

Proceedings of the UK Controlled Environment Users' Group

1993 SCIENTIFIC MEETING

“LIGHT AND LIGHTING IN CONTROLLED ENVIRONMENTS”

Volume 4

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CONTROLLED ENVIRONMENT USERS GROUP**1993 SCIENTIFIC MEETING****LIGHT AND LIGHTING IN CONTROLLED ENVIRONMENTS**

The scientific part of the annual meeting consisted of five invited contributions. Summaries of 4 of these, supplied by the speakers, follow.

SUMMARIES OF PAPERS**H. Smith** (Department of Botany, University of Leicester, Leicester) **Light quality and plant growth - some recommendations**

The growth of most higher plants can be markedly affected by the spectral distribution of radiation incident upon the plant. Growth responses to light quality are manifestations of the capacity of plants to acquire ecologically-meaningful information from the light environment, and to direct their growth and developmental patterns in a way most appropriate for the perceived environmental conditions. Acquisition of information from the radiation environment depends on the action of specific photoreceptors, molecules that absorb light of specific wavelengths and transduce the environmental signal to a biological signal. Two broad groups of informational photoreceptors operate in this way; the blue/UV absorbing photoreceptors and the red/far-red absorbing phytochromes. The blue/UV photoreceptors have been implicated in phototropism, in the regulation of stomatal opening and in certain types of extension growth regulation; however, our knowledge of these photoreceptors is limited because to date there is not a complete consensus on their chemical nature. The phytochromes, on the other hand, have been intensively investigated at the chemical, biochemical and molecular biological level, and there is also a large body of evidence on their functions in plants growing in the natural environment.

The phytochromes are a family of chromoprotein photoreceptors that have the property of photochromicity; i.e., each phytochrome can exist in one of two forms, interconvertible by the absorption of photons. The Pr form of the phytochromes has a broad absorption maximum at 665 nm, and upon photon absorption is photoconverted to the Pfr form of the molecule, which absorbs broadly in the red (R) and far-red (FR) wavelength regions, with a maximum absorption at ca. 730 nm. because the two forms have overlapping absorption spectra between ca 600-730 nm, natural broad-band radiation establishes an equilibrium between Pr and Pfr (known as a photoequilibrium and denoted as Pfr/Pr) in which the proportions of Pr and Pfr are a function of the relative amounts of R and FR radiation present. In daylight, the ratio of R (i.e., 655-665 nm) to FR (i.e., 725-730 nm) is virtually constant at 1.15:1; this R:FR ratio establishes about 60% of the phytochrome as Pfr. When radiation interacts with chlorophyllous tissues, the R wavelengths are absorbed whilst the FR ones are not; thus light transmitted through or reflected from green leaves is depleted in R and relatively enriched in FR. In vegetation canopies, plants receive high R:FR ratio light directly from the sun or sky, and also reflected or transmitted light from other vegetation that has a low R:FR. Reducing the R:FR ratio from the normal 1.15:1 to levels typical of vegetation canopies has striking effects on plant growth and development, and these effects are mediated by the phytochromes.

Most plants exhibit the so-called 'shade avoidance syndrome' when exposed to light of a reduced R:FR ratio. The syndrome is characterised by marked elongation growth of stems and petioles, reduced leaf expansion and thickness, enhanced apical dominance, increased allocation of resources to stems at the expense of leaves and accelerated flowering. These responses are of ecological and evolutionary advantage in that they enhance the probability of an individual plant projecting its photosynthetic structures into those parts of the environmental mosaic in which the resource of light is plentiful. In other words, plants use information on light quality, transduced through the phytochromes, to improve their chances of acquiring the resource of light energy.

When investigating the responses of plants to R/FR light quality, it is important to keep a number of points in mind. First, plants also show growth responses to light quantity, and therefore it is vital to ensure that any responses attributed to changed R:FR ratio are not confounded by simultaneous responses to changes in amount of light caused by the applied experimental treatments. It is technically quite a formidable task to construct growth facilities in which the R:FR ratio can be manipulated whilst the photosynthetically active radiation (PAR = 400-700 nm) is held uniform and constant between treatments; nevertheless, if it is decided to carry out experiments that will provide acceptable data, then these technical demands must be met. A connected point is that it is extremely important not to be seduced by the notion that growing plants under simple coloured filters will suffice; such filters always affect both light quality and light quantity within the PAR range, and therefore cannot give useful data on the potential roles of the phytochromes. Finally, all experiments that are designed to investigate the responses of plants to light quality must be supported by spectrophotometric measurements of light spectra. This requirement seems to me as obvious as having to have a balance before one can measure fresh and dry weights, but it is amazing how often I see papers on light quality effects without any data on the spectra. If you do not have access to a spectroradiometer, do not attempt to investigate light quality effects on plant growth

Finally, I list some summarised requirements and suggestions for those interested in studying light quality effects.

