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Jacob A. Nelson

Bruce Bugbee
Utah State University, bruce.bugbee@usu.edu

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Supplemental greenhouse lighting:
Return on Investment for LED and HPS fixtures

Jacob A. Nelson and Bruce Bugbee
Crop Physiology Laboratory
Utah State University

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LED fixtures are being marketed as a replacement for high pressure sodium fixtures in greenhouse lighting. Here we compare the cost per photon for LED and HPS fixtures based on their ability to convert electrical energy into photons delivered to a horizontal surface below the fixture. Some LED fixtures now exceed the efficiency of the best HPS fixtures by 23%, but the initial capital cost per photon delivered is 5 to 10 times greater. HPS fixtures with electronic ballasts and optimized luminaires (reflectors) are 27% more efficient than widely-used HPS fixtures with magnetic ballasts. Our analysis, however, demonstrates that light distribution and radiation capture are more important than the electrical efficiency of the fixture. No single fixture is optimal for all applications. The lowest cost per photon is realized when an efficient fixture is coupled with effective radiation capture, but the value of uniform plants may outweigh the cost of wasted photons. Just as precision irrigation can improve water use efficiency, precision lighting can improve electrical use efficiency.

The importance of light distribution

Lighting technologies vary widely in how radiation is distributed (Figure 1). There is no ideal pattern. In large greenhouses with uniformly spaced plants, a broad, even output pattern (e.g. the Cycloptics 315W, Ceramic Metal Halide (CMH) fixture) provides the most uniform light distribution. In smaller greenhouses, or areas with spaced benches, a more focused pattern can maximize radiation falling on plants. As the area covered by plants gets smaller, the need for focused radiation increases (Figure 2).

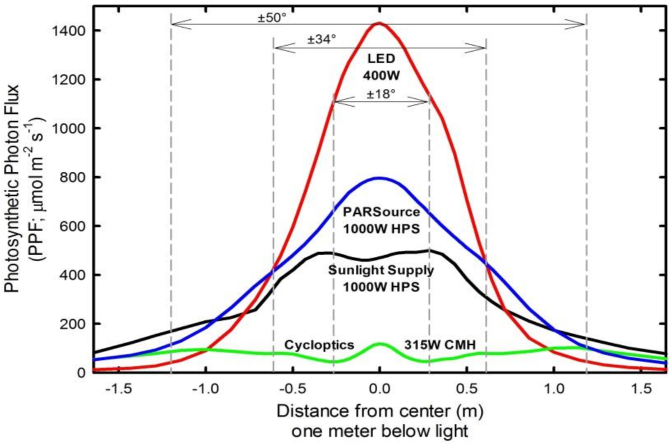

Figure 1. **The light distribution of four fixtures with similar PPF efficiency. The LED fixture (Lighting Sciences Group) uses optics to achieve a narrow distribution, with the majority of the photons falling in a concentrated pattern directly below the fixture. Conversely, the Cycloptics CMH fixture is designed for even light distribution, and therefore casts uniform radiation over a large surface area. Since the area increases exponentially as the distance from the center increases, the PPF farther from the center is weighted more than the photons at the center.**

