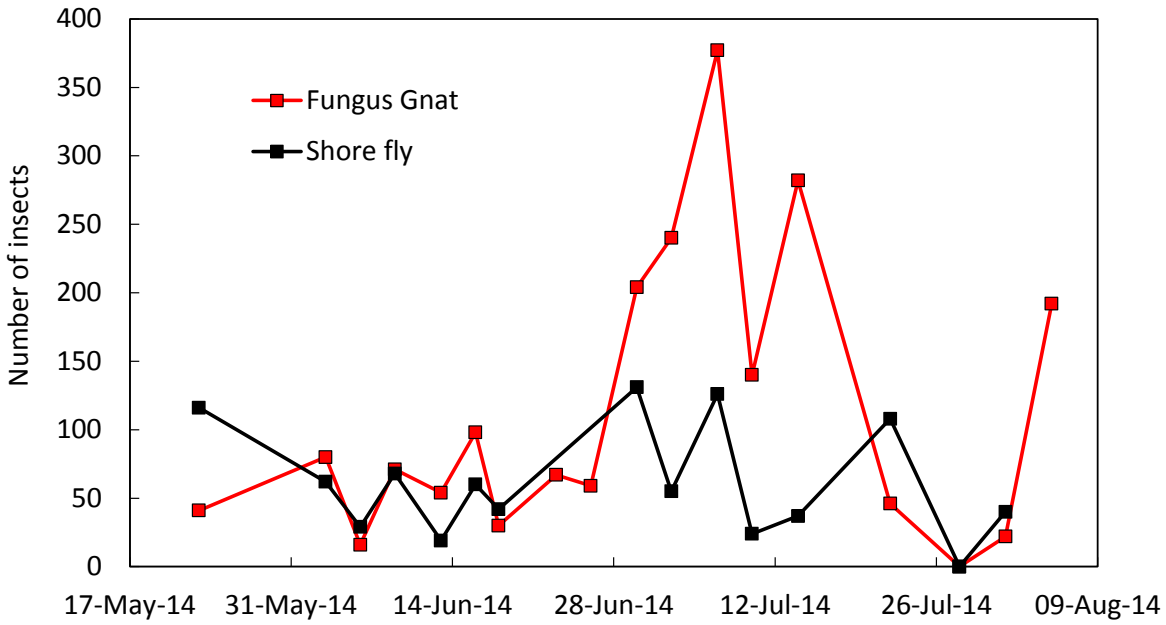


Figure 75. Numbers of shore fly and fungus gnats observed on sticky traps in the LED4CROPS research facility between May and August 2014.

Trap data – colour preference.

Under white-LED-light, fungus gnats were 5 times more likely to be caught by a yellow trap than a blue trap (Figure 76). This is similar to the colour preferences observed in natural light environments. Under red:blue light conditions, the fungus gnats were 3 times more likely to land on a yellow sticky trap than a blue trap, indicating a reduction in attraction towards yellow

traps. Under white-LED-light shore flies were 30% more likely to land on blue traps compared to yellow traps, but no preference for either colour was observed under red:blue light.

Thrips were observed to have a preference for blue sticky traps (especially under the 100% blue light treatments) with up to five times more insects landing on blue rather than yellow traps; however, the overall number of insects caught was low, so caution must be employed with this dataset and results are not shown. The preferences of other insects were also difficult to determine due to low trap counts.

Closer examination of the trap data from the fungus gnat and shore flies (the two species where sufficient numbers of insects were observed to perform this analysis) was able to show alterations for the blue/yellow count ratios (Figure 77) as the blue percentage of the LED light changed. For fungus gnats, the greatest preference for yellow was observed under 33% blue light and the least preference occurred under 100% blue light. For the shore flies, a slight increase in preference for blue traps was observed as the blue light percentage increased.