1. Controlled environment facilities

The provision of growth cabinets with a reasonable level of PAR (up to $600 \text{ mmol m}^{-2} \text{ s}^{-1}$) and yet with the capacity to alter R:FR ratio is technically difficult. It has been achieved by the use of fluorescent tubes for the PAR (up to ca. $200 \text{ mmol m}^{-2} \text{ s}^{-1}$) with additional tungsten halogen lamps filtered through FR-plastic filters for the FR; the radiant heat from the FR sources must be removed, and this is in practice only achievable by using so-called 'water windows', in which cooled flowing water is circulated in tubes below the light sources. The engineering costs of removing the radiant heat is the major limitation in such cabinets. Recently, cabinets have been constructed that provide up to $600 \text{ mmol m}^{-2} \text{ s}^{-1}$ PAR using metal-halide lamps, with the additional FR provided as above. Both of these types of cabinet can be obtained from Vindon Scientific, at Diggle, near Oldham; the Vindon engineers worked with us to design and build cabinets that allowed maximum control over R:FR ratio whilst providing high flux density PAR.

2. FR filters

Plastic FR filters are relatively easy to construct. The cheapest way is to make a sandwich of red and green Perspex (check the transmission with a spectrophotometer or spectroradiometer). More expensive is FR-transmitting black Plexiglas; we use this at Leicester because it is much thinner than the Perspex sandwich, but it has to be ordered specially.

3. Measuring R:FR ratio

The only safe and proper way to estimate the R:FR ratio is to use a calibrated spectroradiometer, but these instruments are very expensive and difficult to justify for most labs. We have also used devices comprising two photodiodes to which light is piped via bifurcated optical fibres through R and FR interference filters to obtain crude estimates of R:FR ratio. There are major technical pitfalls in doing this, many of them not apparently considered by suppliers, and I have not yet seen a commercial device of this nature that I would trust. The problem in buying such a device from a commercial supplier is that you have to trust the calibration provided by the company. My advice would be to require the company to provide authenticated spectroradiometric calibration data for a range of narrow and broad band sources before investing. Even so, measurements of R:FR ratio can be very misleading, particularly with artificial light sources. R:FR ratio is a good estimate of light quality for natural radiation, but should never be used for artificial sources.

Further information can be obtained by writing to the author.

I. Gilbert (Department of Botany, University of Leicester, Leicester) **Light quality in controlled environments.**

The light that we 'see' is the product of filtered radiation focused and adsorbed by our retinas and the processing of the information by our brain. The colours that we see are over a very small waveband, and our sensitivity to those colours varies, being 1000 times greater in green (555 nm) than the minima at the limits in red (700 nm) and blue (400 nm). Further, the colours that we deduce are also processed so that the light we see is always as near to 'white' as possible. Chlorophyll in plants adsorbs radiation mainly in the blue range of 400 - 500 nm and red range of 640 - 700 nm, towards the limits of our perception. Similarly phytochrome adsorbs mainly at 665 or 730 nm, in the red and far-red, where we cannot see at all. Therefore we are rather unsuited for the task of designing lighting for the requirements of plants - we are spectrally most sensitive to green - the waveband that is reflected and little used.

We have to rely on our radiation measuring equipment to undertake the task of measuring the 'light' environment for us. Even the term light is incorrectly used, as it refers to the radiation range and quantities that our eyes can detect, and has absolutely no connection with photon flux densities that are intercepted by plants. The most desirable equipment to use is a spectroradiometer, but as they usually cost £20 000 or more they are often outside the financial range of many people. Much simpler devices are Quantum meters, Radiation meters and Lux meters. However all have their problems. The basic biochemistry of photosynthesis involves photons of light, and so measuring radiation is not very meaningful, even worse is the measurement of lux, as the spectral sensitivity of the sensor is akin to our eyes and is of little use at all. Quantum meters appear to be the ideal cheaper alternative to using a spectroradiometer, but they integrate over the 400 - 700 nm

waveband, and may give similar flux density readings for lamps of widely differing spectral emissions.

