ENERGY-EFFICIENT, UNIFORM, SUPPLEMENTAL PLANT LIGHTING FOR RESEARCH GREENHOUSES

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Abstract:

Teaching and research greenhouses at universities and research stations typically require supplemental plant lighting. Lighting for research greenhouses is unlike lighting for commercial greenhouses; aisles are often wider to permit group access, only parts of the greenhouse may contain plants, and light requirements may differ from place to place throughout the growing space. This paper describes an innovative luminaire reflector design that can provide a rectangle of light uniformly where and when required. With the luminaires housing Philips Elite AGRO® 315 W ceramic metal halide lamps, as an example, 280 µmol m^{-2} s^{-1} of PPF can be provided 1.07 m below the luminaire, with no light falling outside the boundary of the lighted area and providing a 0.91m x 1.83m lighted area with a uniformity CV of 0.05 over the entire pattern. Luminaires can be mounted to provide larger or smaller lighted rectangles, or spaced to create adjoining or overlapping rectangles, creating lighting patterns with greater or less light intensity, greater or less vertical light uniformity, and different lighted areas, all with comparable CV values. Sections of benches can be controlled individually to provide different daily light integrals, or other control protocols may be used. The luminaire was designed using commercial computer software and this paper presents light values from those simulations to demonstrate the flexibility of the resulting luminaire. The paper discusses a multiplicity of ways to combine and overlap light patterns to produce a wide range of uniform PPF intensities, while retaining the capability to light plants without wastefully spilling light onto the aisles, or lighting sections of benches temporarily empty of plants.

INTRODUCTION

Academic and industrial professionals who rely on greenhouses for research and teaching typically use less than a full greenhouse for an experiment (or class demonstration) but luminaires may not be individually operable to light only a portion of the bench space without harming uniformity. Researchers are able to achieve better statistical sensitivity for data analysis when plant lighting is uniform, which is typically not the case when a single row of luminaires is installed over the top of a bench. Required photosynthetic light intensities may need to be varied from bench to bench when lighting is a parameter to be varied in an experiment, and perhaps even within the same bench. Commercial growers seek a high benching ratio (often 90% or greater) for best space use efficiency, but research greenhouses and growth rooms typically require wide aisles to accommodate specialized research equipment and groups of people (such as students). For numerous reasons, lighting objectives for research greenhouses can differ from plant growth chambers or commercial greenhouses. With these considerations, the efficacy (mol/kWh) of lighting a greenhouse with lighting everywhere uniform can be expressed as

$$\frac{useful}{mol/kWh} = \frac{luminaire}{mol/kWh} x \frac{benching}{ratio} x \frac{ratio\ benches}{occupied} x \frac{ratio\ occupied\ benches}{requiring\ lights}$$

Even when each ratio is as large as 0.8 in a greenhouse with general lighting, the useful light reduces to just over half of the light from the luminaire, meaning nearly half is wasted.

Previous work by the authors (de Villiers, et al., 2012) reports how "beam shaping" can be used to create luminaire reflectors that provide uniform lighting patterns for plant growth chambers and, when coupled with a newly available 315 W, ceramic metal halide (CMH) lamp from Philips Lighting®, creates a significantly more efficient lighting system. That philosophy, using computer-driven reflector design, is carried forward into this work.

This paper reports a plant lighting luminaire design methodology that provides a uniform, rectangular light pattern that can illuminate greenhouse benches in modular (domino) fashion. Modularity permits (1) lighting only bench sections as needed, (2) location-specific dimming options, (3) overlapping light patterns for higher light intensities, but (4) precludes spilling light into the aisles, where it is wasted. Computer design software is used as the means to evaluate and predict light patterns. Planned future work includes luminaire fabrication and testing in a greenhouse as the next step to bring the design to commercial availability.

