# Grower Summary

## CP 125

## Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs.

Final Report 2017

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| **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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## 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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Business Manager

Stockbridge Technology Centre

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# GROWER SUMMARY

## Headline

- Spectral manipulation achieved with LEDs can control plant morphology and flowering time, improve crop quality, and increase strike rates of vegetative cuttings.
- Many of these benefits can be achieved in glasshouses under low light conditions.
- Careful design of a light spectrum could replace the use of PGRs while increasing crop yields.
- Insect light responses and performance are also strongly affected by light quality.
- An improved understanding of insect light responses will aid the development of better sticky traps for improved pest monitoring and aid design of light treatments that minimise pest performance while also helping select and optimise the best biocontrol agents for LED systems.

## Background

In protected horticulture there is an ongoing process of technical advancement and optimisation of production systems. These processes drive improvements in both quality and consistency while reducing environmental footprints. In the current market, many crops are in demand year-round and extending seasons or achieving year round production holds significant business potential. While year-round production is desirable, a major limiting factor for profitable winter production is the energy required to both heat and light glasshouses. The high energy efficiency of LED lighting systems was one factor that attracted attention and the most energy efficient LED currently on sale provides an energy saving of 36% (latest Philips interlights have a lamp efficacy of 3 µmol $J^{-1}$) compared to 600W HPS lighting systems (lamp efficacy 1.92; Lighting: In Practice). A 36% saving in electricity costs has the potential to greatly improve the economics of winter production especially if yields can be improved, as is often reported for tomato crops in the press (Practical hydroponics & greenhouses article, Philips news room). LED efficiency continues to improve, promising further efficiency improvements in the coming years. While the energy efficiency of LEDs is of significant benefit for horticulture, the spectral flexibility (colour options) of LEDs also hold equal if not greater potential gains for many aspects of horticulture.

During the winter months, crop yield and quality diminish due to the low natural light levels that limit photosynthesis. Plants become etiolated under these conditions and mitigating the effects of low light can be required, such as by the use of plant growth regulators to prevent stretching in ornamental plant production. Increasing the light intensity with artificial lighting systems boosts winter growth rates, but plants may still stretch and be of poor quality if the light spectrum is incorrect. This is because plants possess an array of light-sensitive compounds called photoreceptors that regulate plant responses by sensing different parts of the spectrum. There are several types of photoreceptor, each of which is sensitive to specific regions of the spectrum (Figure GS1, see Lighting: The principles for more detail of plant light responses). Plants respond to the amounts of blue, red, far-red, and UVB light encountered in their environments. For high quality plant production, plants must receive sufficient light for photosynthesis but must also receive light of the correct spectral balance to achieve the appropriate morphology.

Light quality has the potential to influence many aspects of plant growth, but the effects of light quality on pests and beneficial invertebrates are also highly relevant. Invertebrate vision systems are highly diverse. Some insects have monochromatic vision, whereas bees and wasps can perceive UV, blue, and green light, and some flies have the ability to see five colours of light. Altering the light environment is expected to disrupt invertebrate behaviour as their colour perception and ability to sense light intensity will be altered. In addition to the direct effects of light quality on invertebrates, indirect effects are also expected as a result of changes in the chemistry and/or morphology of the host plants. Light quality is expected to alter the flavour and scent of plants, which could alter pest host selection and feeding behaviour, as well as the ability of the plant to respond chemically to pest attack.

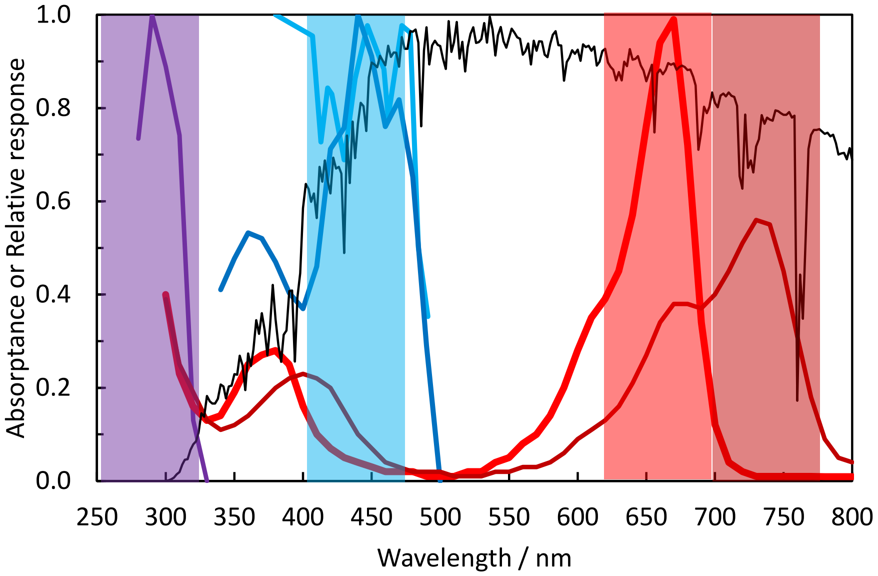

**Figure GS1.** Plant light responses. Action spectra for UVR8 (purple line, Gardner *et al.,* 2009), cryptochrome (pale blue line, Briggs and Christie 2002), phototropin (dark blue line, Briggs and Christie 2002), and the absorption spectra of phytochrome B in its dark inactive state (dark red line) 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.

In this report, we examine the potential for manipulating plant light responses by altering the light spectrum with LED lighting systems. The results are separated by sector (PO, PE, and HNS), with an additional entomology section sector examining invertebrate responses.

