Going Green
Lighting Design for Horticulture
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Illuminating Engineering Society

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What are the opportunities for professional lighting designers in the horticultural lighting market? Despite the rather breathless coverage being given to the topic in the solid-state lighting trade journals lately, the market itself is fairly small when compared to the overall lighting market. Various figures are available from market research reports, but a reasonable estimate is three percent, or about five billion USD a year in a 150 billion-a-year worldwide market. Most of this market, moreover, is for greenhouse lighting. Still, the are opportunities for professional lighting designers interested in an evolving market.

Now, my original plan for this presentation was to discuss the current state of horticultural lighting design practices, something that I have been doing since my 2016 Lightfair presentation, "LED lighting for Horticulture." I could continue (endlessly) on this theme, but I have something better. After three years of development, the IES Horticultural Lighting Committee has completed its work, and IES RP-45-21, "IES Recommended Practice: Horticultural Lighting," is currently being prepared for publication. As chair of the committee, I have the privilege of previewing its contents.

IES RP-45-21, Recommended Practice: Horticultural Lighting

- ~80 pages
- 26 authors
- 10 sections
- 150 references

First, a quick summary. The document is approximately eighty pages in length, with ten sections representing the combined knowledge of 26 authors from around the world. The IES mission statement talks about "bringing together those with lighting knowledge [and] translating that knowledge that benefits the public." The committee took this directive to heart, beginning with a botanist who was hired specifically to survey the academic literature regarding the effect of different spectral bands on plant photosynthesis, growth and development.

This was one of the issues that we encountered: despite some forty years or more of academic research spread across nearly one thousand papers published in over 100 journals, very little of this information has been translated into horticultural lighting design practice. RP-45 addresses this issue directly with in-depth discussions and references to the literature from both professional lighting designers and horticulturalists. The goal was the establish a document that serves as common ground for discussion and understanding.

IES RP-45-21, Recommended Practice: Horticultural Lighting

- Botany Overview
- Describing the Spectra of Optical Radiation
- Light Source and Luminaires
- Daylight
- Controlled Environments
- Agricultural Films
- Optical Sensors

The publication covers a diverse range of topics, beginning with an overview of botany and followed by a review of optical radiation and its effect on plants, from ultraviolet-C to near-infrared.

The discussion continues with the basics of daylighting (from a horticultural perspective) and controlled environments, including greenhouses and vertical farms.

Agricultural films might seem like a curious addition to a discussion of horticultural lighting, but they are important from the perspective of daylighting design, including photovoltaic films for electrical power generation.

Finally, there is the all-important discussion of optical sensors for horticultural lighting.

IES RP-45-21, Recommended Practice: Horticultural Lighting

- Annex A - Light Interactions
- Annex B – Recommended Daily Light Integrals
- Annex C – Lighting Design Process for Horticultural Lighting Projects
- Annex D – Plants and Atria

The four annexes are equally important. Written by a botanist, Annex A provides an in-depth review of the academic literature regarding how plants interact with optical radiation, including ultraviolet wavelengths.

Annex B provides essential information on how much light plants need each day. Nearly 100 different greenhouse crops and ornamental plants are listed.

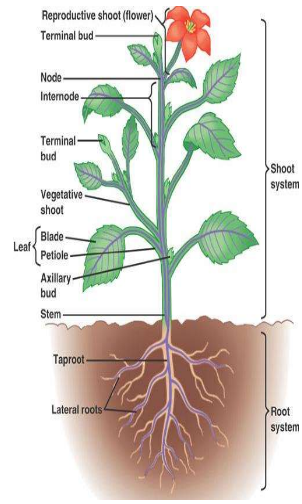
Annex C outlines the design process for horticultural lighting projects. It is almost the same as for architectural lighting design, but with a few key differences.

Finally, Annex D discusses horticultural lighting for building atria, including "living walls."

With this overview, it is time to look at the different sections in more detail

Botany Overview

- Photosynthesis
  - Conversion of visible light (400 nm – 700 nm) into chemical energy to fuel plant growth and development
- Photomorphogenesis
  - Any change in the morphology (shape) of plant or plant part in response to optical radiation (280 nm – 800 nm)
- Shade Avoidance
  - Changes in morphology, altered flowering time and partitioning of water and nutrients to maximize photosynthesis



The fields of plant biology and botany are wonderfully complex, with perhaps one thousand academic papers devoted to the response of plants to optical radiation. Fortunately, this is similar to the many medical research studies on circadian rhythms – professional lighting designers mostly need to know and understand just the basic concepts and terminology.