When considering light sources for plant growth, the aim of the experiment, the design and layout of the cabinet have to be considered, along with cost and safety. Plant growth and development will be varied under differing light quantities, qualities and periodicities, therefore all of these have to be near the optimum required for the experiments to be undertaken.

Five types of lamps are available.

(1) Incandescent lamps produce a smooth spectrum, but produce little blue light and a lot of heat. They also consume a lot of energy for their light output. However they are easy to install and replace. Tungsten halogen lamps are similar, but run at a higher temperature so giving slightly more blue and more light output overall for the energy consumed.

(2) Low pressure discharge lamps can be used, but only for specific experiments, as they emit line spectra (e.g. SOX), and are not suitable for normal plant growth. They, like the following lamps, need control gear and special housings, which often makes them expensive to install.

(3) Fluorescent lamps are a type of low pressure discharge lamp, but the gas emission causes a surface phosphor to fluoresce. The spectrum produced can be tailored using different phosphors. The lamps are relatively cheap to buy and run, and produce a uniform light over a large area. They are probably the most often used lamps for plant growth chambers.

(4) High pressure discharge lamps are more efficient than the lamps described above. The line emissions are broadened under high pressure (e.g. SON-T), and by adding metal halides several spectra can be added to produce a desirable output (e.g. HQI). They are often expensive to buy, including the cost of the control gear.

(5) Discharge lamps can give the closest solar simulation, but are even more expensive to buy and run, and have the greatest UV output, which is undesirable to plants as well as people.

The growth chambers used in the Botany Department at Leicester can be broadly categorised into five types.

(1) Fisons cabinets with white fluorescent tubes (Phillips Pluslux 4000) supplemented with 40 W incandescent lamps. These are used for general plant growth where the R:FR ratio can be made to near daylight, although the spectral quantity is far lower than daylight. They can be run with continuous light or variable night breaks. Photon flux density is $< 100 \mu\text{mol m}^{-2} \text{s}^{-1}$.

(2) Fisons/Vindon cabinets using the same fluorescent lamps as above, but with the addition of 12 or more 500 W tungsten halogen lamps, filtered with water windows for infrared and with far-red filters. These can give low and very low R:FR ratios simulating canopy shade and are used specifically for studying aspects of phytochrome physiology. They can be run with continuous light or variable night breaks. Photon flux density is still low at $100 - 200 \mu\text{mol m}^{-2} \text{s}^{-1}$.

(3) Fluorescent-only growth rooms. Used mainly for tissue culture work, or growing stock plants for experiments. Lights are run continuously. Photon flux density is low at $< 100 \mu\text{mol m}^{-2} \text{s}^{-1}$.

(4) Vindon growth cabinets with HOI lamps and tungsten halogen lamps. All are filtered with water windows. Tungsten halogen lamps can be filtered for far-red, or left unfiltered giving total photon flux densities of $600 - 800 \mu\text{mol m}^{-2} \text{s}^{-1}$. They can be run with

continuous light or variable night breaks.

(5) Several specialised light environments are also used in the department. Some plants are grown under 400 W SON-T lamps to accurately study and manipulate growth rates. Blue fluorescent tubes and SOX lamps are used in some chlorophyll studies. Most recently, red and far-red LEDs have been utilised for growing seedlings under continuous high intensity red and far-red light.

L.D.Incoll (Department of Pure & Applied Biology) **Nits, phots, einsteins, intensity, fluence and various other beasts that plague the terminology and units of measurement of radiation** (Subtitle: measurement of radiation in controlled environments).

What should be measured, what physical quantities and units are appropriate and what measuring instruments should be used?

If the user is interested in a process for which the energy content of the radiation is important e.g. energy balance or transpiration, then it is relevant to measure the amount of **energy**. The **flux** of energy, or **radiant flux**, is the rate of propagation of energy through space i.e. the number of joules per unit time - in the international system (SI), joules per second, J s^{-1} or watts, W. The radiant flux passing through a plane of unit area is the **radiant flux density** in joules per second per metre squared, $\text{J m}^{-2} \text{s}^{-1}$ or W m^{-2} . This is the net flux density and has to take into account radiation reflected as well as transmitted. It is not easy to measure in practice, so **incident flux density** or **irradiance**, is measured with a planar (flat) detector and expressed in the same units.