## Summary

### *Protected edibles*

The influence of different combinations of red, blue and far-red light, as well as intensity of light, on morphology and growth rate were examined in lettuce, tomato, cucumber, sweet pepper, basil, sage, parsley and coriander. All species were sensitive to changes in light quality and the responses were similar between species. Increasing the blue light percentage resulted in plants becoming more compact with shorter internodes and leaves (Figure GS2). Light treatments with higher blue percentages also resulted in the strongest pigmentation. Light treatments with 60% blue: 40% red light resulted in the most compact plants. Plants grown under 100% red light had long but curled leaves, whereas plants grown under 100% blue light had long but flattened leaves (Figure GS3). Plant biomass was found to correlate with total plant leaf area and so changes in light quality influenced growth rate via manipulation of leaf size, not via spectral effects on photosynthetic rate. Plant biomass was greatest in plants grown under treatments with between 6% and 20% blue light (Figure GS4). Under 100% red light, plant mass decreased due to a combination of factors including low light capture (leaves were curled) and reduced stomatal opening (leading to lower photosynthetic carbon gain). Biomass decreased as the blue light proportion increased, largely due to the reduction in leaf area.

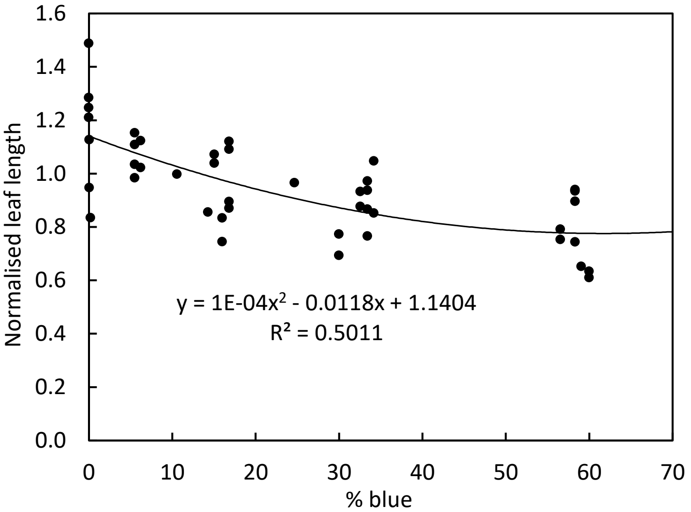

**Figure GS2.** The influence of blue light percentage of red: blue mixtures on leaf length. Leaf lengths were normalised so the relative changes in leaf length of different species could be compared. Graph includes data from tomato, cucumber, parsley, coriander, cucumber, lettuce and sweet pepper.

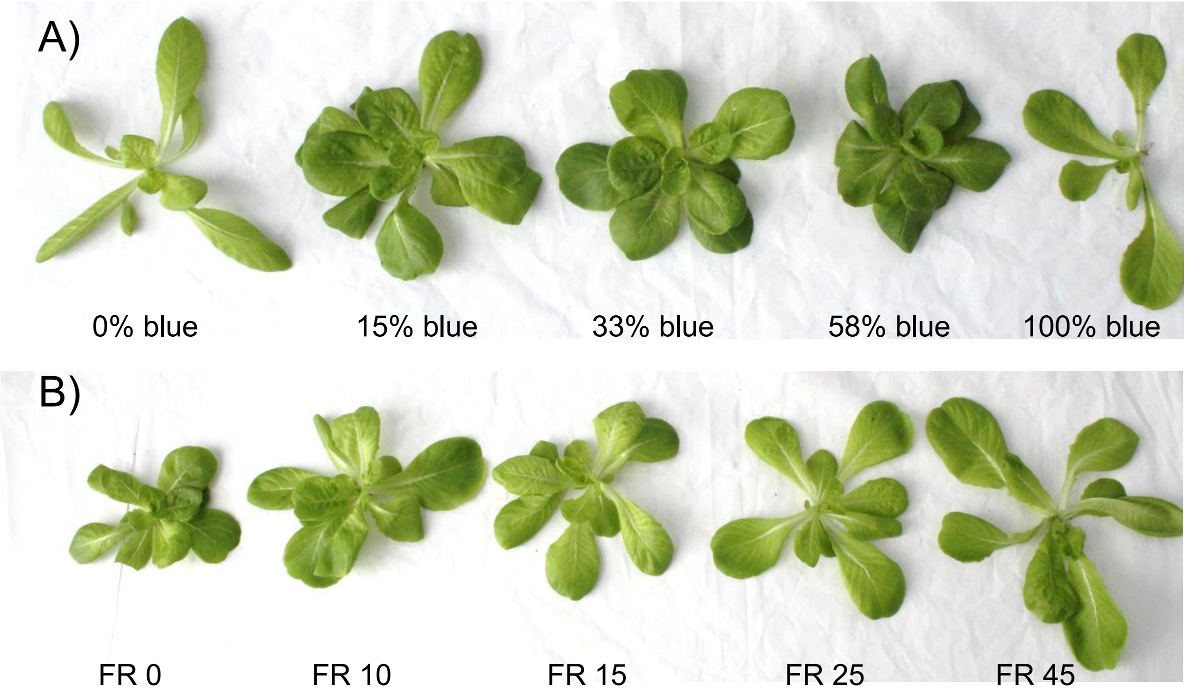

**Figure GS3.** The influence of light quality on the morphology of young lettuce plants. **A)** Plants grown under different red: blue ratios. **B)** Plants grown under different amounts of far-red (FR) light (values provided in units of µmol $m^{-2}$ $s^{-1}$).

