Horticultural Lighting Guide

Foundations for effective horticultural lighting

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"The more I learn, the more I realize how much I don't know."
-Albert Einstein

Attempting to research and engage with horticultural lighting strategies may leave you feeling like Einstein, for better or worse.

The following guide is the application of a decade of learning at TotalGrow to provide the foundations to facilitate effective horticultural lighting discussions and planning to meet your growing goals with confidence.

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2. Light Quantity
   a. DLI
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   c. PPFD → PPF
3. Light Quality
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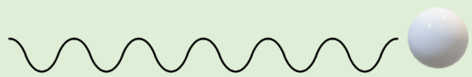
Key Terms

Horticultural lighting foundations and discussions must begin with an understanding of the key terms that allow the quantification of light in the manner most relevant to plants.

- Photons – Tiny packets of energy emitted by a light source (the sun or artificial lights). Each photon has the potential to be absorbed by the plant to drive photosynthesis or other reactions.
    - For human lighting, lumens/lux/foot-candles of a light represent how bright they are to the human eye. Because plants utilize light differently we must focus on the quantity and color of photons.



- Spectrum – The color or mix of colors of light. More precisely, each photon has a specific wavelength, measured in nanometers (nm), which corresponds to a color. Spectral effects discussed below.

- Photosynthetically Active Radiation (PAR) – The spectral region that generally best drives photosynthesis, including 400-700nm photons.
    - The less used, but arguably better region on which to focus is Plant Biologically Active Radiation (BAR) from 280-800nm to incorporate other important photons and their effects as well.

- Daily Light Integral (DLI) – The quantity of photons that hit a surface in a 24-hour period.
    - Think of a 1m X 1m box (approx. 10.8 sq. ft.) filling up with photons like a bucket fills up with rainwater. The DLI is the number of photons collected per day in that area, measured in moles per square meter per day (mol/m^2/day).
    - One mole of photons is 602,200,000,000,000,000,000,000 photons. We use "moles" to make the numbers manageable, e.g. a northern US greenhouse might receive 5 mol/m^2/day DLI on a winter day.

- Photosynthetic Photon Flux (PPF) – The quantity of photons emitted from a light every second. This is the best single quantification for the growing power of a light, measured in micromoles per second (μmol/s).
    - Think about a hose spraying water. PPF is like the total flow rate of water spraying out.
    - Micromoles are one millionth of a mole, which again makes numbers more manageable when addressing photons per second, e.g. most grow lights emit 100 – 2,000 μmol/s.

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- Photosynthetic Photon Flux Density (PPFD) – The quantity of photons hitting a surface at any moment.
  - Using the box imagery from DLI, this is how quickly the 1m² box is filling up with photons, i.e. the intensity of the light at a leaf surface, measured in micromoles per square meter per second (μmol/m²/s). Comparing to water, PPFD would be how quickly the bucket is filling.

- Photoperiod – The portion of a 24-hour period with light. For example, a spring/fall day has around a 12-hour photoperiod with 12 hours of darkness. A winter day has a shorter photoperiod; a summer day has a longer photoperiod. Short day plants flower with short (12 or less hour) photoperiods; long day plants flower with longer photoperiods (>12 hours, may require 14+ hours).
  - Considering only the artificial lights, the photoperiod is how long the light is on each day. Longer photoperiods allow greater DLI's like leaving a hose on longer fills a bucket more.

- Photoperiodic Light – Providing light during dark hours to increase the photoperiod perceived by the plants. This is done to keep short day plants vegetative or to force mature long day plants to flower, and it can be accomplished with low intensities of light with the proper spectrum (red + far-red light is universally effective).

- Supplemental Light – Providing extra light in an environment with insufficient sunlight to achieve the desired plant growth.
  - Assimilation Light is a less used term encompassing both supplemental (i.e. greenhouses) and sole source (i.e. grow rooms) lighting.

Light Quantity

While there are several very important aspects of horticultural lighting, the single most important factor is the quantity of light. If too few photons of light are delivered, plants cannot grow with good quality and yields.

A helpful analogy is comparing water sprinklers filling a bucket to photons hitting a plant. We are concerned with the flow rate out of each sprinkler (PPF coming from a light), the flow rate actually entering each bucket (PPFD hitting a plant), how long the sprinklers are running (photoperiod), and how full the bucket gets from a day of watering (DLI).