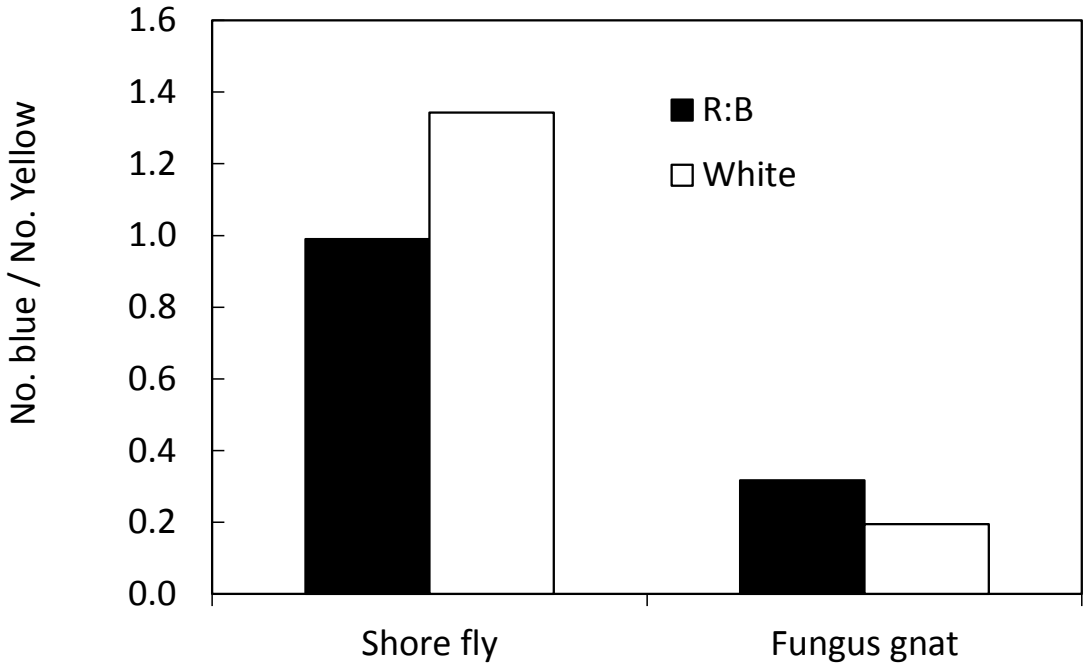


Figure 76. Insect colour preference (standard yellow versus standard blue sticky traps) for sticky traps illuminated with red:white (white) compared with traps illuminated with a red:blue (11% blue) LED lights.