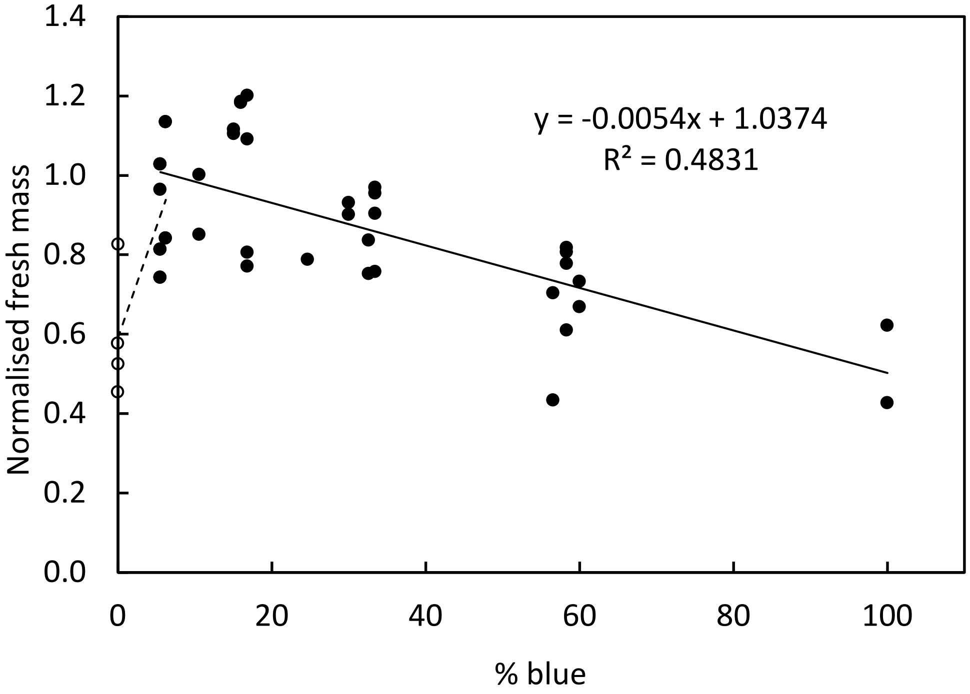

**Figure GS4.** The relationship between blue light percentage (red: blue mixture) and normalised plant fresh mass. Data are normalized so relative changes in biomass can be compared between species that differ greatly in size. Graph includes data from tomato, cucumber, parsley, coriander, cucumber, lettuce and sweet pepper.

Inclusion of far-red light in the spectrum resulted in increases in internode, petiole and leaf length, and a reduction of leaf pigmentation (Figure GS3). Fresh mass was found to increase as far-red intensity increased (Figure GS5). Some of the increase in fresh mass was caused by an increase in plant water content, presumably caused by an increase in cell size. In general, the far-red responses were stronger than blue responses. This means that blue light treatments may be insufficient to completely correct issues with plant morphology if far-red light is the cause. However, trials performed in a glasshouse demonstrated that the benefits of LED lights (manipulation of morphology) can be achieved in the glasshouse during the winter months when problems with plant quality are most likely to be encountered.

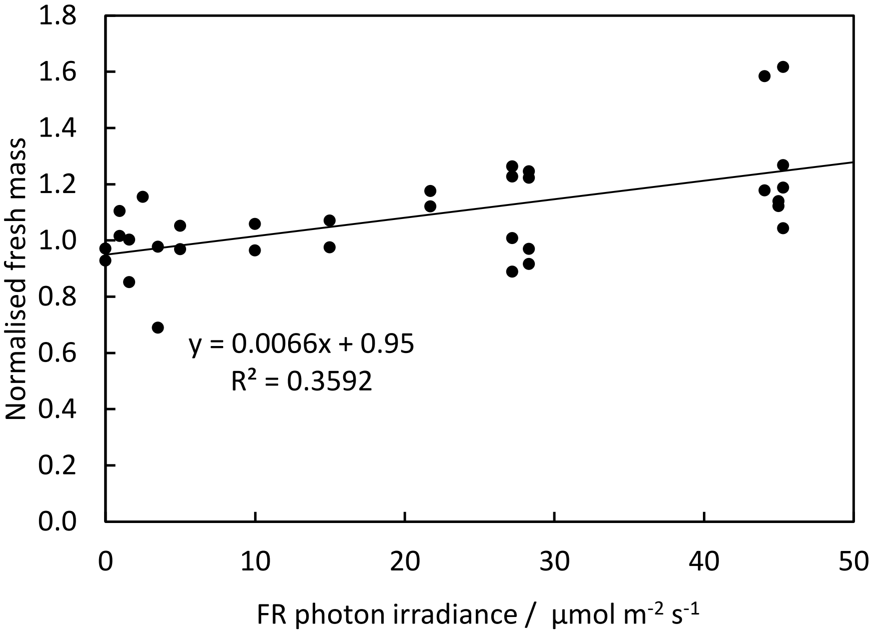

**Figure GS5.** The relationship between far-red photon irradiance (added to a red: blue mixture containing 15% blue) and normalised plant fresh mass. Data are normalized so relative changes in biomass can be compared between species that differ in size. Graph includes data from tomato, cucumber, parsley, coriander, cucumber, lettuce and sweet pepper.

Increasing the total amount of LED light (increasing the daily light integral) increased the growth rate (measured as fresh or dry mass) and robustness of leaves and stems. However, higher light intensities increased running costs but did not necessarily result in better plant quality. This was because higher light intensities also resulted in plants becoming more compact (often ‘too compact’). In the case of sweet pepper this resulted in the plants becoming shorter as the intensity increased, even though the plant mass increased (Figure GS6). Combining spectral manipulation and intensity could potentially be used to maximise growth rates while maintaining plant morphology.

**Figure GS6.** The influence of light intensity on sweet pepper plants.

Our improved understanding of plant light responses has aided the development of a model that can predict the size of lettuce leaves under any combination of light quality and intensity. This model will be useful in testing our understanding of crop light responses and, once applied to different crops and morphologies, the model will provide a useful new tool to help growers select the appropriate LED lights for specific crop applications.

While the different species responded in a fairly consistent manner to changes in light quality, the light treatments that produced the best quality plants differed between species. For example, cucumber required far-red light to form natural looking plants, while other crops benefited from treatments without far-red. Overall, the results demonstrate that plant morphology can be manipulated by changing the light quality. Light spectra can be adjusted to meet the needs of growers and light treatments can be selected to maximise yield or deliver plants that meet specific morphological requirements.