METHODS

An inventory of benches within the Cornell research and teaching greenhouses showed widths of 0.91, 1.22, 1.52 and 1.83 m and lengths from 4.3 to 8.5 m. To achieve economic and energy efficiency, the goals of this project were simplified to having a single luminaire design to irradiate, uniformly and adequately, the range of greenhouse bench sizes at Cornell. Restricting light to only the benches (minimizing light spilling onto the aisles) suggested a design that, by adjusting only the mounting height, uniformly irradiates benches of various widths (Fig.1.)

Having determined the luminaire layouts for various bench widths, illumination software (Photopia®, LTI, Westminster CO) was used to determine optimal spacing between luminaires at different mounting heights; target efficiencies; luminaire efficiencies; as well as average irradiation levels, max/min, avg/min, and CV values. Results indicated a rectangular beam with 2:1 aspect ratio will irradiate an area of 1.67 m^2 at a luminaire mounting height of 1.07 m and produce at least 280 µmols m^{-2} s^{-1} over a 0.91 m wide bench when used with the Philips Elite Agro® 315 W lamp (Fig. 2.) An aspect ratio of 2:1 permits equal spacing between luminaires when a 50% overlap of the beams is employed, while effectively doubling irradiation on the plant canopy (Fig. 3), yet retaining uniform irradiation.

If luminaire mounting height increases by 1/3, the rectangular beam irradiates a bench 1.22 m wide, with concomitant irradiance reduction. A further mounting height increase by the same distance expands the beam to cover a bench 1.52 m wide, while reducing irradiance further (Fig. 1.) A bench 1.83 m wide can be irradiated as two benches, each 0.91 m wide. A 1.52 m wide bench can also be irradiated as two benches, 0.76 m wide (Fig.4). If greater PPF intensity (>800 µmol m^{-2} s^{-1}) is desired, then four luminaires can be configured as in Fig.5.

RESULTS

The irradiation pattern on a 0.91 m wide table from a single luminaire is shown in Fig. 6, with accompanying photometric data. The illumination plane is divided (rows and columns) into squares 15 cm on a side. PPF values are calculated by averaging over the squares. Photometric results with two luminaires spaced 1.9 m apart are shown in Fig.7. Photometric results with a 50% beam overlap in the center area, and luminaire spacing of 0.95 m, are shown in Fig. 8. Photometric results with four luminaires spaced at 1.68 m in two rows 0.84 m apart on a 1.52 wide table are shown in Fig. 9. Results for a layout with 50% beam overlap to minimize spill light at the end of a 1.52 m wide bench are shown in Fig. 10. Mounting height is 0.9 m and spacing between the luminaires is 0.84 m, as it is in Fig. 9.

DISCUSSION

Luminaire design considers seven factors: energy efficacy, luminaire size and shape, lamp and ballast performance, the illumination plane and mounting height, beam modularity, adaptability to higher lamp wattage, and manufacturing ease. The factors are discussed below.

- Energy efficiency: Luminaire efficacy is determined by PPF (µmol s^{-1}) delivered to an illumination plane and is a function of both the conversion of wall plug electricity to PPF by the lamp and delivery by the reflector of that PPF to the illumination plane. Reflector efficiency is measured as the fraction of lamp radiation delivered to the illumination plane. Total solid angle capture of lamp radiation by the reflector and its effectiveness in reshaping the radiation into the required beam determines reflector efficiency. A reflector material with high specular reflectance assures maximum collection of lamp radiation and beam control for delivery to the illumination plane.
- Luminaire size and shape: The luminaire should be kept as small as possible to minimize shadowing of natural solar radiation. A vertical lamp position was used to maximize control of the beam and assure irradiation uniformity over the illumination plane. In the vertical position, lamp radiation is directed to the reflector. The reflector shape was designed to capture the maximum amount of lamp radiation and redirect it into a uniform rectangular beam.
- Lamp and ballast: The 315 W Elite Agro® lamp from Philips Lighting delivers 1.95 PPF/watt from a small emitter in a compact lamp package. A small emitter in a compact lamp package permits a smaller reflector, which reduces solar shading. The Elite Agro lamp uses a light cap and holder (socket) system. Two pins of different shape on the cap twist and lock into the holder, permitting the lamps to be always mounted in the same focal position and orientation in the reflector. The specific fit of the pins in the holder guarantees accurate positioning of the lamp with the reflector. The lamp ballast is electronic, compact, and dimmable to 50%
- Mounting Height: Many research greenhouses are old, with low gutter heights, necessitating low luminaire mounting heights. The 2x1 luminaire produces a bundle of rays that cross the central axis, creating an area of maximum flux density. This area was designed to be as close to the luminaire aperture as possible, permitting low mounting heights without creating a hot spot on the plant canopy. To accommodate the various bench widths, the mounting height ranges from 0.89 m for 50% overlapping of the 1.52 m wide bench to 1.78 m for the non-overlapping beams on the 1.52 m bench.
- Modularity: The 2x1 luminaire design permits a variety of luminaire layouts to accommodate the various bench widths. Fig. 11 is provided to demonstrate the flexibility of the proposed luminaire and its ability to achieve a wide variety of uniform irradiation values over several common bench widths.