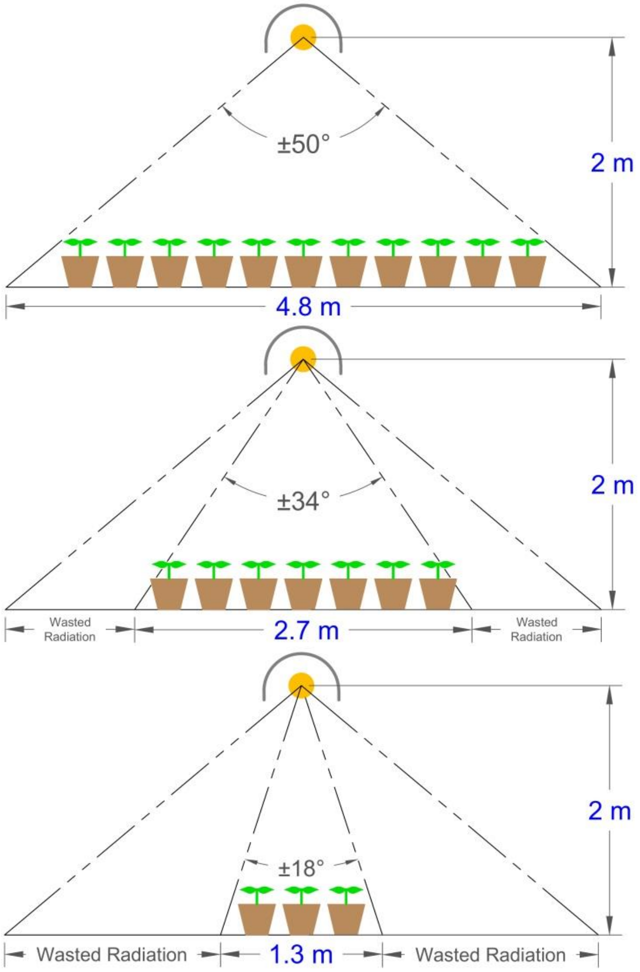

Figure 2. **As the plant growth area under the fixture gets smaller, wasted radiation often increases. Values are shown in meters, but this can be scaled as a unit-less ratio. Multiple overlapping fixtures are typically used to achieve uniform light distribution.**

Table 1. PPF efficiency and cost per mole photons
Assuming all radiation is captured by plants

Lamp Type and Ballast	Fixture Manufacturer See Table 5 for more information	Voltage Input	Electrical Input (J/s or Watts)	PPF Output[1] (µmol/s)	PPF Efficiency[2] (µmol/J)	Energy Requirment (400-700 nm) (J/µmol)	Energy Efficiency[3] (400-700 nm) (%)	Cost of one Fixture[4] ($)	Fixtures needed per mmol photons per second[5]	Cost of Fixtures per mol photons per second[4] ($)	Electric Cost per mol photons[6] $\$/(^{mol}/_{s})$*yr	Five Year Electric plus Fixture Cost per mol photons[7] $\$/(^{mol}/_{s})$*yr	Ten Year Electric plus Fixture Cost per mol photons[7] $\$/(^{mol}/_{s})$*yr
High Pressure Sodium													
400 W Magnetic	Sunlight Supply	120	443	410	0.93	0.202	18.9	$200	2.44	$0.49	$0.36	$0.41	$0.32
1000 W Magnetic	Sunlight Supply	120	1067	1090	1.02	0.206	21.0	$275	0.92	$0.25	$0.32	$0.33	$0.27
1000 W Magnetic	PARsource	208	1004	1155	1.15	0.206	23.7	$350	0.87	$0.30	$0.29	$0.31	$0.25
1000 W Electronic	PARsource	208	1024	1328	1.30	0.206	26.7	$380	0.75	$0.29	$0.25	$0.28	$0.23
LED													
Red/Blue	Lighting Sciences Group	120	391	626	1.60	0.194	31.1	$1,200	1.60	$1.92	$0.21	$0.56	$0.35
Red/White	Lighting Sciences Group	120	397	599	1.51	0.192	29.1	$1,200	1.67	$2.00	$0.22	$0.59	$0.37
Red/Blue	Lumigrow	120	317	266	0.84	0.199	16.7	$1,200	3.77	$4.52	$0.39	$1.24	$0.76
Red/White	Illumitex	120	281	384	1.37	0.192	26.3	$1,200	2.60	$3.13	$0.24	$0.83	$0.50
Ceramic Metal Halide													
315 W 3100 K (Agro)	Cycloptics	208	337	483	1.44	0.209	30.0	$700	2.07	$1.45	$0.23	$0.49	$0.32
315 W 4200 K	Cycloptics	208	340	456	1.34	0.214	28.7	$700	2.19	$1.54	$0.25	$0.52	$0.34

[1]-Integrated total photosynthetic photon flux (PPF) output of fixture.
[2]-PPF Output per Electrical Input (µmol per second divided by joules per second).
[3]-Energy Output per Electrical Input (watt per watt).
[4]-Cost of fixtures as of June 2013.
[5]- The number of fixtures to get 1 mmol (1000 µmol) of photons per second.
[6]- Assumes 3000 hours per year operation and $0.11/kWh.
[7]-Cost of fixture (multiplied by fixtures needed) plus cost of electricity over 5 or 10 years.
Electric rates have been discounted at a 5% per year interest rate to account for the time value of money.