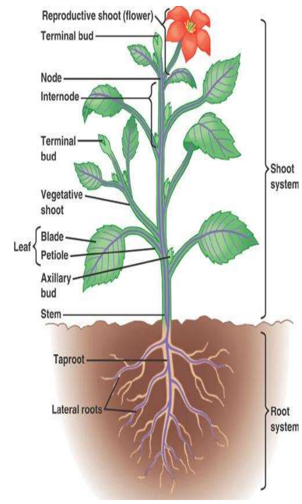
The most important topic is *photosynthesis*, where plants absorb visible light (400 nm to 700 nm) to convert carbon dioxide into complex sugars.

Next is *photomorphogenesis*, where optical radiation from 280 nm (ultraviolet-B) to 800 nm (far-red) influences how the plant grows and develops. This is where the spectral power distribution of the light source becomes important. Excess UV-B, for example, typically causes plants to become more compact, while the ratio of red (650 nm) to far-red (725 nm) strongly impacts how the plant grows in order avoid competitors and maximize its exposure to light. This is usually referred to as *shade avoidance*.

Floriculturists often use far-red light (formerly using incandescent lamps at night) to influence the flowering time in order to bring seasonal plants such as poinsettia to market. Today, special-purpose lamps with 660 nm and 725 nm LEDs fulfill this purpose.

Botany Overview

- Circadian Rhythms
  - Plants have daily cycles of activity and rest
  - Circadian rhythms and fluctuating temperatures inform plants when to flower
- Secondary Metabolites
  - Organic compounds not directly involved in plant growth, development and reproduction
  - Typically provide protection against environmental threats
  - Useful to humans as medicines, flavorings, pigments, and drugs



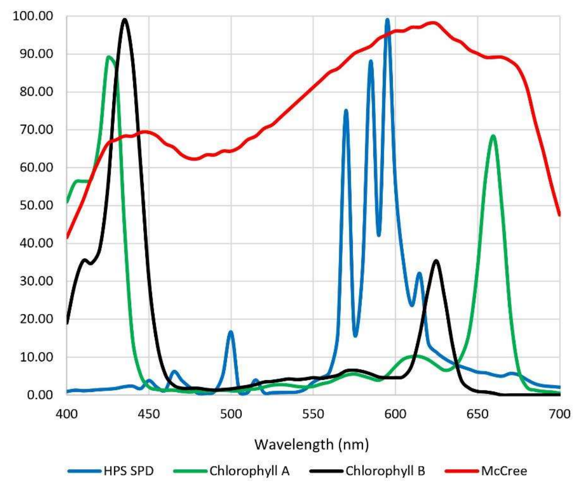
Professional lighting designers will be familiar with circadian-based lighting, so it should be no surprise that plants also have *circadian rhythms*. The length of day, for example, informs the plant what the season it is and when to flower for maximum reproductive success.

Beyond maximizing photosynthesis for rapid plant growth, the production of *secondary metabolites* by plants is hugely important to horticulturalists and farmers. The spectral power distribution of the light source can strongly influence this production, but the effect varies from species to species and even between cultivars, such as different varieties of lettuce.

There have been many studies done of the spectral requirements of different crops, but this information is scattered and not easily available. Lighting designers who take an interest in such information will have an advantage here.

Describing the Spectra of Optical Radiation

- Chlorophyll A and B
  - Responsible for absorbing light for photosynthesis
  - Plots shown absorption of pigments in solvent
- McCree curve
  - Shows photosynthesis activity versus wavelength
- Plants are complex organisms
  - Cannot predict behavior from analysis of *in vitro* photopigments



The spectral response of plants to optical radiation is a very complex topic. Many articles have been written about how 450 nm blue and 660 nm red LEDs are optimal for plant photosynthesis because these wavelengths correspond with the absorption peaks of chlorophyll A and B photopigments. However, these represent the absorption of chlorophyll extracts dissolved in a solvent such as ethanol. Many other components in the plant leaves interact with the absorbed light.