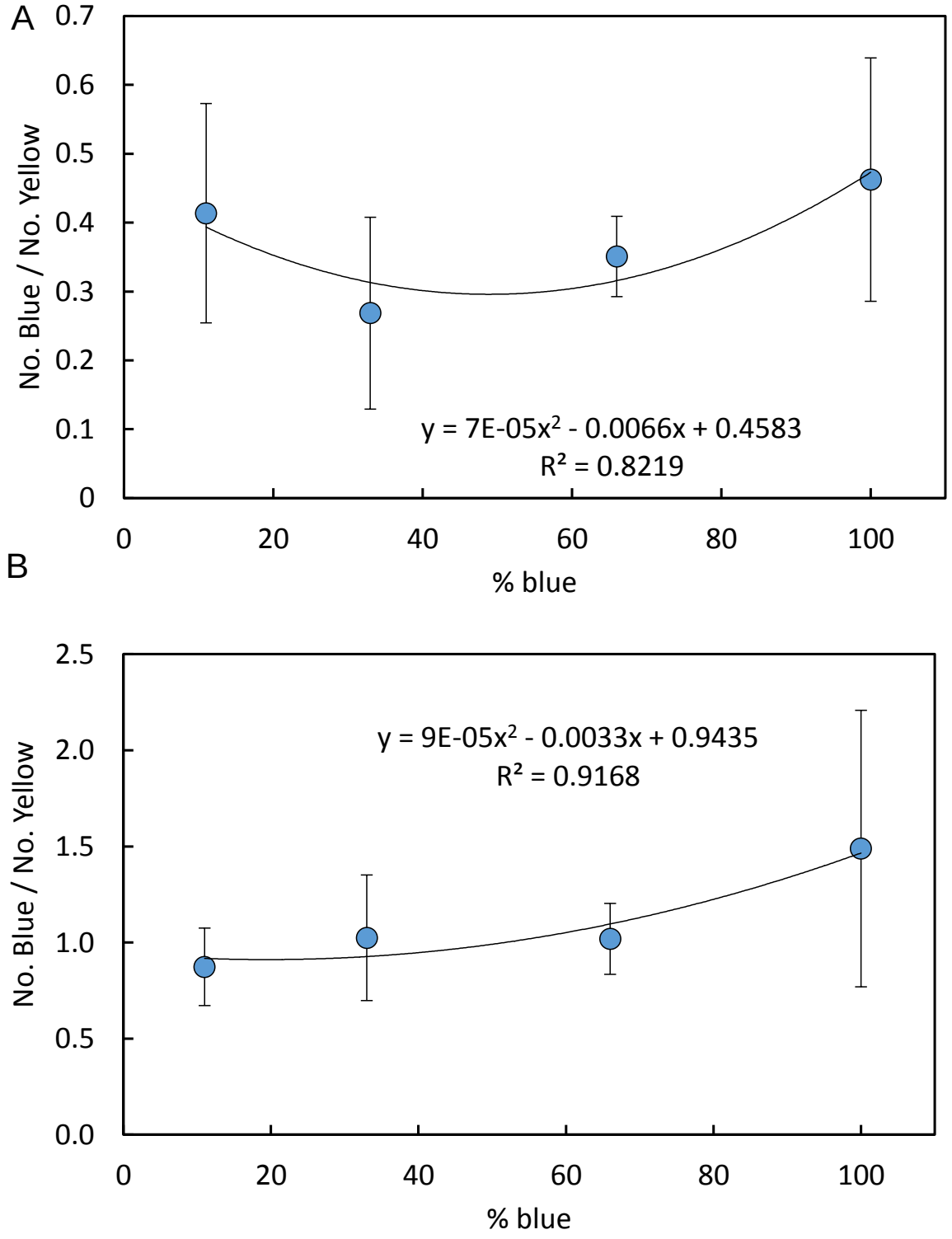


Figure 77. The influence of red:blue ratio of the illuminating light on the colour preference (yellow versus blue sticky traps) of **A)** fungus gnats and **B)** shore flies. Data are expressed as the ratio of the number of insects caught on blue traps divided by the number of insects caught on yellow traps.

Trap data - enhancing trap effectiveness.

As many insects are sensitive to green light and there is no green light present under the red:blue light treatments, we tested the reflectance spectra of several fluorescent cards to identify colours that may improve sticky trap effectiveness (Figure 78). Under 100% blue light, the standard blue traps reflected the greatest amount of light in the blue region and reflected no other colours of light. The standard yellow sticky traps reflected the least amount of blue light and reflected no light in the rest of the spectrum. The fluorescent yellow and green traps reflected an intermediate amount of blue light and fluoresced in the green region of the spectrum, with an emission peak near 525nm. The emission band of the yellow fluorescent trap extended further into the red region than the green and this is the basis for the different colours of the traps. The orange and pink sticky traps fluoresced at a longer wavelength than the yellow and green traps (peak emission near 610nm). The orange trap emitted more fluorescent red light than the pink trap while the pink trap reflected more blue light (the orange trap reflected the same amount of blue light as the fluorescent yellow trap). These reflection spectra indicate that the fluorescent yellow and green traps should increase insect trapping efficiency if the insects are sensitive to green light.