### *Protected ornamentals*

The effects of different combinations of red, blue and far-red light, as well as the overall amount of light, on morphology and flowering time were investigated in pansy, petunia, pelargonium (Figure GS7), begonia and chrysanthemum. Morphological responses of ornamental plants were similar to those of the edible crops examined. Light treatments containing 60% blue light produced the most compact plants, the greatest biomass was achieved under 11% blue light, far-red light increased plant stretching, and higher light intensities increased growth rate and plant compactness.

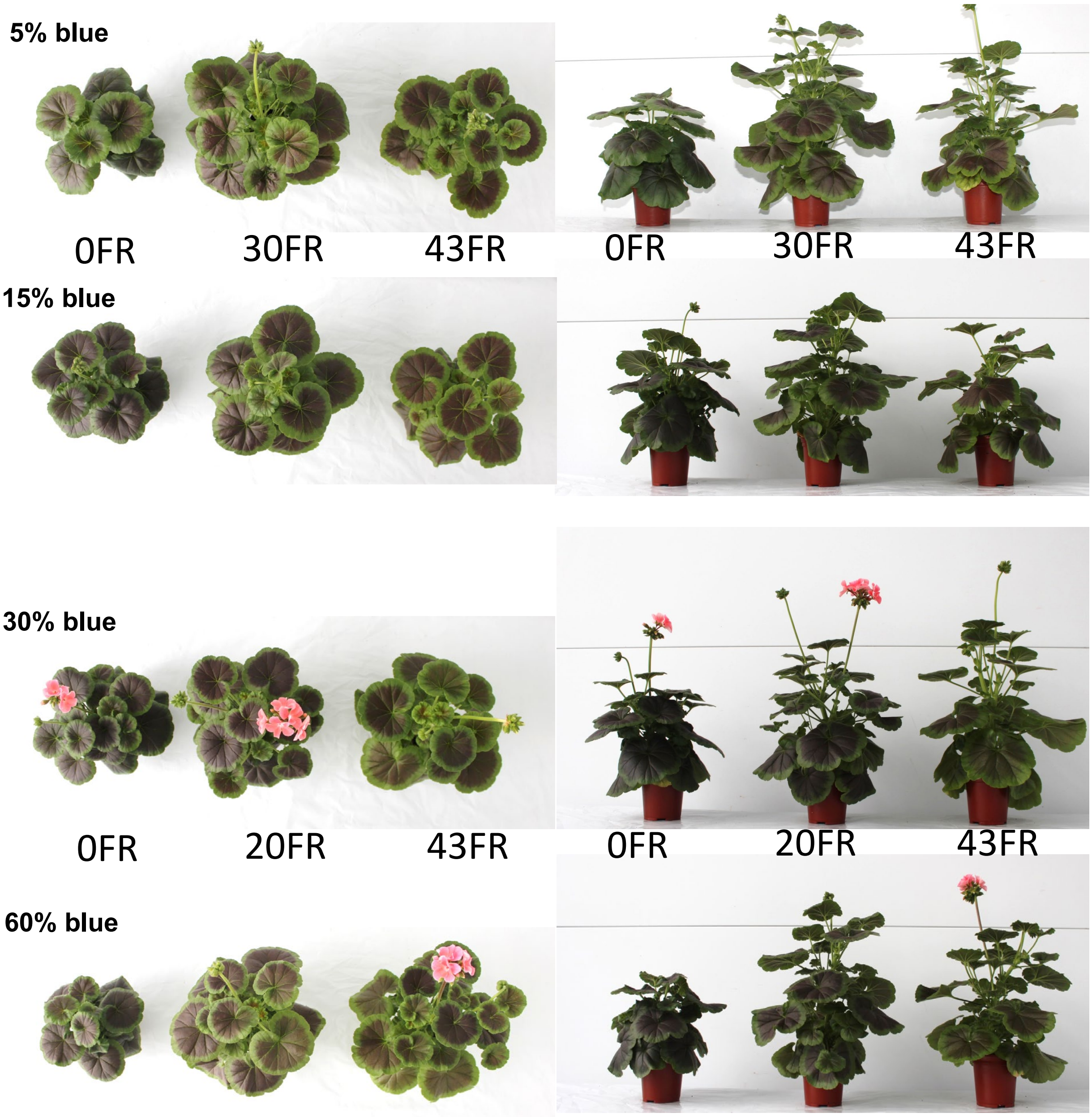

**Figure GS7.** Photographs of pelargonium plants grown under twelve combinations of red, blue and far-red light. Plants were imaged from above and from the side.

Flowering times were also strongly influenced by light quality and quantity. Red light was found to delay flowering while blue and far-red light promoted flowering. Flowering speed was also affected by speed of growth. This meant that for petunia, while flowering was promoted by blue light, the 30% blue treatment flowered before the 60% blue light treatment because the overall growth rate was slower in the 60% blue treatment. Inclusion of far-red in the light treatments promoted flowering in long-day flowering plants (Figure GS8). Under the highest far-red treatments, flowering occurred up to 2 weeks sooner than the no far-red treatment. While far-red promoted flowering, its negative impact on crop morphology meant that the plants, with the exception of begonia, were unmarketable. Further investigation of transient far-red treatments that initiate flowering but do not alter morphology are desirable.

**Figure GS8.** The influence of far-red light on petunia morphology and flowering after 52 days growth.

Increasing the light intensity provided mixed results for the ornamental plants. For petunia and chrysanthemum the brightest light intensity (360µmol m$^{-2}$ s$^{-1}$) resulted in excellent quality plants, and the petunias from this treatment began flowering 35 days after sowing (Figure GS9). However, pansy and pelargonium morphology became too compact at the highest light intensity and pansy flowering speed was maximised at 200 µmol m$^{-2}$ s$^{-1}$. For pansy, 200 µmol m$^{-2}$ s$^{-1}$ resulted in the most energy-efficient treatment and arguably produced the best quality plants. For petunia, while the 200 µmol m$^{-2}$ s$^{-1}$ treatment was the most energy-efficient, there were clear improvements in plant quality and time to flowering at higher intensities that may provide improved sales.