The PPF efficiency and cost per mole of photons for three types of lighting systems, in several fixtures, are shown in Table 1. Most fixtures (lamp, luminaire and ballast) are now more efficient than the common magnetic-ballast HPS fixtures from Sunlight Supply (1.02 µmol per joule). Table 1 assumes that all PPF distributed on a horizontal surface is absorbed. In Table 2, the area in which the radiation is considered captured by plants is progressively reduced, and the cost per mole of photons increases as more photons are lost around the perimeter. The lowest cost per photon is realized when a large area of plants can be arranged to capture the photons.

Table 2. Cost per mole photons for four PPF capture assumptions

Lamp Type and Ballast	Fixture Manufacturer See Table 5	**Assuming all radiation (±90°) is captured**		**Assuming radiation within a 1 to 2.38 height to width ratio (±50°) is captured**		**Assuming radiation within a 1 to 1.35 height to width ratio (±34°) is captured**		**Assuming radiation within a 1 to 0.65 height to width ratio (±18°) is captured**	
		Fixtures needed per mmol photons per second[1]	Five Year Electric plus Fixture Cost per mol photons[2] $\$/(^{mol}/_{s})$*yr	Fixtures needed per mmol photons per second[1]	Five Year Electric plus Fixture Cost per mol photons[2] $\$/(^{mol}/_{s})$*yr	Fixtures needed per mmol photons per second[1]	Five Year Electric plus Fixture Cost per mol photons[2] $\$/(^{mol}/_{s})$*yr	Fixtures needed per mmol photons per second[1]	Five Year Electric plus Fixture Cost per mol photons[2] $\$/(^{mol}/_{s})$*yr
High Pressure Sodium									
400 W Magnetic	Sunlight Supply	2.4	$0.41	4.0	$0.67	8.6	$1.43	32.5	$5.42
1000 W Magnetic	Sunlight Supply	0.9	$0.33	1.6	$0.57	3.4	$1.21	12.3	$4.41
1000 W Magnetic	PARsource	0.9	$0.31	1.3	$0.47	2.8	$1.01	9.5	$3.39
1000 W Electronic	PARsource	0.8	$0.28	1.1	$0.42	2.5	$0.92	8.4	$3.10
LED									
Red/Blue	Lighting Sciences Group	1.6	$0.56	1.7	$0.60	2.1	$0.74	5.3	$1.87
Red/White	Lighting Sciences Group	1.7	$0.59	1.8	$0.63	2.2	$0.78	5.5	$1.96
Red/Blue	Lumigrow	3.8	$1.24	4.0	$1.33	6.2	$2.04	19.2	$6.35
Red/White	Illumitex	2.6	$0.83	2.7	$0.87	3.9	$1.24	12.1	$3.89
Ceramic Metal Halide									
315 W 3100 K (Agro)	Cycloptics	2.1	$0.49	5.6	$1.31	20.2	$4.77	99.0	$23.38
315 W 4200 K	Cycloptics	2.2	$0.52	5.9	$1.39	21.1	$5.01	102.4	$24.28

[1]- The number of lamps to get 1 mmol (1000 µmol) of photons per second.
[2]-Cost of fixture plus cost of five years of electricity times the number of lamps needed; 3000 hours per year operation and $0.11/kWh.
Electric rates have been discounted at a 5% per year interest rate (time value of money).