- Adaptability: The 2x1 Luminaire was designed to accommodate either the 315 W or the 600 W Philips Elite Agro lamp. The 600 W lamp is still in the prototype stage and should be available later this year. Computer modeling indicates the 600 W luminaire should increase PPF by 85%.
- Manufacturability: High reflectance sheet aluminum is an ideal material for energy efficient reflectors. The deposition of thin metallic and ceramic films on sheet aluminum can produce surface specular reflectance values up to 0.98 (15% higher than anodized aluminum) while protecting against surface damage, humidity, dirt pick-up and static dust attraction. Unfortunately, forming the material over a deeply drawn shape damages the surface finish on the aluminum. A new method of preparing sheet aluminum before forming is being tested by Cycloptics with the goal of remedying this problem. First prototypes are anticipated by the end of March, 2012.

Literature Cited

De Villiers, D.S., L.D. Albright and R. Tuck. 2012. Next-Generation, Energy-Efficient, Uniform Supplemental Lighting for Closed-System Plant Production. Acta Hort. (in press.)

Acknowledgements

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FIGURES

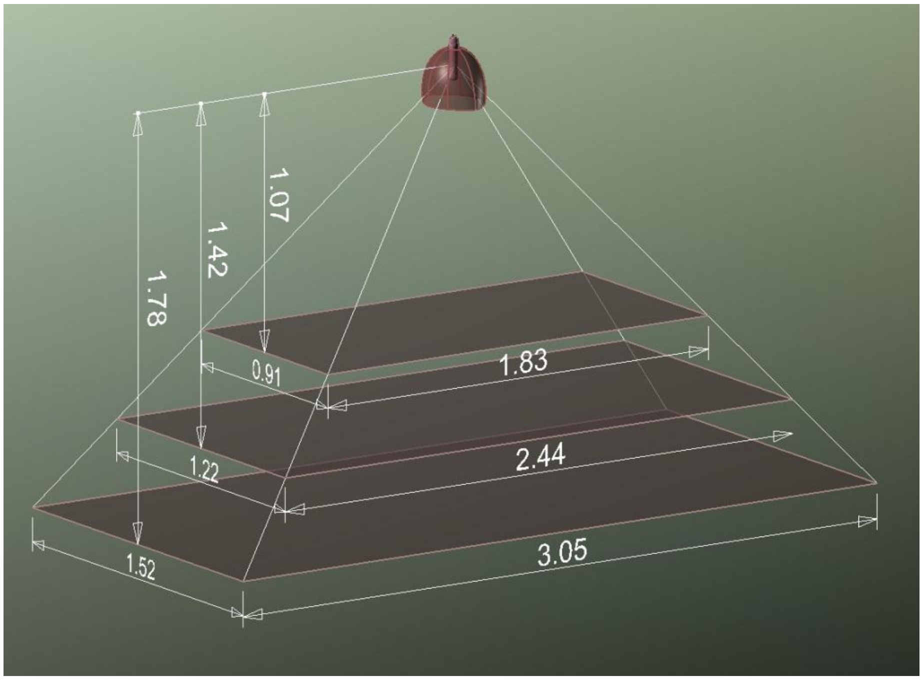


Figure 1. Light spread and beam coverage on a greenhouse bench as a function of luminaire mounting height.