Photosynthesis activity – determined by the amount of carbon dioxide assimilated – versus wavelength is shown by the McCree curve. This explains why HPS lamps, which emit essentially no red and blue light, are effective as horticultural light sources.

Describing the Spectra of Optical Radiation

- Photosynthetic Photon Flux (PPF)
  - Same as luminous flux, but measured in number of photons (micromoles) per second (μmol/sec) rather than lumens
- Photosynthetic Photon Intensity (PPI)
  - Same as luminous intensity, but measured micromoles per second per steradian (μmol/sec-sr) rather than lumens per steradian (candela)
- Photosynthetic Photon Flux Density (PPFD)
  - Same as illuminance (lumens per square meter), but measured in micromoles per second per square meter (μmol/sec-m^2)
- Photosynthetically Active Radiation (PAR)
  - Can refer to either PPF or PPFD

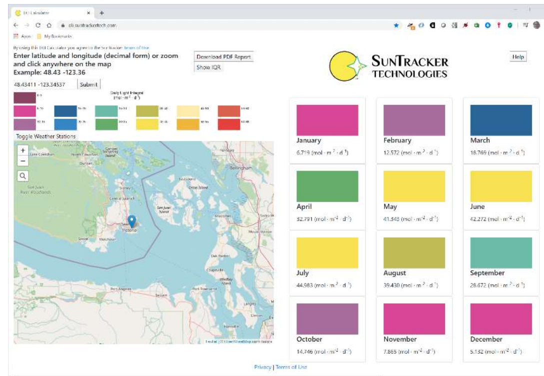
Photon metrics (<u>not</u> "photometrics") for horticultural lighting will be immediately recognizable to lighting designers.

The energy of an individual photon is inversely dependent on its wavelength – what we perceive as "blue" photons, for example, have more energy than "red" photons. For photosynthesis, however, the photon's energy does not matter – the plant absorbs the photon and initiates a chemical reaction; any excess energy is converted into thermal energy (i.e., heat). We therefore measure the number of photons in micromoles rather than in lumens or watts. (As a matter of interest, a *micromole* of light consists of 6.022 x 10^{19} – that is sixty billion billon – photons.)

With this, photosynthetic photon flux is the equivalent of lumens, photon intensity the equivalent of candela, and photon flux density the equivalent of illuminance.

Describing the Spectra of Optical Radiation

- Photoperiod
  - Cumulative amount of time during the day when plants are exposed to photosynthetic radiation
  - Varies outdoors depending on time of year
- Daily Light Integral (DLI)
  - Photosynthetic photon flux density integrated over 24-hour period
  - Measured in moles per square meter
  - All plants have minimum DLI requirements



Free online calculator for DLI calculations worldwide:

https://dli.suntrackertech.com/

Two of the most important concepts for horticultural lighting are *photoperiod* and *Daily Light Integral* (DLI). Whether the plants are grown in greenhouses, vertical farms, or building atria, they usually require a 24-cycle of light and dark. Plants, like animals, need time to sleep and restore their molecular machinery They further require a minimum amount of photosynthetic photon flux density each day (although too much light can harm them), which varies between species. (A common rule of thumb amongst horticulturalists is that a one percent increase in DLI equals a one percent increase in plant growth.)

To date, Daily Light Integral information has been available only for continental United States locations. This is not a commercial advertisement, just a statement that we have developed a free online calculator that can determine monthly DLI for any location in the world (including Canada) where World Meteorological Organization (WMO) data is available.

Light Sources and Luminaires

- High-Pressure Sodium (HPS)
  - Commonly used in greenhouses and vertical farms
- Metal Halide (MH)
  - Higher blue and UV content may promote flowering
- Light-Emitting Diodes
  - 450 nm blue and 660 nm red for photosynthesis
  - 725 nm far-red for photomorphogenesis
  - Full spectrum (inc. UV-A) for secondary metabolites
- Linear Fluorescent
  - Alternative to LEDs in vertical farms
- Plasma

Light sources are of course familiar to lighting designers. The only nuances are their application to horticultural lighting.

High-pressure sodium lamps have been the mainstay of greenhouse and vertical farm lighting since their introduction in the 1960s. Metal halide lamps are sometimes used for cannabis production because their higher blue and ultraviolet content reportedly promotes THC production in the flowers. However, their efficacy is less than that of HPS lamps.