**Figure GS9.** Petunia plants grown under different light intensities. Photographs taken 35 days after sowing and nine days after transplantation to six-packs. Numbers indicate the total PAR photon irradiance measured in µmol m$^{-2}$ s$^{-1}$.

Chrysanthemum was the only short-day flowering plant examined in this trial. Light quality had no influence on flowering time and plants produced flower buds 2 weeks after the day length was shortened to 8 hours. Once under short days, the negative influence of far-red on morphology was enhanced and flower stems rapidly elongated, with plants becoming unmarketable. The highest light intensity treatment kept plants compact without the need for PGRs and resulted in plants with the greatest number of flowers.

These results demonstrate the potential to manipulate crop morphology and flowering by manipulating the spectral composition of light. Trials performed in a glasshouse setting demonstrate that the control of plant morphology can also be achieved in the presence of background sunlight, at least during the winter months when natural light levels are low and day lengths are short. These results demonstrate the potential for LED lighting systems to reduce the requirements for PGRs.

### *Hardy nursery stock propagation*

We investigated the influence of different combinations of red, blue and far-red light on the survival and rooting of cuttings of photinia, eleagnus, rhododendron, lavender, thyme, santolina, iberis and clematis. We also used tomato to examine the effects of light quality on hormonal status of cuttings and how this influences root development.

Light quality was found to strongly influence cutting survival. Blue light was found to decrease survival (Figure GS10), probably due to increased dehydration caused by blue-light-induced stomatal opening. Across all species 100% red light resulted in the best survival rates, though some species, such as iberis, were unaffected by up to 30% blue light. In light treatments with more than 30% blue light, eleagnus cuttings were found to shed all their leaves. This was probably due to a drought-induced increase in ABA synthesis. Far-red light was also found to reduce cutting survival in these species. Identifying the reasons for this response was beyond the scope of this project and further experimentation is required to understand this phenomenon.

In addition to affecting survival, the rooting of cuttings was also influenced by light quality (GS11). Rooting was highly variable between species but overall 100% red light treatments provided the best conditions for rooting. While cuttings rooted fastest under these conditions, any shoot growth that occurred was etiolated, reducing plant quality. If cuttings are to be rooted under red light they should be moved to treatments containing some blue light as soon as rooting occurs. Timing and careful consideration of quantities of blue light may be crucial here, however, as increasing blue light percentage was found to inhibit root formation. Far-red light was also found to reduce rooting in the species examined in these

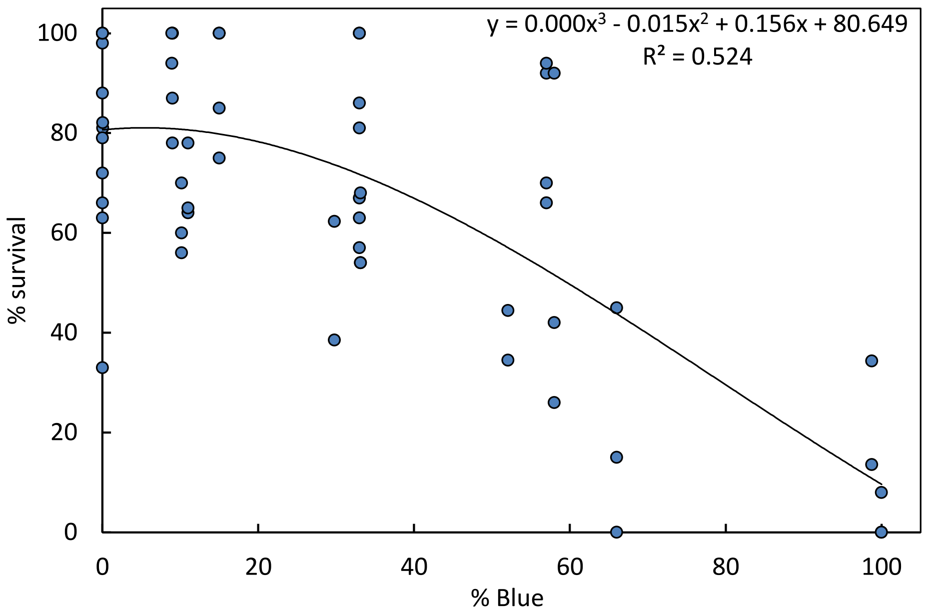

**Figure GS10.** The relationship between post-excision blue light percentage (% blue) and the percentage of cuttings surviving. The data are combined from experiments performed on eight species (photinia, rhododendron, eleagnus, santolina, iberis, clematis, lavender, and thyme).

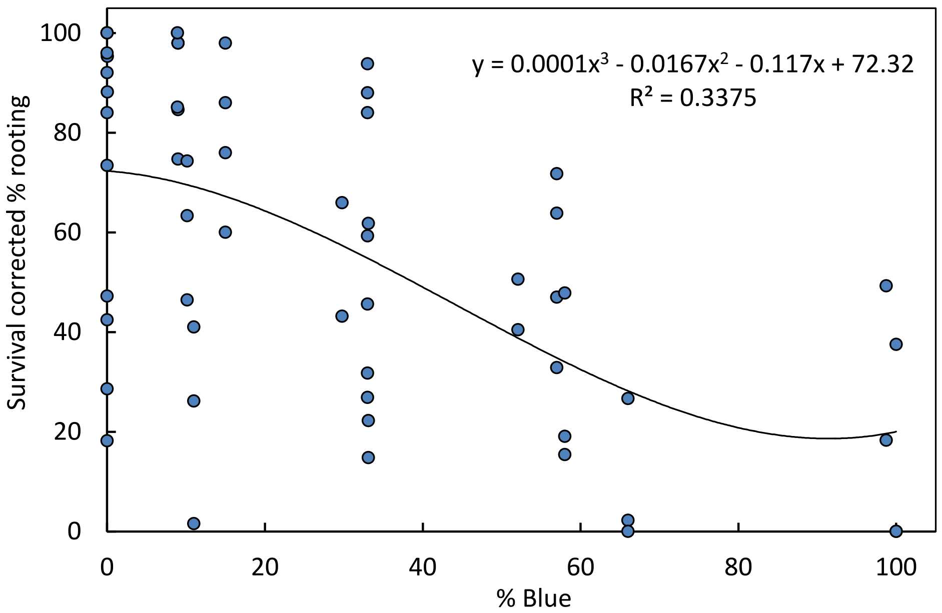

**Figure GS11.** The relationship between post-excision blue light percentage (% blue) and the survival-corrected percentage of cuttings that rooted. The data are combined from the experiments performed on eight species (photinia, rhododendron, eleagnus, santolina, iberis, clematis, lavender, and thyme).

trials. This was in contrast to the results for chrysanthemum (reported in the PO section), where far-red was found to increase speed of rooting.