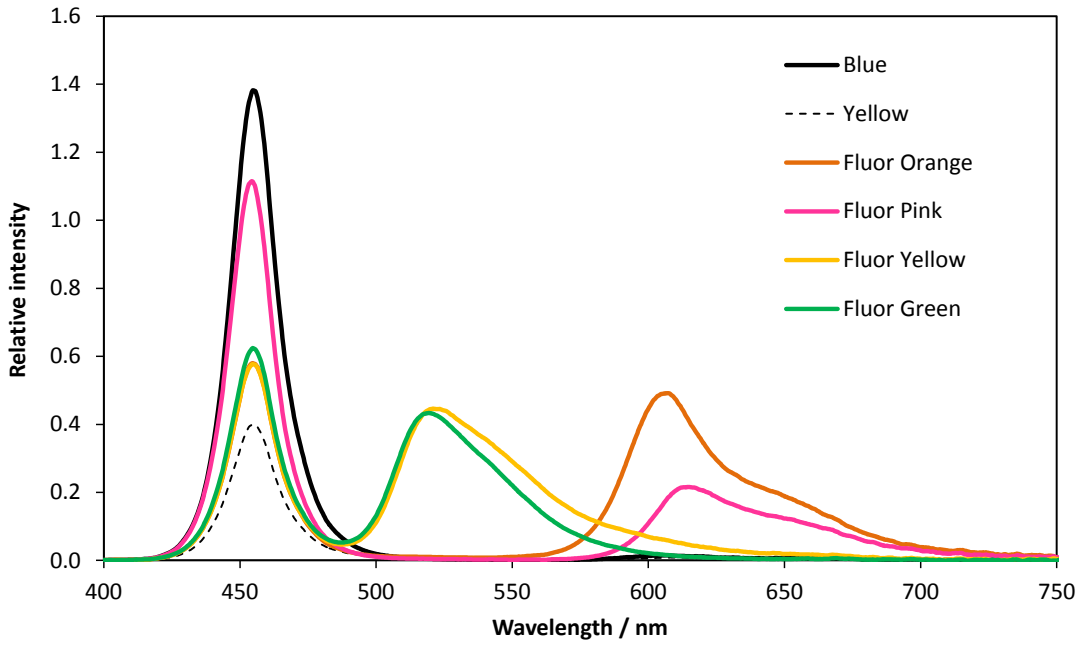


Figure 78. Reflectance spectra of the six colours of sticky trap used in the insect colour preference experiments when illuminated with only blue LEDs.

Shore flies were found to exhibit different preferences for the different coloured traps, with fluorescent yellow green and orange traps attracting more insects than standard yellow traps. Fluorescent pink traps attracted fewer insects than standard yellow but more than standard blue (Figure 79). For fungus gnats, a similar, more pronounced, response was observed. Yellow and green fluorescent traps were twice as likely to trap fungus gnats as standard yellow traps. Pink trap effectiveness was similar to the standard blue traps, with about half the insects trapped as on the standard yellow traps. When total numbers of insects caught is expressed versus the amount of green light measured in the reflectance spectrum, a positive correlation is observed for both shore flies and fungus gnats (Figure 80). When the colour preference relative to the standard yellow sticky trap is plotted versus green reflectance, the effect of colour is found to be greater for the fungus gnats than for shore flies (Figure 80B).