Early LED luminaires featured 450 nm blue and 660 nm red because these wavelengths coincide with the peak absorption of chlorophyll A and B, thereby (in theory) maximizing photosynthesis. Plant flowering can be advanced or delayed using a combination of 660 nm red and 725 nm far-red LEDs. (This function was previously performed using incandescent lamps.)

Recent research has demonstrated that plants may also benefit from green light and possibly UV-A (315 nm – 400 nm) radiation. The only color that plants do not appear to respond to, apart from photosynthesis, is yellow (amber) … which exactly where HPS lamps emit most of their light.

Light Sources and Luminaires

- Diffuse light
  - Plants grown in greenhouses with diffusing glazing grow stronger and with improved health
- Inter-row and intra-row lighting
  - LED strip lighting between or within trellised vine tomatoes in greenhouses have improved photosynthesis
- Pulsed light
  - Pulsed lighting (kilohertz) improves photosynthesis
  - Flickering light ("sun flecks") beneficial for some crops grown in shady conditions

Greenhouse glazing has traditionally consisted of clear glass or rigid plastic panels, but studies over the past decade have shown that diffuse glazing results in higher photosynthesis rates, stronger plant stems, and less *leaf senescence* (i.e., premature aging) under the leaf canopy. It also prevents damage to leaves from overly intense direct sunlight.

Inter-row and intra-row LED strip lighting has proven effective in emulating the effects of diffuse greenhouse glazing, distributing the light to lower leaves that would otherwise be shaded and not fully contributing to photosynthesis. It is unclear, however, whether the additional expense justifies the benefits.

Pulse width modulation of LED lighting in the kilohertz range has also proven effective in improved photosynthesis rates, likely due to quirks of the complex photosynthesis process. Also, plants that grow on the forest floor in the wild respond to flickering sunlight – this can be easily emulated with LED lighting, although horticultural luminaire manufacturers have yet to explore the possibilities..

Light Sources and Luminaires

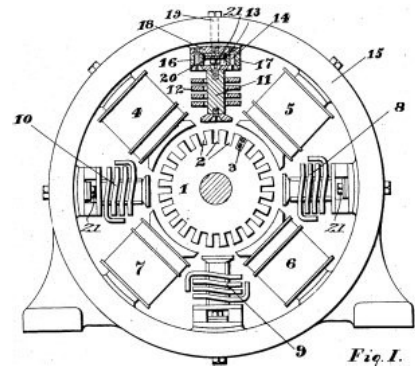
- Photon intensity distribution
  - Equivalent to luminous intensity distribution
- Photosynthetic Photon Flux Density (PPFD)
  - Equivalent to illuminance (lumens per square meter)
- Photobiological risks
  - Ultraviolet exposure risks for farm workers
- IP ratings
  - IP-65 and IP-66 water resistance
- Chemical corrosion resistance
- Passive and active cooling

The design and specification of horticultural luminaires is very similar to that of architectural and roadway luminaires. In fact, ANSI/ASABE S642 relies on IES test and measurement documents for LED modules as normative references.

Likely the only unfamiliar specification for horticultural luminaires will be active cooling, where cooling water is pumped through the luminaire heatsinks to improve LED efficacy.

Light Sources and Luminaires

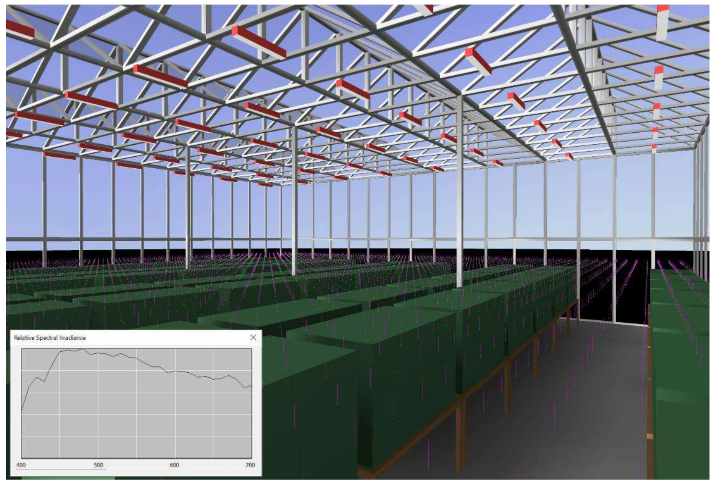
- Power factor
- Inrush current
- Surge protection
- Controllers



Lighting designers will again be familiar with these electrical requirements. Any electrical considerations that apply to architectural and roadway luminaires apply equally to horticultural luminaires.