Lighting stock plants was found to influence the survival and rooting of cuttings. Supplemental light treatment (50 µmol $m^{-2}$ $s^{-1}$ provided for 12 hours per day) of stock plants increased the survival and speed of rooting of santolina and iberis cuttings. The supplemental lighting is thought to increase the carbohydrate reserves in the cuttings, which aids rooting and survival. Night-break LED lighting provided to santolina stock plants, with the aim of preventing winter dormancy, resulted in etiolation of the stock plants, which produced weaker cuttings. In this case the carbohydrate reserves of cuttings are thought to have been reduced by the night-break lighting treatments.

We used tomato as a model system for examining the influence of light quality on the hormone status of cuttings and how this influenced rooting. We examined the concentration of 11 plant hormones (Table GS1) and found that their concentrations changed over the first 48 after cutting collection. Large transient changes in hormone concentration were observed, especially over the first 24 hours. After 48 hours the concentration of auxin (IAA) in the bottom 4 cm of the stem of cuttings was found to decrease as the blue light percentage increased (Figure GS12). This demonstrates that light quality alters the endogenous concentration of hormones in cuttings and re-emphasizes the importance of auxin in the process of rooting cuttings.

**Table GS1.** List of the plant hormones measured by CEBAS-CSIC, Murcia, Spain.

| **Type of hormone** | **Acronym** | ***Full chemical name*** |
|---|---|---|
| Ethylene biosynthesis | ACC | *1-Aminocyclopropane-1-carboxylic acid* |
| *Cytokinins* | tZ | *trans-Zeatin* |
| | ZR | *Zeatin riboside* |
| | iP | *Isopentenyladenine* |
| Gibberellins | GA1 | *Gibberellin A1* |
| | GA3 | *Gibberellin A3 or Gibberellic acid* |
| | GA4 | *Gibberellin A4* |
| Auxin | IAA | *Indole-3-acetic acid* |
| Other | ABA | *Abscisic acid* |
| | JA | *Jasmonic acid* |
| | SA | *Salicylic acid* |

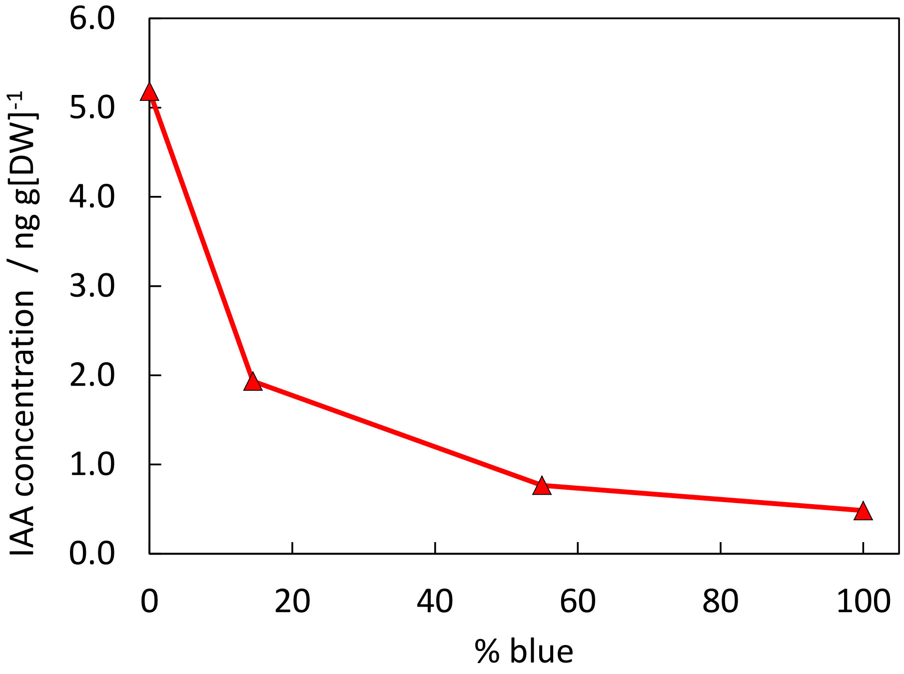

**Figure GS12.** The average concentration of auxin (IAA) in the bottom 4 cm of stems of tomato cuttings 48 hours after collection and exposure to the different red: blue light treatments.

### *Entomology*

Under red: blue light treatments, yellow sticky traps no longer appear yellow. This reduces their attractiveness to pest species making it difficult to detect pest populations using conventional yellow sticky traps prior to damage being seen in the crop. Blue sticky traps were also found to be less attractive to pests in the LED unit at STC, even though they did appear blue. This is thought to be due to the presence of numerous blue LEDs in the unit that were more attractive to insects than the blue traps. Our research indicates that under red: blue LED treatments fluorescent materials that emit yellow or green light in the presence of blue light are far more attractive than standard yellow sticky traps, enabling earlier detection of pest species. Such improved sticky traps are also expected to be beneficial in glasshouse settings.