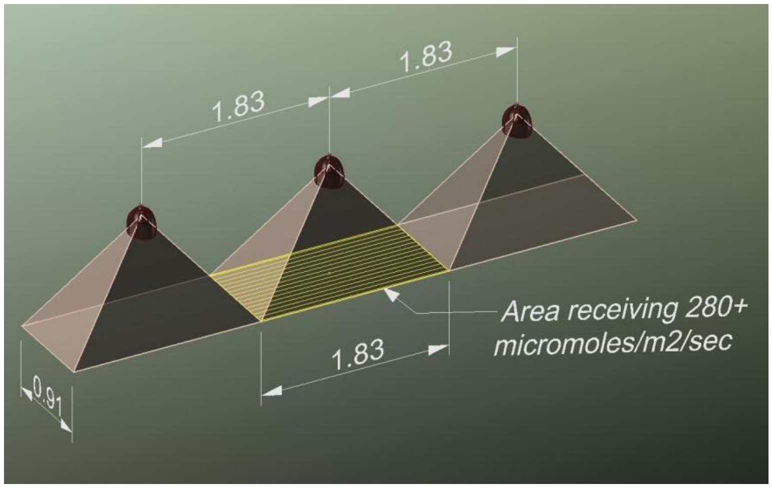


Figure 2. Luminaire arrangement for a narrow bench and moderate PPF irradiation.

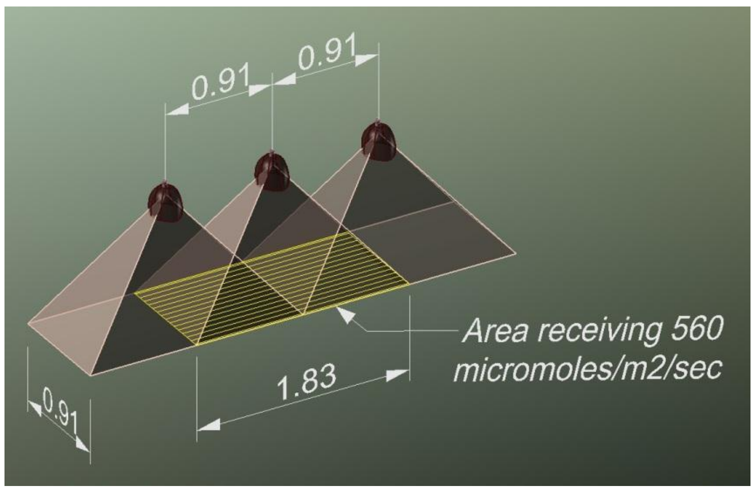


Figure 3. Using overlapping uniform light patterns to double PPF intensity

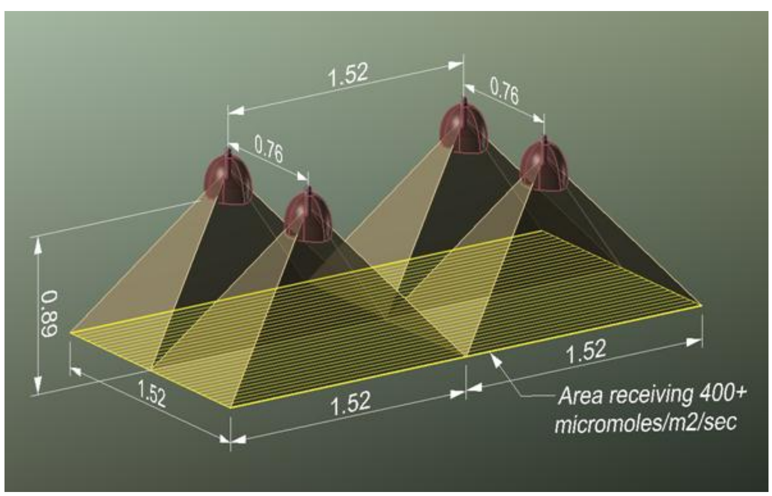


Figure 4. Four non-overlapping luminaires with the mounting height reduced by half