Daylight

- Architectural lighting design software
  - Climate-based annual daylighting
  - TMY3 historical weather records
  - Glazing transmittance
  - Analytic diffusion
  - PAR sensor arrays
  - Spectroradiometers



Much of what lighting designers know about daylighting design, such as IES LM-83 requirements for climate-based annual daylighting and LEED daylighting design requirements, apply equally to daylighting design for greenhouses.

Unfortunately, today's architectural lighting design software does not have all of the features needed to model climate-based daylighting in architectural spaces. Suffice it to say, however, that horticultural lighting design software is under development.

Controlled Environment Agriculture

- 500,000 hectares

- 5,130,000 hectares

Ref: International Greenhouse Vegetable Production – Statistics (2018 and 2019). Cuesta Roble (Oak Hill) Consulting.

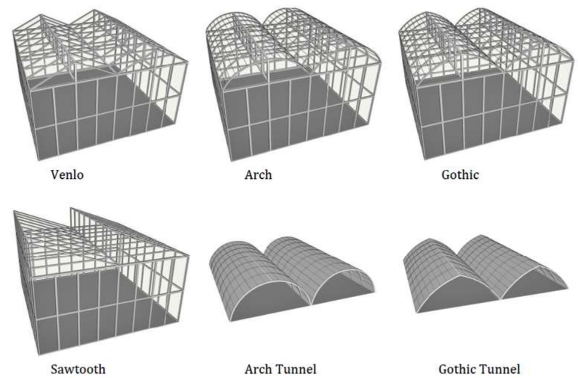
Controlled Environment Agriculture includes greenhouses, plastic-covered *polytunnels*, and fully-enclosed indoor *vertical farms*.

Make no mistake – there are a lot of greenhouses around the world, from Finland to New Zealand. Half a million hectares of glass greenhouses is nearly the size of Metro Toronto, while the plastic-covered polytunnels in southern Spain alone cover so much land that they are visible from the International Space Station.

The problem for lighting designers is that polytunnels do not require supplemental electric lighting, while the lighting used in greenhouses – currently a combination of high-pressure sodium (HPS) and LED luminaires – consists mostly of many thousands of the same product arranged in simple rectangular grids.

Controlled Environments

- Greenhouses
  - Daylight insolation determined by:
    - Site location and building orientation
    - Glazing
    - Roof styles
    - Energy curtains
  - Light pollution considerations
- Vertical Farms
  - Fluorescent or LED for tray lighting?
  - Government regulations (energy efficiency)
- Building Atria
  - Architectural considerations

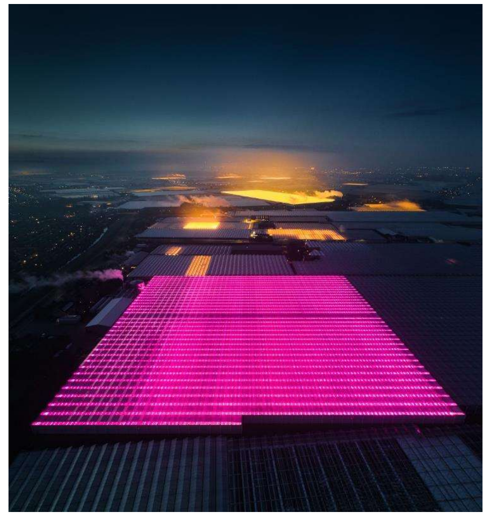


At present, the market for horticultural lighting consists of luminaire manufacturers who advise horticulturalists and farmers directly on what products to buy, and greenhouse manufacturers who design and install the buildings. The larger luminaire manufacturers provide basic light plan services using architectural lighting design software, but there is currently nothing available to predict the distribution of climate-based daylight inside greenhouses.