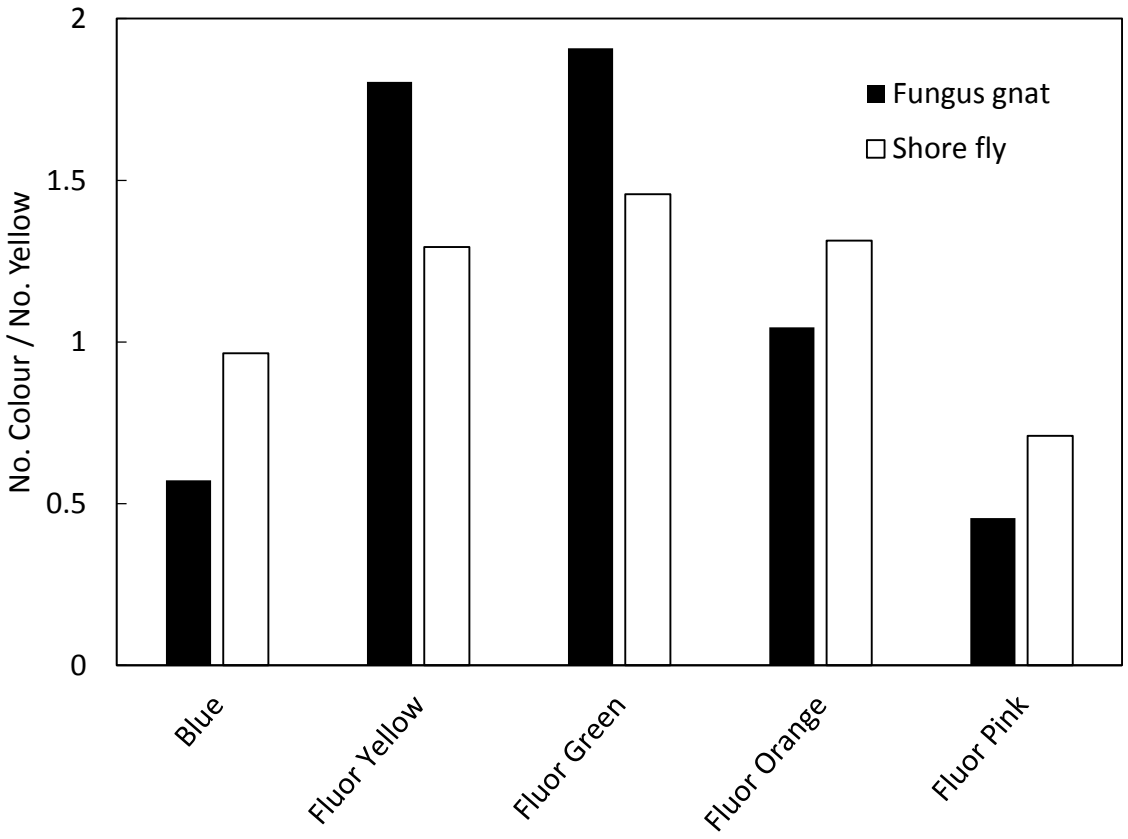


Figure 79. The colour preference of shore flies and fungus gnats for standard blue and four fluorescent coloured sticky traps in comparison to standard yellow sticky traps when illuminated with red:blue light mixtures.