> 1% more light will generally drive approx. 1% more growth.

DLI

Ultimately, the most important metric is the DLI (Daily Light Integral). This determines how much energy a plant receives each day to facilitate life and growth. The best DLI to target depends on the crop, stage of growth, environmental conditions, crop values, and business model/goals (maximize yields vs. minimize costs). The table below provides the typical range of reasonable DLI targets for various crops, along with the PPFD and the artificial lighting photoperiod for great results. Working with a lighting specialist will help you discern a more precise target level to achieve your goals. Especially at lower light levels, each 1% increase in DLI corresponds to about 1% more growth, so this has a huge impact on overall success.

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Crop/Stage	DLI (mol/m²/day)	Sole Source PPFD (µmol/m²/s)	Supplemental PPFD (µmol/m²/s) *Depends on location*	Photoperiod (hours/day)
Cuttings	4-10	120	40	18
Seedlings	6-15	150	60	18
Finishing Ornamentals	10-20	230	70	18
Cut Flowers	15-25	300	150	18
Grafting	5-7	100	30	18
Microgreens	6-14	200	60	18-24
Leafy Greens, Herbs	10-17	260	80	18
Strawberries	17-25	300	150	12/18
Cucumbers, Peppers	20-40	500	200	18
Tomatoes	20-50	600	250	18
Cannabis Cloning	8-14	150	30	18-24
Cannabis Vegetative	20-40	500	250	18
Cannabis Flowering	25-60	1000	500	12

DLI → PPFD

The interaction between DLI and PPFD, which is critical for determining an appropriate light plan, can be understood better with an application example as shown below:

- Application – Leafy green vertical farm
- DLI target – 17 mol/m²/day to optimize growth (higher light levels can cause tip burn; lower light levels will proportionally decrease yields)
- No natural light
- Maximum safe photoperiod – 18 hours/day
    - 20 hours/day is less commonly used, but appears effective to increase DLI without adverse effects for almost all crops

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- Convert the 17 mol/m²/day DLI target to PPFD (μmol/m²/s) by converting moles to μmoles and an 18-hour day to seconds:
  - 17 mol/m²/day X 1,000,000 μmol/mol ÷ 18 hours/day ÷ 60 minutes/hour ÷ 60 seconds/minute = 262 μmol/m²/s needed from artificial lights
    - Simplified, DLI X 278 ÷ Hours/Day = PPFD
    - Further simplified – use this DLI Calculator

This process becomes more complicated in a greenhouse where the natural light levels are variable. Here is an example growing the lettuce in a greenhouse instead of fully indoors:

- Application – Michigan greenhouse for year-round lettuce
- DLI target – 10+ mol/m²/day, ideally around 17
- Greenhouse DLI without lights – approx. 5 mol/m²/day in December
  - We generally recommend providing enough light to meet the minimum acceptable light level at the darkest time of year. Extra light won't be useful during brighter months, causing a slower ROI on lighting investments impractical for many crops.
  - Based on these U.S. Daily Light Integral Maps and about 40% light loss due to greenhouse structures and materials, the inside of a typical Michigan greenhouse in December receives approx. 5 mol/m²/day naturally.
- Minimum supplemental light target - 5 mol/m²/day to achieve 10+ total DLI
- Maximum safe photoperiod – 18 hours/day
- Convert the 5 mol/m²/day supplemental DLI target to PPFD (μmol/m²/s) based on 18 hours/day by converting moles to μmoles and an 18-hour day to seconds:
  - 5 mol/m²/day X 1,000,000 μmol/mol ÷ 18 hours/day ÷ 60 minutes/hour ÷ 60 seconds/minute = 77 μmol/m²/s needed from artificial lights.

PPFD → PPF

With a PPFD target selected, the PPF needed from all of the lights to cover all of the grow areas can be estimated. This estimate then allows refinement of a light plan based on the requirements and limitations of the grow structures.

A rough estimate can be made by considering the PPFD target, the grow area size, and proportion of emitted light expected to reach the grow area.