Pest performance was found to vary with changing light treatment, though with pest responses varying according to pest / host combination. Peach-potato aphids (*Myzus persicae*) were found to have high mortalities and low fecundity when cultured on lettuce plants grown under 66% blue: 33% red light. This was thought to be caused by the aphids finding it difficult to feed on the compact plants. The same aphid species performed least well on verbena plants cultured under 33% blue: 67% red light. In contrast, cotton aphid (*Aphis gossypii*) performed least well on verbena plants grown under 100% red light. Two-spotted spider mite (*Tetranychus urticae*) performed best on cucumber plants grown under

100% red light and worst on plants grown under 33% blue light. Further work is required to understand the factors driving differences in pest performance under different light treatments, and explain why these vary according to pest/host combinations. Characterising whether effects on pests are direct (i.e. light influencing the pest) or indirect (e.g. light influences the plant, which effects the pest) will also be of use to understand and optimise lighting regimes as a pest control tool. Though no consistent patterns in pest responses were found between species/hosts, these results are encouraging nonetheless as they support that pest populations can be manipulated using light in LED production systems. Furthermore, as pest performance was generally poor under combined red: blue treatments, it is perhaps safe to surmise that production systems using these wavelengths should not be highly susceptible to pest outbreaks, at least for those pests tested. .

The effectiveness of biocontrol agents under the different light spectra was also investigated. Casual observations have indicated that biocontrol agents that fly (for example parasitic wasps) perform less well than those that crawl (for example predatory mites) when released in the LED4CROPS facility. Our experimental results indicate that the parasitic wasp *Aphidius matricariae* was able to parasitize the aphid *Myzus persicae* when placed in the vicinity of infested plants illuminated with different red: blue light mixtures. Flight activity trials indicate that two wasps species, *A. matricariae* and *A. colemani,* fly when exposed to all the different light treatments, even 100% red light, only minimal flight activity was recorded when wasps were given no light at all. This supports that premise these wasps can use their green photoreceptors (which are expected to detect red LED light), as well as their blue photoreceptors, to initiate flight under red: blue LED production systems. Extended flight trials, designed to see if these wasp species can travel towards aphid host plants in a larger flight arena, showed flight towards host plants was greatest under light treatments with low blue percentages. This result perhaps hints again at the importance of the wasps green photoceptors in promoting visual plant recognition under red light, , though the influence of different light treatments on the ability of the plant to produce wasp-attracting chemicals (e.g. volatile chemicals produced in response to pest attack) could also explain this result. This is a particularly interesting topic for future work, as it may be possible to select light regimes that promote pest-infested plant signalling to biological control organisms, optimising biological control efficiency by allowing infested plants to ‘stand out from the crowd’ more clearly. In any case, these data indicate that parasitic wasps can potentially be used as biocontrol agents in red: blue LED-lit systems. However, further work will be required to identify what release rates and release strategies would be required for effective aphid control when wasps are not restrained within flight cages. The predatory activity of *Phytoseiulus* on two-spotted spider mite was found to be unaffected by different red: blue

LED light treatments. This backs up our casual observations that predatory mites provide good control of pests in LED-lit systems.

## Financial Benefits

### *Reduced running costs*

Advances in LED technology continue to improve energy efficiency, with the newest systems achieving efficacies of 3.0 µmol $J^{-1}$ (Philips, Interlights), a 36% energy saving when compared to 600W HPS lamps, which have an efficacy of 1.92 µmol $J^{-1}$. LED systems with the highest efficacy tend to produce predominantly red light with as low as 6% blue light. To achieve the light regulation of growth described in this report, higher percentages of blue light may be required and this will lower the lamp efficacy ratings.

Glasshouses lit with LED lighting systems are expected to require an increased heating requirement of approximately 10% in comparison with HPS lit systems. These increased heating requirements should be considered when making the transition to LEDs, but it should also be noted that the costs associated with running heating systems are considerably lower than those associated with lighting systems and, overall, LED systems will result in a reduced energy bill. Furthermore, because LEDs cause less heating, light and temperature management can be uncoupled allowing greater control over crop performance and reduced loss of $CO_2$ (vents open less regularly). Lights can also potentially be used during warmer weather when light levels are low but when HPS lamps would overheat plants. This increased climate control may enable improved crop quality and yields. Improved yields for reduced energy inputs provides opportunity for sustainable intensification of UK horticulture.

While reduced energy bills provides a compelling reason to invest in LED lighting systems, the ability to manipulate light spectra (change the colour of the light) provides a wider range of opportunities to optimise commercial crop production that may have a greater impact on business competitiveness than energy saving alone.

### *Protected Edible crops*

There is a growing demand for season extension and/or year round production of UK-grown fresh produce. Maintaining plant yields through the winter requires supplemental lighting. HPS lighting has been the standard system of choice for many years but maintaining plant quality with HPS lamps can be challenging due to the low amount of blue light they produce (6%). Under supplemental HPS lamps plants grow taller, leading to quality issues, and generating red pigmentation in lettuce crops is difficult. With spectral manipulation, plant quality can be kept within specification without the need to resort to other climate control measures, such as drops in temperature that potentially increase the risks of plant disease due to the concurrent increases in humidity. Removing the need to steer crops using temperature will potentially increase growth rates as optimal temperatures for growth can be maintained. With a more consistent light environment, plant growth will be more consistent which potentially reduces labour costs as less intervention will be required to control crop quality.

The measurements examining growth rates under the different intensities of light can be used to determine crop light requirements. When combined with measurements of sunlight this information could be used to refine lamp switching controls. Lights could then be turned on when low natural light levels are expected to reduce plant growth and/or quality and turned off when natural light levels are not limiting to growth rates and quality. This information has implications for current HPS installations but as more sophisticated LED lighting systems with integrated dimming become affordable we will have a better understanding of how to exploit them to best effect.

### *Protected Ornamental crops*

Many ornamental crops are grown during the winter months when low light conditions result in poor morphology. Multiple applications of plant growth regulator may then be required to maintain plant quality. The morphology of ornamental crops explored in this trial responded similarly to the PE crops. Increasing blue light (up to 60%) increased plant compactness but reduced growth rate, and far-red caused plant stretching. The results from these trials indicate that spectral manipulation has the potential to replace the use of PGRs, especially for crops than only require PGRs during periods of low light. This provides businesses with alternative approaches to crop management and 'protects' future crop production against the possible loss of PGRs.