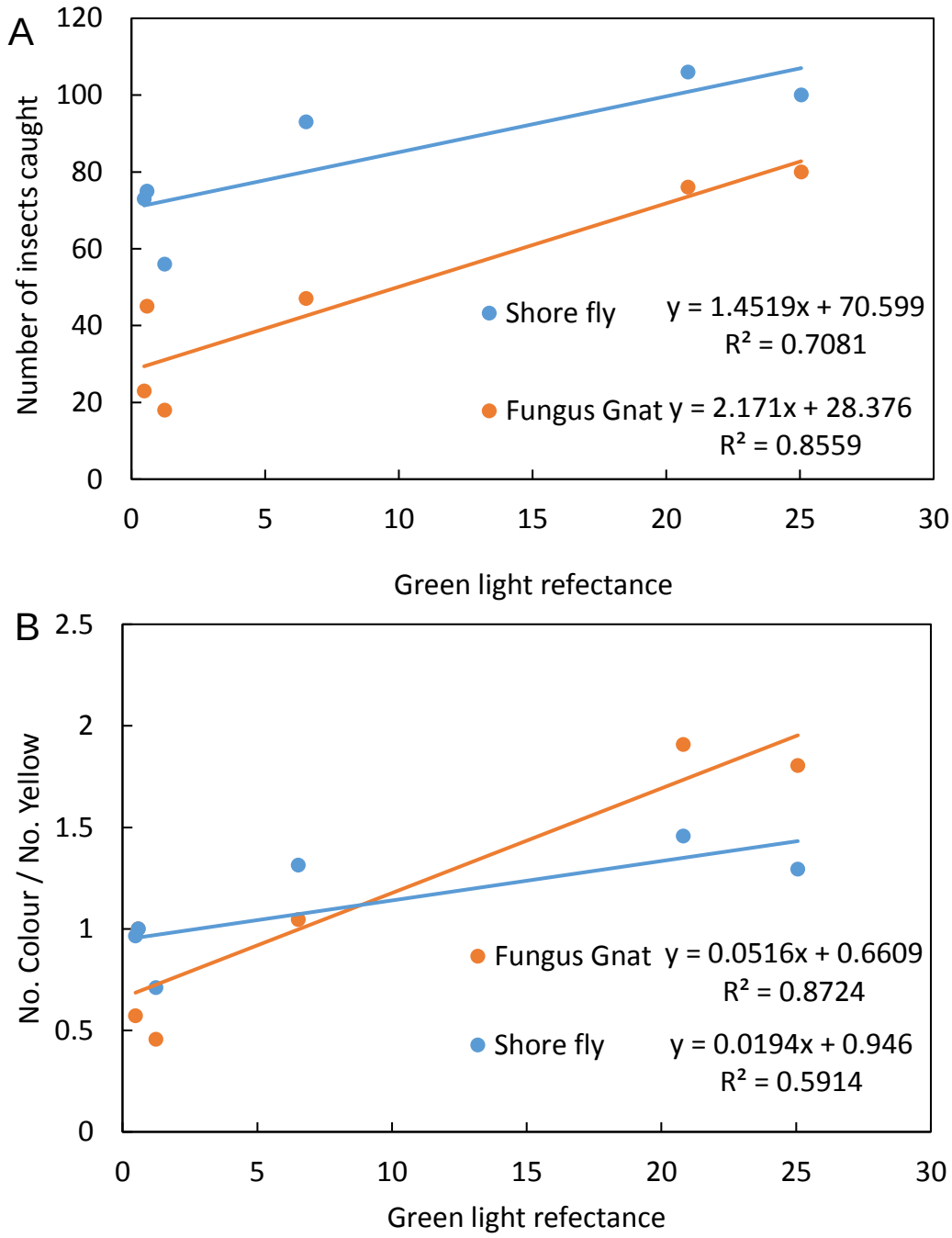


Figure 80. The influence of the amount of green light reflected from the different coloured sticky traps on A) the total number of insects caught and B) the relative preference for the 5 colours of sticky traps compared with a standard yellow trap.

Discussion WP3.1 Insect monitoring

Insect monitoring using sticky traps under red:blue light was effective for some species but not all. Fungus gnats and shore flies were found to land on standard yellow and blue sticky traps regularly and trap counts closely tracked changes in observed populations. For other species such as aphids and thrips, sticky traps were less effective. No aphids were observed on sticky traps and thrips were only observed when pest numbers were high enough to have already caused significant damage to plants. The most likely reason for poor trap efficiency under the LED light treatments in these species is reduced insect flight. If the insects remain on the plants, the traps will be unable to attract the insects. Aphid and thrips populations attained high numbers at specific locations but their spread within the facility was limited. Aphids were not observed to spread from their initial location. Thrips were observed to spread between light racks but at a lower frequency than expected based on their population sizes.

Even though the standard yellow and blue traps caught certain insect species under the red:blue light mixtures, insect colour preference was altered. If insects are less able to distinguish between colours under the red:blue lights then it is expected that the traps will be less attractive and therefore less effecting at providing an early warning system. Use of fluorescent materials that appear yellow or green under the red:blue lights improved the relative trap attractiveness. The improvement in trap attractiveness is likely to result from the traps appearing brighter to insect vision systems, with brighter traps more effective at trapping insects (Bowden 1982). Further trials will be conducted to further assess the potential for use of fluorescent traps in LED lit systems.

Knowledge and Technology Transfer

Presentations

International conference on vertical farming and urban agriculture (VFUA) held Nottingham University in September 2014. Dr Phillip Davis. Title: The challenges of producing plants in vertical farms.

BHTA meeting held at the University of Worcester on 21st October 2014 Dr Phillip Davis. Title: Herb responses to LED light.

Growsave event held at STC on the 6th November 2014. Dr Phillip Davis. Title: LED update.

IPPS/ HDC/ Fargo/GroSouth/WSNSDG Study Day - Innovation in Plant Production held on 11th November 2014. Dr Phillip Davis. Title: The influence of light and the future of LEDs.

HDC PO panel meeting held at STC ion 18th November 2014 at STC. Dr Philip Davis. Title: HDC project CP125 - Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs.

BPOA Technical Seminar held at The Oxford Belfry Hotel, Milton Common, Thame, Oxfordshire on 21st January 2015. Dr Phillip Davis & Dr Dave George. Title: Understanding crop and pest responses to LED lighting (CP 125).

AAB/FES Conference: Knowledge exchange: from research to the food supply chain held at Lancaster University in June 2015. Dr Phillip Davis. Title: Exploiting photobiology in protected cropping

HDC News articles

Colour reactions. December 2014/January 2015 issue pages 16-17.

Glossary

Cryptochrome	A photoreceptor that is sensitive to blue and UVA light.
Daily light integral (DLI)	A value of the total amount of light received over a 24 hour period. The values can be calculated using measurements made in different units. If irradiance (Wm^{-2}) values are used, the DLI has units of J m^{-2} d^{-1}. If photon-irradiance (µmol m^{-2} s^{-1}) values are used, the DLI has units of mol m^{-2} d^{-1}.
Photon irradiance	A measurement of the number of photons incident on a surface, which has units of µmol m^{-2} s^{-1}.
Photoreceptor	Light-sensitive proteins that initiate light responses.
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.
Photomorphogenesis	The processes that causes plant morphology and pigmentation to change following exposure to light. These processes are activated and controlled by several photoreceptors.
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.

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