Aside from building atria, it is unclear whether there are market opportunities here for professional lighting designers. If anything, the opportunities will likely lie in being subject matter experts who can advise horticulturalists and greenhouse / vertical farm operators on the best lighting practices for different crops.

As one example, a prominent Ontario greenhouse operator specializing in tomato production had good success growing beefsteak tomatoes with LED lighting some six years ago, and spent millions on a full-scale installation for a different tomato variety. (There are over 10,000 documented tomato cultivars.) Unfortunately, the variety did not thrive, resulting in the lighting system having to be replaced.

Greenhouse Light Pollution



- Nothing to say …

In the meantime, any lighting designer who has worked with outdoor or roadway lighting will be familiar with the concerns of light pollution. This issue is subject to regulation in the Netherlands, where greenhouses operators must block 98 percent of the light at night … with no indication of how this is to measured. In Canada and the northern United States, it has recently drawn the attention of very irate neighbors and the threat of municipal bylaws.

The latest battleground in North America are the townships of Kingsville and Leamington, where over 1,000 citizens demanded by-laws to curb greenhouse light pollution. This particular battle is ongoing, pitting the municipalities with hastily-written and basically unenforceable by-laws against the Ontario Greenhouse Vegetable Growers Association. The problem is that neither side knows how to quantify light pollution or determine whether light abatement screens for greenhouse roofs and sides are successful.

Agricultural Films

- Ultraviolet blocking films
  - Block harmful UV-B radiation (280 nm to 315 nm)
  - Discourage insect pests
- Thermic films
  - Block mid-infrared radiation (3 μm to 50 μm)
  - Keeps soil warm at night
- Near-infrared blocking films
  - Limits water evaporation
  - Keeps soil cool during day
- Photovoltaic films
  - Absorb blue light and generate power

Finally, about those five million hectares of plastic-covered hoop greenhouses, or "polytunnels." While they may not use horticultural lighting, there is a growing selection of agricultural films available that have specific spectral transmittance distributions ranging from ultraviolet to mid-infrared. Choosing the right film involves knowing what daylight is available throughout the growing season and how the polytunnels are oriented … in other words, it requires climate-based annual daylighting knowledge and expertise – another potential opportunity for professional lighting designers.

Experiments are also been conducted with semitransparent photovoltaic polytunnel coverings, and with quantum-dot films that absorb ultraviolet radiation and emit blue and green light for increased photosynthesis in northern climates.

Optical Sensors

- Portable Spectroradiometer
  - Must provide absolute rather relative spectral power distributions
  - Preferably has 5 nm spectral bandwidth
  - Must have built-in PAR calculation function or appropriate software
- PAR (Quantum) Meter
  - Measures photosynthetic photon flux density (PPFD)
  - Same concept as illuminance meter
  - Output is micromoles per second per square meter (μmol/sec-m^{-2})

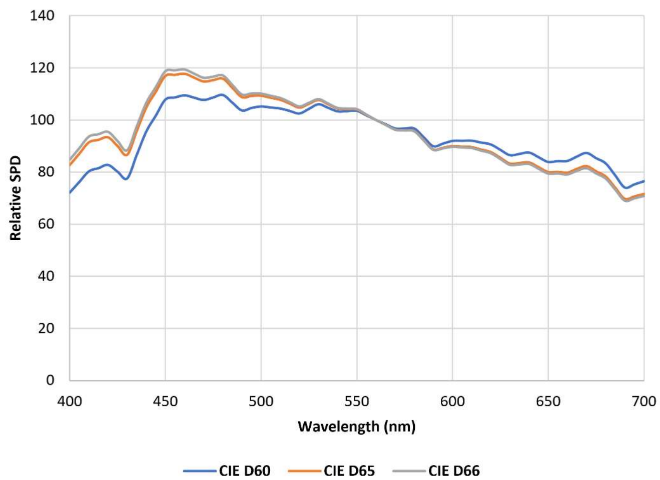
Professional lighting designers are more likely to own or have access to a portable spectroradiometer, either as a standalone unit or as a smartphone attachment, that provides absolute rather than relative spectral power distributions. For accurate measurements, the spectral bandwidth of the unit should be 5 nanometers. Less expensive units may have larger bandwidths (up to 10 nm), but they may provide less accurate results with semiconductor blue and red LEDs.