In addition to morphological control, spectral manipulation can also alter flowering time and provide growers with more control of when crops hit full bloom. As the changeable weather during the spring season greatly affects bedding plant sales, delaying (exclude far-red from the growth environment or provide more red light) or hastening (addition of far-red light) flowering by adjusting light quality could help reduce crop waste and improve profitability. Even ensuring plants are in flower for specific target dates can be challenging with variable weather conditions. Flexible LED lighting strategies will help steer plants into flower at the appropriate date to ensure sales target are met.

### *Hardy Nursery Stock*

Improving the strike rates of cuttings has the potential to greatly improve the efficiency and profitability of a propagation business due to the labour intensive nature of this work. Achieving an optimal lighting environment provides one route by which strike rates can be improved. The relative improvements that can be achieved with LED lighting will partly depend on the ability of each species to root and the factors that currently limit rooting. In these trials, altering the light spectrum had profound effects on strike rates. Strike rates of santolina cuttings ranged from 100% under red light to as low as 8% under 60% blue + 40% red light.

Assuming a challenging species currently achieves a strike rate of 50%, generating 1000 plants to meet market demands will require collection, processing, and sticking of 2000 cuttings. Assuming optimisation of lighting improves strike rates to 80%, the total number of cuttings required to meet market demands would be reduced to 1250 cuttings. This would result in a 38% reduction in space, labour, and resource use, or an equivalent increase in sales. Even lighting easy-to-root species could be beneficial if rooting speeds are increased, as this can enable improved turnover and space-use efficiency. Furthermore, optimising the lighting for cuttings could reduce the need for treating cuttings with rooting powder, which would further reduce production and labour costs.

From the perspective of installation and running costs, lighting cuttings is more compelling than lighting stock plants because more cuttings than stock plants can be illuminated with a single lamp. Assuming the lighting requirements of cuttings are 50 µmol $m^{-2}$ $s^{-1}$ and the selected lamps have an efficacy of 2.7 µmol $J^{-1}$, lighting a 10 $m^2$ growing area only requires 195 W of electricity (approx. 1 Philips top light). Assuming the lights operate for 16 hours each day, energy consumption would be 3.1 kWh per $10m^2$ per day. If rooting takes 30 days and electricity costs range between £42 and £56 per MWh (energy pricing based on data taken from FEC Energy Weekly update email), then lighting a $10m^2$ growing area will cost between £3.9 and £5.2 per month in electricity. At a plant spacing of 4cm, 6250 cuttings can fit in 10 $m^2$ area bringing the electricity cost to between 0.06 and 0.08p per cutting. Assuming each cutting sells for 50p an improved strike rate of 10% would increase sales volume by 625 plants with a total value of £313 from the $10m^2$ area per month, more than enough to cover the installation and running cost of an LED system. It is also expected that the quality of the cuttings would be improved. This could result in further increases in sales due to improved customer satisfaction or the ability to produce a more diverse portfolio of products.

## Action Points

To make use of most of the data generated in this report, growers would need to invest in LED lighting systems. The results outline the benefits provided by different regions of the light spectrum and how light intensity influences plant quality. These results will provide a baseline from which growers can begin to develop their own light treatments while performing small scale trials. It is recommended that small onsite trials are carried out before large scale investments are made. This is for two reasons: 1) to ensure the light treatments are appropriate for the specific varieties being grown, and 2) to help growers develop the appropriate crop management strategies (it is expected that LED lighting systems will require altered crop water and heating requirements). This research program has generated a considerable amount of information about plant light responses that will aid design of light treatments aimed at achieving specific plant responses.

The cutting rooting experiments indicate that light spectra have a large influence on strike rates. LED lighting systems can be used to greatly improve rooting efficiency of cuttings directly, or indirectly if mother stock plants are lit. Propagation requires relatively low intensities of light so installation and running costs would be proportionally lower than for crop growth. If the installation of lights is deemed too expensive, similar results may be achievable by using spectral filters that remove the majority of blue light.

For growers interested in using LED lighting we have outlined several steps that should be taken to ensure a successful installation. It is advisable to seek out independent expert advice to help you through this process.

1. Identify the desired outcome of a lighting system. The aim of an installation may be to improve crop quality, increase yield, or reduce energy consumption, and each desired outcome may require a different lighting system. Equally it may be possible to select a lighting design that achieves a good compromise between quality and yield.
2. Determine the lighting regimes required to achieve these goals and consider whether LEDs are required or if spectral filters can be used. For guidance on lighting measurements and converting between different measurement units see the AHDB Horticulture technical guide Lighting: The principles. If available, historical records of crop yield and the light environment at your site can be used to identify periods of the year where insufficient natural light is available. This can be used to infer crop light requirements. Crop lighting requirements should be determined in units of µmol $m^{-2}$ $s^{-1}$ or mol $m^{-2}$ $d^{-1}$ and lighting suppliers should be able to advise how many of their lights will be required to achieve these goals.

3. Conduct small-scale trials to examine crop performance and learn how management strategies will need to be revised. If possible, the LED trials should be performed in a region/zone of your crop production facility where irrigation and temperature can be controlled independently to the rest of the production area. This is not always possible but crop water and temperature requirements may differ, especially in comparison with HPS lighting.
4. It is important to have accurate measurements of the light environment within a crop production area when performing lighting trials. LED lighting systems should not be measured using Lux meters. The best type of sensor for measuring LED lighting for crop production would be a PAR meter which measures the light that can be used by plants for photosynthesis and makes measurements in units of $\mu$mol $m^{-2}$ $s^{-1}$. Good quality sensors should be used, and it should be noted that some models of PAR sensor are not designed for red:blue light environments and should be avoided.
5. Use the trial results to determine the economics of an LED lit production system for your site / crop, and use this information to inform decisions on further investment in LED lighting.