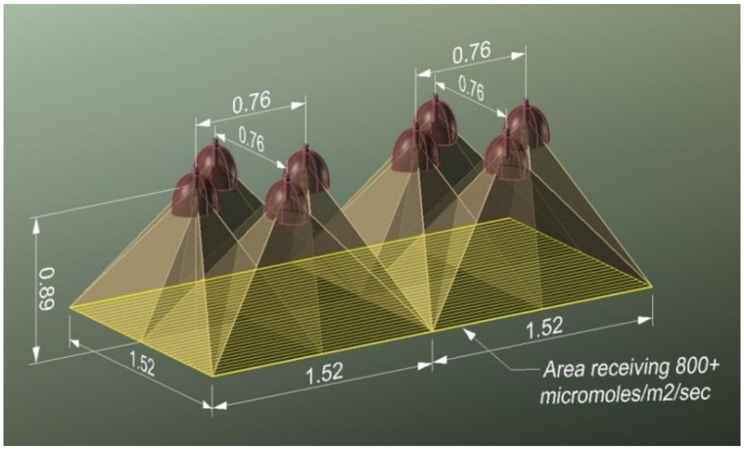
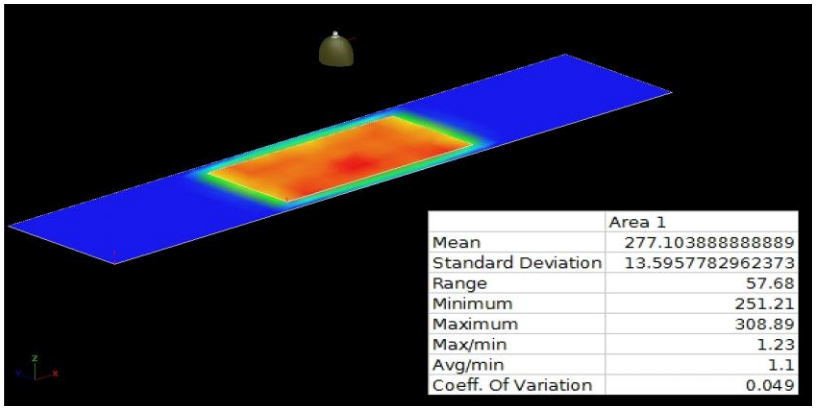
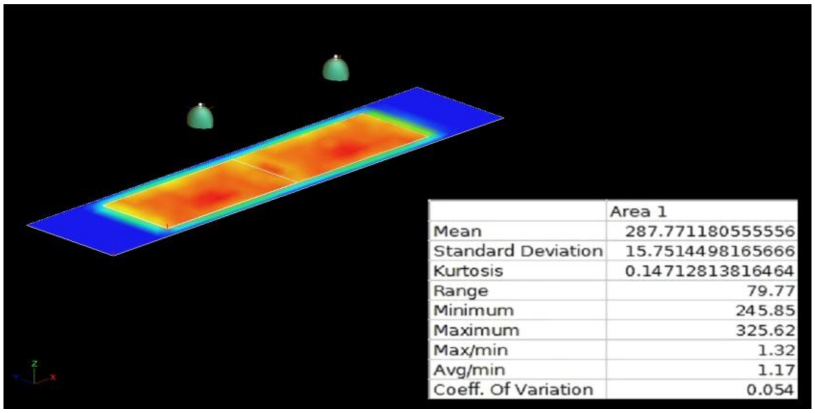


Figure 5. Luminaire arrangement to achieve high PPF irradiation on a wide bench.