For horticultural lighting design, portable spectroradiometers must have either a built-in PAR calculation function or appropriate software than can calculate PAR units from downloaded SPDs.

PAR, or "quantum" meters, measures the photon flux density within the range of 400 nm to 700 nm, which is the nominal range of the spectrum that plants utilize for photosynthesis. A PAR meter is basically a photosensor with a color filter that provides the necessary spectral response to measure the quantity of photons (or "quanta") rather than their radiant or luminous flux.

The output of a PAR meter is expressed in micromoles (that is, the number of photons) per second per square meter.

Optical Sensors



- **DAYLIGHT ONLY !!!**
- Typical clear sky CCT is 6500K
- Typical overcast sky CCT ranges from 6000K to 6600K
- PAR conversion factor is 18.2 $\pm$ 0.2 kilolux per μmol/sec-m^{-2}

Source: Lee, R. L., and J. Hernández-Andrés. 2006. "Colors of the Daytime Overcast Sky," Applied Optics 44(27):5712-5722.

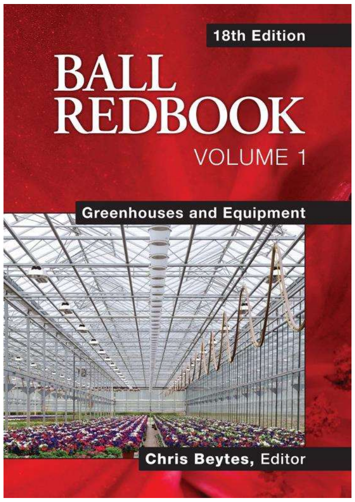
Illuminance meters should be used only for daylight measurements in greenhouses and in the field. The conversion factor for illuminance measurements to PPFD depends on the spectral power distribution (SPD) of the light source.

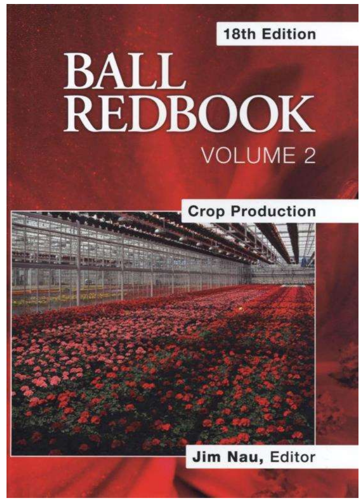
With high-pressure sodium lamps, the PAR conversion factor can vary by a factor of three to four, depending on the lamp SPD.

With LED luminaires, the spectral response of even laboratory-grade photometers can vary by a factor of two or more for blue and red LEDs.

Having said this, the CCT of daylight varies remarkably little throughout the day, regardless of whether the sky is clear or overcast. It therefore makes sense to recommend greenhouse crop illuminance levels in foot-candles rather than PAR units if daylight is the sole light source.

Horticultural Industry Bible



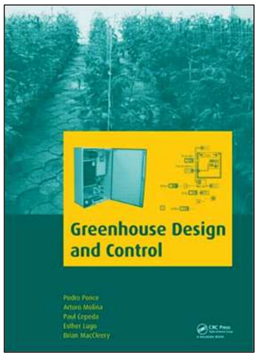


… which brings me to the two-volume Ball Redbook, an outstanding resource for greenhouse operators that has been in publication for over 80 years. The second volume lists over 160 flower, herb, and vegetable crops, most with recommended minimum light levels (in foot-candles) for optimum plant growth and development.

Having said, the IES Horticultural Lighting Committee must thank Ball Publishing for providing the material for Annex B, Recommended Daily Light Integrals, from their forthcoming 19th edition of the Ball Redbook. Writing IES RP-45 really has been a collaborative effort between the IES and the horticultural industry.

Greenhouse Design and Control

- Several excellent books on greenhouse design are available:



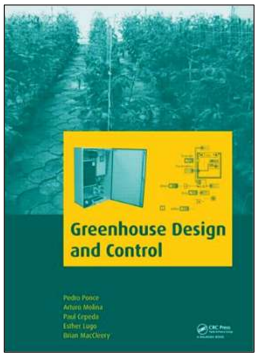
Ponce, P., et al. 2015. Greenhouse Design and Control. CRC Press.