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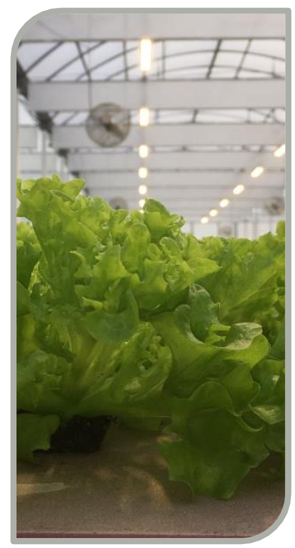
High Light Preservation (85-95% delivered)	Low Light Preservation (50-75% delivered)
Large grid of lights (spilled light is shared)	Isolated lights (spilled light is wasted)
High reflectivity (walls/barriers reflect light)	Low reflectivity (light escapes/is absorbed)
Low-hanging lights (tighter light patterns)	High-hanging lights (wider-spread light)

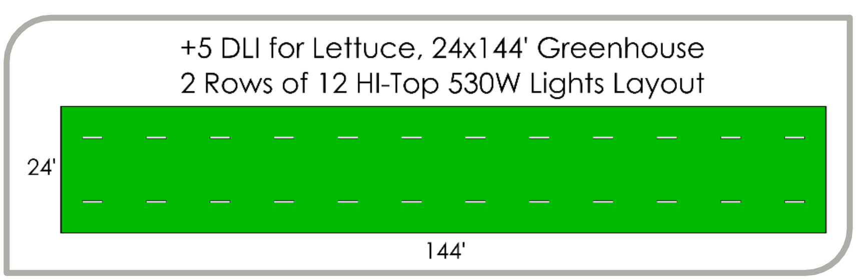
An expansive grow area with a large grid of lights, a grow room with excellent reflectivity, and/or placing lights relatively close to the canopy minimizes light spillage and waste to deliver 85-95% of the light. A setup that has few lights, poor reflectivity and/or high-hanging lights may waste as much as 50% of the light.

It is also wise to factor in future light losses as lights get dirty and have some years of use which causes small reductions in output and light delivery by providing 10% extra light initially.

Using the lettuce greenhouse example again, here is how this plays out:



- The PPFD target is approx. 77 $\mu mol/m^2/s$
- For a single bay with a 24′ x 144′ grow area, we will calculate the area in square meters:
  - 24 ft X 144 ft ÷ 10.76 ft^2/m^2 = 321 m^2
- The PPFD and area determine the PPF that we need to deliver to the plants:
  - 77 $\mu mol/m^2/s$ X 321 m^2 = 24,700 μmol/s to deliver to the plants
- Light spillage will be moderate with a single, long bay, so we will start with an estimate of 80% light delivery, and we will only plan around 90% of each light's output to budget for future losses:
  - 24,700 μmol/s to deliver ÷ 80% delivery ÷ 90% light maintenance = 34,300 μmol/s PPF that we need from our lights.
- If we use the TotalGrow 530W HI-Top with 1380 μmol/s PPF per light, we need about 24-25 lights for this approach:
  - 34,300 μmol/s needed ÷ 1380 μmol/s per light = 24.9 lights
  - 2 rows of 12 lights (12′ x 12′ spacing) is often a very convenient setup to install, so we will round down to 24 total lights as long as the greenhouse structure facilitates this setup.



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Light Quality

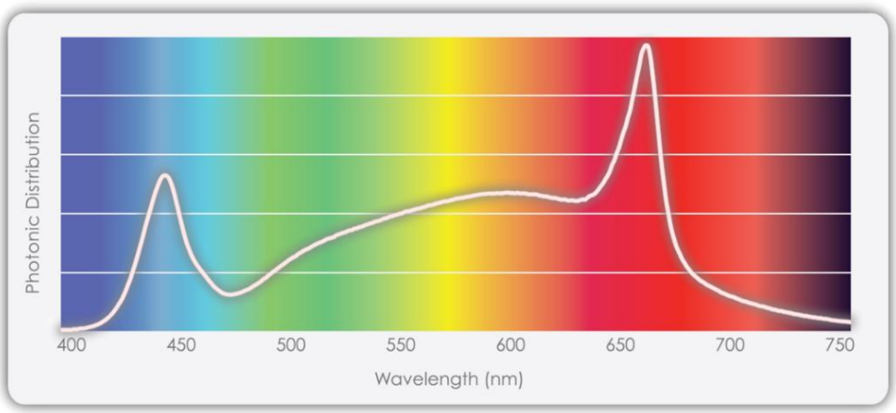
In addition to how much light is provided, plant growth can be strongly influenced by the light spectrum and uniformity. Managed poorly, morphology will be undesirable and different parts of a grow area will have bad variances in yields, quality, nutrient uptake, and water consumption. Handled well, a good light spectrum and uniformity contribute significantly to efficient, even, high quality growth.