	Area 1
Mean	277.103888888889
Standard Deviation	13.5957782962373
Range	57.68
Minimum	251.21
Maximum	308.89
Max/min	1.23
Avg/min	1.1
Coeff. Of Variation	0.049

Figure 6. Photometric results of a single luminaire irradiating a bench 0.91 m wide, with no light spilled to the aisles



	Area 1
Mean	287.771180555556
Standard Deviation	15.7514498165666
Kurtosis	0.14712813816464
Range	79.77
Minimum	245.85
Maximum	325.62
Max/min	1.32
Avg/min	1.17
Coeff. Of Variation	0.054

Figure 7. Photometric results of two luminaires spaced 1.9 m apart irradiating a bench 0.91 m wide, with patterns abutting but no light spilled to the aisles or ends of the bench.

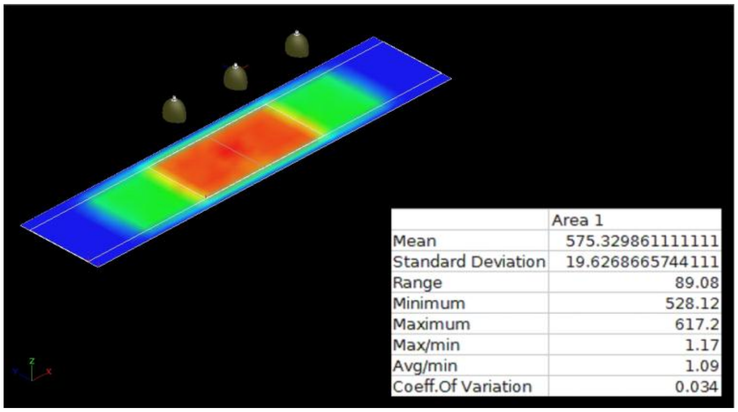


Figure 8. Photometric results of three luminaires spaced at 0.95 m for 50% overlap and irradiating a bench 0.91 m wide, but no light spilled to the aisles and little spilled to the ends of the bench.

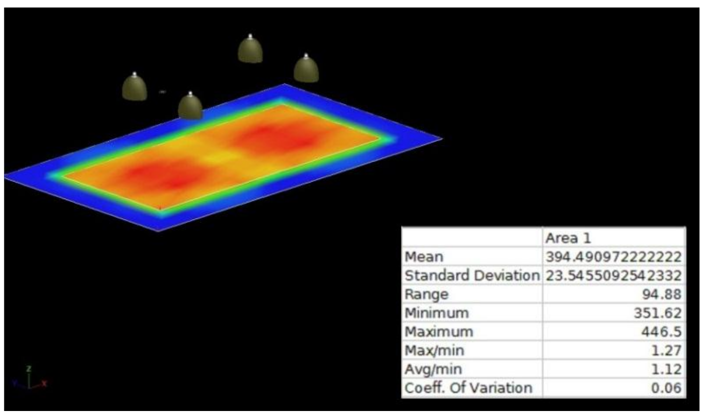


Figure 9. Photometric results of four luminaires with mounting height 0.9 m and spaced at1.68m along the bench and 0.84m across the bench, irradiating a bench 1.52 m wide.

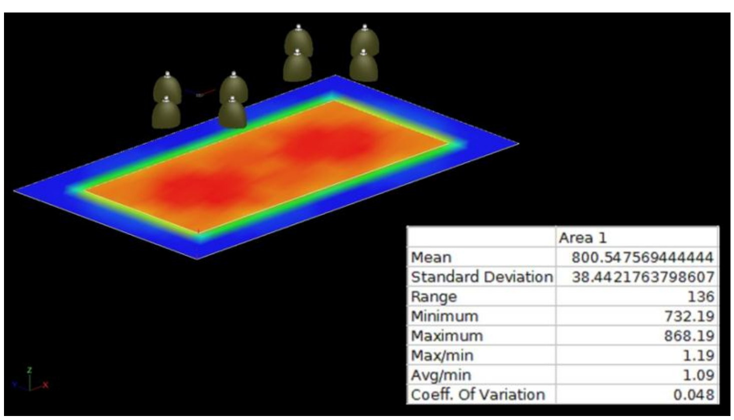


Figure 10. Four luminaires spaced 0.84 m apart in a grid for 50% overlap and irradiating a bench 1.52 m wide, with no light spilled beyond the bench. Mounting height is 0.9 m