- Site selection
- Structural design and materials
- Cladding materials
- Foundations and floors
- Ventilation and heating
- Irrigation and CO_2 enhancement
- Sensors and controls
- Automation
- Et cetera

I will also take the opportunity to recommend another excellent book, titled Greenhouse Design and Control, from CRC Press. If an engineering firm is considering adding not only horticultural lighting but overall greenhouse design to their repertoire of design services, this is a must-have book.

Greenhouse Design and Control

- … but with nothing on lighting !



Ponce, P., et al. 2015. Greenhouse Design and Control. CRC Press.

“The light level in the greenhouse should be adequate and uniform for plant growth.”

I would be remiss, however, in not mentioning a glaring omission: this is the summary of the book’s discussion of lighting for greenhouses:

> “The light level in the greenhouse should be adequate and uniform for plant growth.

If this suggests that there are at present few horticultural lighting experts, it would be hard to disagree.

Horticultural Lighting Standards

- American Society of Biological and Agricultural Engineers (ASABE)
  - S640, Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms)
  - S642, Recommended Methods for Measurement and Testing of LED Products for Plant Growth and Development
  - S644, Performance Measurements of Electromagnetic Radiation Systems for Radiation (in preparation)

There are also emerging industry standards for horticultural lighting. The American Society of Biological and Agricultural Engineers (ASABE) has, in close collaboration with IES members and horticultural luminaire manufacturers, published two ANSI industry standards and is currently preparing a third standard.

S640 formally defines some 33 radiant and photon metrics for optical radiation pertinent to horticultural lighting. S642 (which is currently being revised) basically extends the various IES publications on LED product testing and measurements for horticultural applications. S644, currently in preparation, discusses how to design horticultural lighting applications, mostly for greenhouse applications.

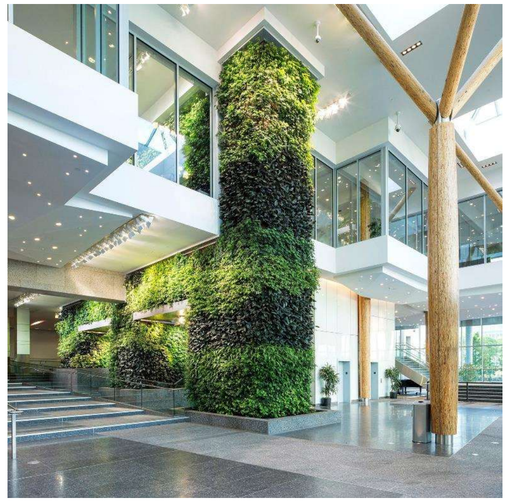
Vertical Farms

- Vertical Farms / Plant Factories
  - Cannabis
  - Leafy green vegetables
  - Medicinal plants
- 30 to 40 percent of building energy consumed by lighting
- 10,000 to 25,000 lux for seedling
- 40,000 to 60,000 lux for mature plants

Greenhouses in northern climates typically need supplemental electric lighting during the morning and evening hours, with 1,000-watt HPS or 600-watt LED luminaires commonly used. However, the true energy hogs are vertical farms, with 30 to 40 percent of the building energy being consumed by lighting of closely-spaced trays for lettuce, basil, spinach and other plants amenable to being grown quickly in confined spaces.

Building Atria

- Building Atria / Living Walls
  - Tropical plants
  - Trees
- 1,500 lux for living walls
- 2,500 to 7,500 lux for atria with trees
- Trees need to be acclimatized (3 to 18 months) in outdoor nurseries to survive lower light levels



Finally, building atria and living walls. Healthy plantings in building atria need to be carefully planned such that the plants have sufficient light during the daytime for photosynthesis (but not too much in order to limit growth rates and prevent flowering), darkness at night in accordance with their photoperiod requirements, relative humidity levels of at least 50 percent, and possibly supplemental carbon dioxide.

Larger plants and especially trees further need to be acclimatized in outdoor nurseries in order to thrive under lower light levels than they typically experience when growing outdoors.

Thank you

Questions?
ian.ashdown@suntrackertech.com

Enough talking – IES RP-45 will be published soon, and it will provide a wealth of information that I could only touch on here.

Thank you for your time.