Light Spectrum

Before recent advancements in LEDs, there was relatively little research on the effects of different light spectra on plants, and little incentive to learn. Especially in the past 10 years this has rapidly changed with constant research. There are helpful generalizations that can be made, but it is important to acknowledge that:

- There is no such thing as a perfect spectrum.
  - The light spectrum interacts with many other variables such as the light intensity, crop variety & genotype, temperature, CO_2 concentrations, nutrients, and more. The most desirable growth traits also vary between grower, customer, crop, and stage of growth.
- We are still learning.
  - With so many confounding variables and constantly improving technologies enabling the production of novel spectra and ways to deliver light, there are sure to be things we think we understand today that will prove incorrect or incomplete.

Nonetheless, helpful generalities can and should be made to facilitate decision-making. The general effects of the 4 main light regions are described below along with the Spectral Quantum Distribution (SQD) of a standard full-spectrum TotalGrow LED light with 18% blue, 37% green, 41% red, and 4% far-red output:



Blue Photons (400-499nm)	Green-Yellow Photons (500-599nm)	Orange-Red Photons (600-700nm)	Far-Red Photons (701-800nm)
• Drive dense plant growth • Support plant health and appearance • Support root development and nutrient production • Stimulate chlorophyll production and gas exchange	• Provide the least amount of growth per photon • Provide the best penetration for subcanopy growth • Enable visual health assessment	• Most efficient at driving plant growth • Best chlorophyll absorption • Critical for flowering and day length control	• Support total plant function • Enhance the photosynthetic efficiency of other wavelengths • Enable day length control

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The main LED spectrum decisions to be considered are:

- Full spectrum or narrow spectrum
    - A narrow spectrum is typically mostly red with some blue light. It is used because red LEDs can provide the highest efficiencies and are absorbed well for photosynthesis.
    - "Full" spectrum is a term used inconsistently, but at a minimum indicates the inclusion of the green-yellow spectrum, and may also include far red and/or UV radiation in order to stimulate all photomorphological responses for more balanced, natural growth.
- Low / Medium / High Blue, i.e. quantity vs. quality
    - Generally, higher proportions of blue light will drive higher quality growth with reduced yield, e.g. approx. 20%+ blue output.
    - Far red has the strongest opposite effect to blue, followed by green then red light, driving more expansion growth for typically greater biomass but less density, coloration, etc.

There is also growing interest and research into the effects of UVA and UVB light. UVA is similar to blue light, but is less effective at driving photosynthesis, so more of the UVA energy can potentially drive morphological effects including increased chemical concentrations. UVB is a more dangerous light region that also has potential to increase chemical concentrations and pathogen resistance, but it can also do more harm than good for the crops and workers.

Uniformity

When a lighting setup does not match a growing setup well, a common problem is a lack of uniformity. Excessive light in some areas and insufficient light in others results in uneven growth/yields, water consumption, nutrient use, labor requirements, and finishing times. Uniformity must be addressed situationally since every setup is unique. A quality lighting manufacturer will be able to model the PPFD light levels across a grow area for a given light setup to ensure that it truly matches growing goals. After installation, a light meter can be used to confirm uniformity at the plant heights.

Light modeling and/or measurements are necessary to ensure good light uniformity, but a few principles should be considered if you are unable to do this:

- Higher hang heights increase uniformity, but they result in reduced light delivery as more light is spilled beyond the edges of a grow area.
- Lower hang heights focus the light into smaller areas which may decrease uniformity.
- A greater quantity of lower-powered lights and/or the use of wider lights increase uniformity by decreasing the space between lights.