If the user is interested in a process where the photons are interacting with pigment molecules such as chlorophyll or phytochrome, it is not the amount of energy that is important, though there has to be enough in a quantum of radiation to cause a change in the physical state of the absorbing molecule, it is the number of quanta. So the **photon flux** is expressed in photons s^{-1} and **photon flux density** in photons $\text{m}^{-2} \text{s}^{-1}$. Again **incident photon flux density** or **photon irradiance** is the easier quantity to measure, as before with a planar detector. In full sunlight there are 1.5×10^{21} photons $\text{m}^{-2} \text{s}^{-1}$. Such a large number is not very convenient to remember, so the base unit for amount-of-substance in the SI, the mole, is used. A mole of elementary entities, electrons, atoms, molecules, photons, contains Avogadro's number of those entities i.e. 6.023×10^{23} entities mol^{-1} . Thus the above quantity becomes $1.5 \times 10^{21}/6.023 \times 10^{23}$ mol $\text{m}^{-2} \text{s}^{-1}$ i.e. about 2500 $\mu\text{mol m}^{-2} \text{s}^{-1}$. In the past the einstein (symbol E) was used as a term for Avogadro's number of photons, it is an unnecessary name not recognised in SI and is no longer used.

The particular problem of flux density or irradiance and fluence rate for photons or energy

There is a common misuse, by biologists, of the physical quantity fluence rate when they mean flux density or irradiance. This problem can be explored by looking at the definitions of the two quantities. **Flux Density** (W) is a directed-surface distribution

$$W(x,y) = dF(x,y)/dA$$

where the flux density $W(x,y)$ is the net flux dF of energy or photons at a point (x,y) , through a surface element of area dA of fixed orientation, from (or to) all (or any) directions within a hemisphere on one side of it. It is measured by a planar detector.

Fluence Rate (F_t) is an omni-directional-surface distribution

$$F_t(x,y,z) = dF(x,y,z)/dA$$

where the fluence rate $F_t(x,y,z)$ is the flux dF of energy or photons at a point (x,y,z) incident on a spherical volume element of cross-sectional area dA centred on that point. Fluence rate must be measured by a spherical detector. Unfortunately some people think, perhaps because the units ($J m^{-2} s^{-1}$, $W m^{-2}$, or $mol m^{-2} s^{-1}$) are the same for each quantity, that they are the same thing. They are manifestly not. In a perfectly diffuse field of radiation, measured fluence rate will be 4 times the irradiance. The only time when they are equal is when you have a collimated beam of radiation at right angles to the surface of the detectors. Fluence rate is sometimes called **spherical irradiance** and for photons, **spherical quantum irradiance**. It is particularly relevant for diffuse radiation and for understanding the amount of radiation received, for example, by a phytoplankton in a column of water.

Nits, photos, stilbs, foot candles, lumens and lux

These are the units for physical quantities in the photometric system of measurement of light which is a psychological system based on the spectral sensitivity of the human eye to visible radiation. It is used appropriately by lighting designers. It is intellectually dishonest to use this system for organisms other than humans unless their spectral sensitivity is identical to that of humans.

Light intensity

In my opinion this is the most misused quantity in biology. **Radiant intensity** is the radiant flux emitted by a point source into unit solid angle in joules per second per steradian ($J s^{-1} sr^{-1}$ or $W sr^{-1}$), i.e it is the property of a source not a receiver of energy. Users of this term are rarely talking about sources.

Recommendations

1. For amounts of **energy**
 - * use *irradiance* or *incident radiant flux density*, with unit $W m^{-2}$
 - * measure with a *solarimeter* (e.g. a Kipp or Eppley, not a pyranometer with waveband 400-700 nm);
2. For amounts of **quanta**
 - * use *photon irradiance* or *incident photon flux density*, with unit $mol m^{-2} s^{-1}$
 - measure with a *quantum sensor* over the waveband 400-700 nm (e.g. a Macam, LI-COR, Skye, or PP Systems sensor);
3. Don't use **intensity** (unit $W sr^{-1}$) unless referring to a source;
4. Don't use **einstein** for a mole of photons;
5. Use **fluence rate** only for omni-directional radiation at a point
 - * measure with a *spherical detector*. (e.g. LI-COR, Biospherical Instruments sensors);
6. Be mindful of the spectral distribution of radiation in the environment, the spectral sensitivity of the plant process and the nature of the process before choosing a method of measurement.