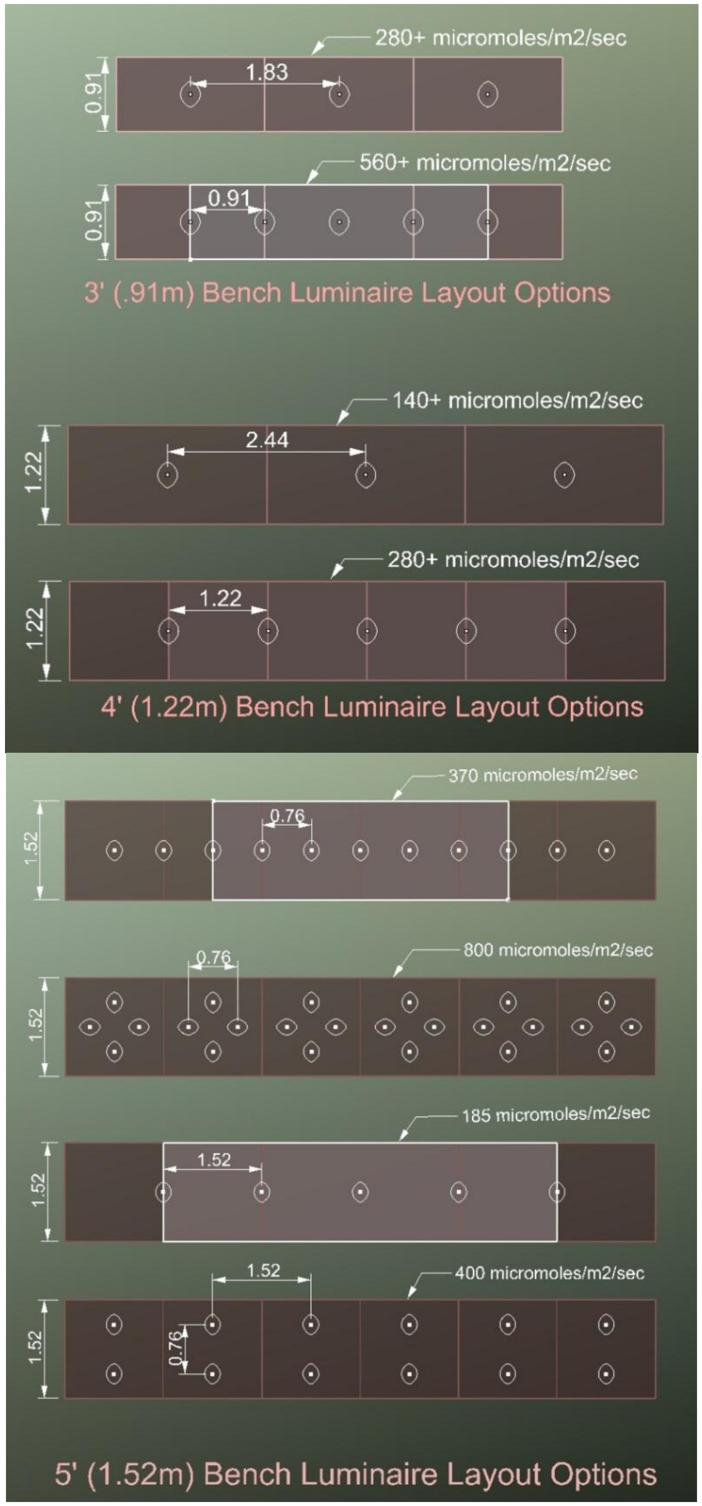


Figure 11. Example luminaire layouts for three common bench widths, with a variety of achievable irradiation intensities.