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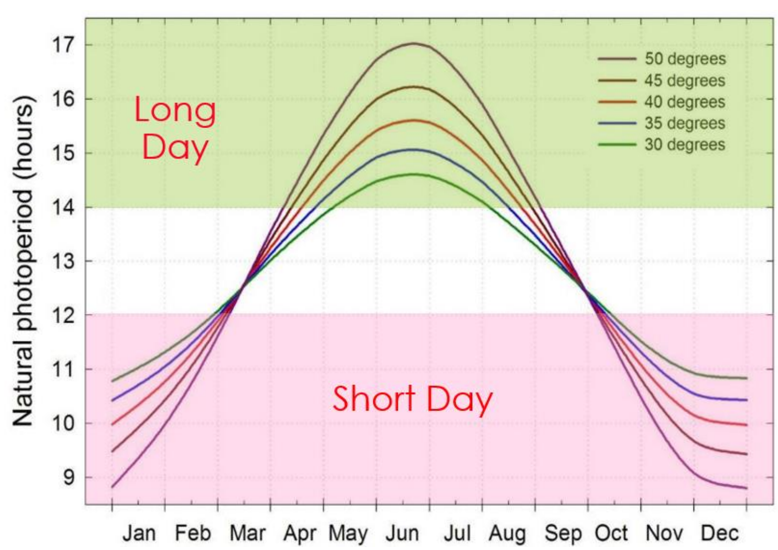
Assimilation (Supplemental or Sole Source) vs. Photoperiodic Lighting

Especially for greenhouse growers it is essential to determine whether the lighting goal is assimilation lighting, i.e. grow lighting, or photoperiodic lighting:

- Assimilation (Grow) Lighting – artificial lighting used when the quantity of natural light is insufficient to achieve the desired growth rates, quality, yields, etc.
    - High intensities of light are needed to increase DLI. Can be compared to a bucket → Faster flow rates/higher light intensities + longer durations of water/light flow provide more energy to grow bigger, faster, and better.
    - In a greenhouse this is called supplemental light.
    - Where there is no sunlight this is called sole source lighting.

- Photoperiodic Lighting – artificial lighting used when the duration of natural light is insufficient to trigger or inhibit flowering. For short day plants this maintains vegetative growth. For long day plants this triggers flowering of mature plants.
    - Lower intensities of primarily red and far red light increase the photoperiod.
    - Can be compared to flipping a light switch → The light "wakes the plant up" to trigger a specific response.
    - The graphic below shows when natural lighting alone triggers long-day and short-day responses based at U.S. latitudes. Photoperiodic lighting triggers long-day responses when natural lighting is insufficient.



Source: Erik Runkle, Michigan St. University

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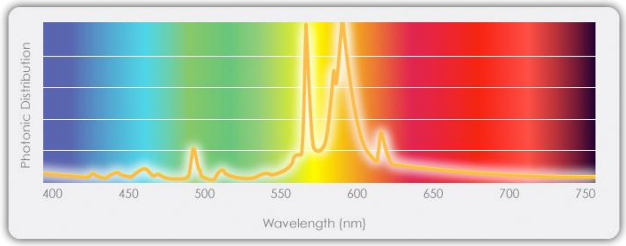
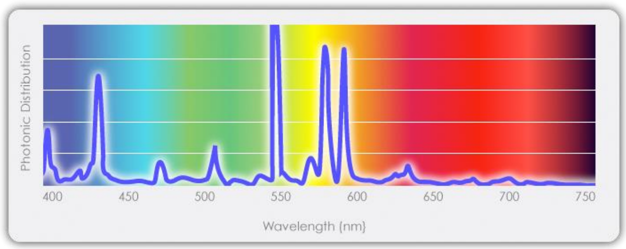
Light Selection

The two main categories of lights to choose between are HID (high intensity discharge) lights, including HPS (high pressure sodium) and metal halides, and LED lights. Fluorescent lights are also an option for low-intensity, multi-tier production, and incandescent lights were historically used for photoperiodic lighting. There are pros, cons, and variations for each type of light, and generalizations are dangerous because there will always be exceptions.