C. Lakwijk (Horticultural Lighting, Phillips, Eindhoven) **Lighting for plants: A manufacturer's point of view.**

On his departure, Mr Lakwijk left a set of Philips Lighting booklets for members. They are in Dutch but contain many of the photos, figures and tables that he used in his talk. They may be borrowed from the Convener. They are

- a) Praktijkboek plantenbelichting. Deel 1 Licht en groei;
- b) Praktijkboek plantenbelichting. Deel 2 Belichtingstechnieken;
- c) Praktijkboek plantenbelichting. Deel 3 Belichtingsinstallaties;
- d) Praktijkboek plantenbelichting. Deel 4 Lampen;
- e) Praktijkboek plantenbelichting. Deel 5 Armaturen.

A. P. Gay (Institute for Grassland and Environmental Research, Aberystwyth, Dyfed, SY23 3EB) **The effects of light quality on clover growth, an example of how simple modifications of standard C.E. facilities can be used in light quality studies.**

Agriculturally, clover is often grown in competition with grasses, and as it is sometimes difficult to maintain adequate amounts of clover in swards the mechanisms underlying this competition are of interest. One of the main areas of competition is competition for light, and in many plants their responses to this competition are influenced not only by the amount of photosynthetically active radiation (PAR, 400-700 nm) but also by the changing balance of red to far-red radiation as PAR is absorbed by the canopy.

In this study, PAR and red to far-red ratios were varied independently in standard controlled environment (CE) facilities and the effects on clover morphology and branching were studied. White fluorescent tubes were used as the source of PAR and tungsten bulbs as the source of far-red radiation. Ideally, measuring the light quality and quantity directly requires an expensive spectroradiometer. Here, red to far-red ratio was measured with a spectral ratio meter and a quantum sensor was used for measuring PAR. Under these conditions the PAR measurements in quantal units gave very similar results (in terms of ratios of PAR between light treatments) to PAR in energy units calculated from measurements using a solarimeter with and without a filter that transmitted radiation above 700 nm. Some shading of the fluorescent illumination was applied in treatments with additional tungsten lighting to correct for the added PAR from the tungsten illumination. Since space was limited, the CE space was divided in a direction parallel to the air flow to give two far-red to red ratios in one CE space. In one experiment, the CE space was further divided and shading was used to give two PAR levels within one light quality. The shading materials were checked for spectral neutrality using a spectrophotometer. Care was taken to check temperature and light uniformity between and within the divided compartments.

In the first experiment, the CE space was divided to give compartments with and without additional tungsten lighting and these were subdivided to provide high and low PAR. The levels of PAR were 147 and 34 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and the 660 : 730 nm (red to far-red) ratios were 1.8 : 1 and 6.5 : 1 in the compartments with and without tungsten. Petioles were longer in higher far-red ratios but unaffected by the fourfold increase in PAR. The rate of leaf appearance was greater with both increased PAR and far-red. The percentage of nodes which developed buds in low light was relatively low and similar in both far-red

treatments. In high light, the percentage of nodes developing buds was at least doubled over the low light value and was increased in the low far-red treatment.

The second experiment examined the effects of light quality and temperature at one PAR level ($130 \mu\text{mol m}^{-2} \text{s}^{-1}$). The 660 : 730 ratios were 0.7 : 1 and 6.5 : 1 in the treatments with and without tungsten and the temperatures were 10°C day and 8°C night (low) and 20°C day and 15°C night (high). Petioles were much longer with added far-red at both temperatures and were also longer at the higher temperature. Rate of leaf appearance was doubled by high temperature and was increased in the presence of added far-red. The percentage of available nodes developing buds was similar in both the light qualities at low temperature and in the added far-red treatment at high temperature, but was doubled at the high temperature in the treatment without added far-red. Internode length was greater at high than low temperature, and added far-red caused further increases in internode length.

These results demonstrate the importance of light quality, as well as PAR and temperature, in controlling the morphology of clover plants. They are consistent with the idea that increasing far-red, which occurs naturally when clover is shaded by competing grasses, results in plants that produce longer petioles and internodes as a shade avoidance response. Conversely, when far-red is low and PAR is high, as in areas subjected to less shade from neighbouring plants, then there is significantly more branching, a response which allows maximum exploitation of the favourable local light environment. Similar changes to those seen here in the morphology of clover in response to light quality are reported in many species and this emphasises the need for careful consideration of light quality in all CE experiments. This is particularly important when sources of radiation of differing in spectral output are used when light intercepted by plants must be measured in all morphogenetically important spectral regions.