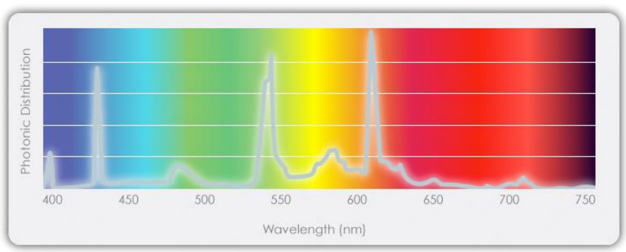
- High Pressure Sodium lights are the traditional standard light for any high intensity application.
    - The light appears yellow-orange due to minimal blue output, a majority output on the orange end of the green spectral region, and moderate red output. This is moderately efficient at driving photosynthesis (red), weak at driving quality growth (blue), and good at providing penetration (green).
    - Efficiencies and longevity are better than other typical legacy lights but less than quality LEDs.
    - Heat is mostly radiated, requiring extra space between the lights and plants. Surfaces are heated proportionally to the light levels provided.



- Metal Halide lights use the same principles as HPS with different gases to produce a different spectrum.
    - The light appears white with a blue tint due to higher blue output, a majority green output and minimal red output. Traditionally this was used to improve vegetative growth quality compared to HPS.
    - Newer Ceramic Metal Halides have a more balanced spectrum and better efficiencies, but again less than quality LEDs.
    - Heat is mostly radiated.



- Fluorescent lights have a similar spectrum to metal halide lights, but lower, more diffuse output impractical for greenhouses and high intensity spaces. They can be useful for a lower cost, lower efficiency, and lifespan option for tiered grow setups. There is some flexibility in light spectrum selection with different CCTs.



- LEDs can be made with a huge variety of shapes, powers, spectra, efficiencies, features, longevities, etc. Focusing only on higher quality horticultural LED lights, general characteristics include:
    - Light spectra designed around the application – generally including a majority red output supported by other light regions based on growing goals.

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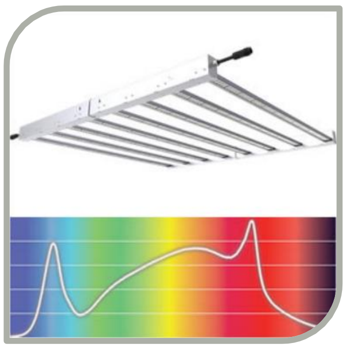
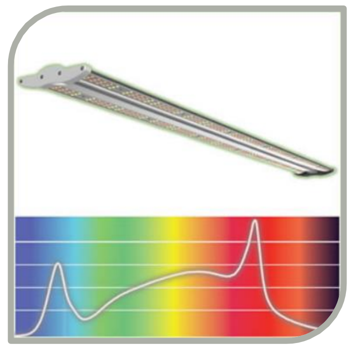
- o Efficiencies typically 50-100% higher than traditional lights. However, lower quality LED lights can be even less efficient than traditional lights; beware of lights that do not list PPF outputs and μmol/J efficacies as their performance may severely underwhelm!
- o Longevities typically 5X or longer than traditional lights. Again, lower quality LEDs can be much worse.
- o Shapes can match the application environment to reduce shading and/or increase uniformity as needed.
- o Heat is dissipated. Temperatures underneath the light are not directly increased, but heat is released into the air to more "gently" increase room temperatures.





In general, it is most economical to use the highest-powered light style within the constraints of the PPFD target and setup space. More constrained spaces and/or lower PPFD targets require lower powered lights. Discerning the best fit requires guidance from a trusted lighting manufacturer because there are several interacting variables, including:

- Max/min mounting height --- higher heights = greater coverage with lower PPFD
- Length and width of the area to be lit --- matching light arrangements to the space
- Shape of the light fixtures --- matching the space and uniformity/shadow reduction needs
- Beam angles --- how quickly the light spreads out with height
- Electrical & support infrastructure --- minimizing upfront costs and shadowing

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There is great value in understanding what horticultural lighting can and cannot accomplish and what criteria are necessary to successfully meet one's goals. It is also critical to identify trustworthy and effective partners to provide the expertise and capabilities that would be impractical for a grower or business owner to master. The experienced team at TotalGrow strives to provide the information, solutions, and service needed to ensure your greatest success and satisfaction for the life of your growing project. Please contact us for personalized advice and light planning, and visit totalgrowlight.com for more information about TotalGrow products.

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