If photons coming out of the fixture at all angles are considered (±90^{o}), LED fixtures cost about 7 times more per photon than electronic ballast HPS fixtures. This makes the five year cost per mole of photons about twice that of electronic ballast HPS fixtures (Figure 3, Top). When only highly focused radiation is considered useful (±18^{o}), some LED fixtures have a lower cost per photon than HPS fixtures (Fig. 1, Fig, 3 Bottom, Fig. 4), but because photons are lost around the perimeter at this narrow angle, the cost per photon absorbed by plants is much greater.

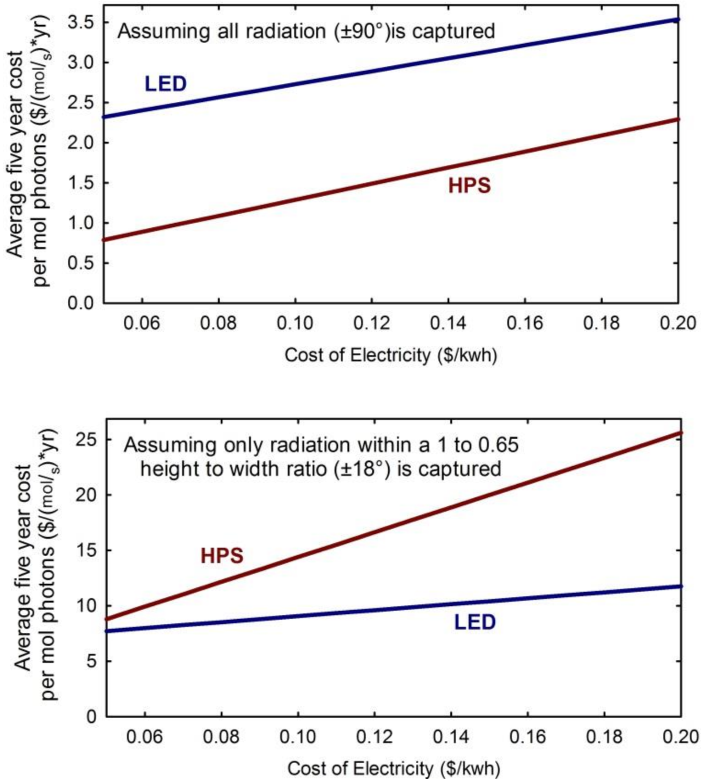

Figure 3. **(TOP) When all radiation is assumed captured, HPS fixtures (electronic ballast, PARSource) have a lower five-year cost per photon than LEDs (Red/Blue fixture, Lighting Sciences Group). (BOTTOM) When only a narrow region below the fixture (±18°) is considered to be captured (e.g. on benches), the LEDs have a lower cost per photon then HPS fixtures, but the cost per photon increases almost ten-fold for both fixtures.**

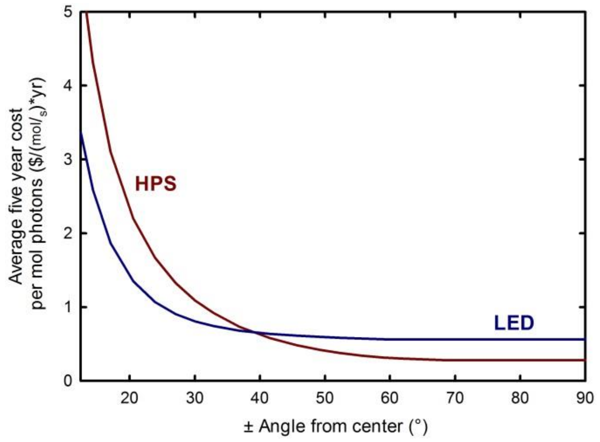

Figure 4. **The return on investment for LEDs (Red/Blue LED from Lighting Sciences Group) becomes more favorable than new, electronic ballast HPS fixtures with improved luminaires (electronic ballast, PARSource) when the lighting area is less than 39° from center, assuming $0.11 per KWH cost of electricity and 3000 hours per year use.**

Photosynthetic efficiency is best measured as µmoles per Joule

The efficiency of lamps is often expressed using units for human light perception (lumens or foot-candles) or energy efficiency (watts in per watt out). Photosynthesis, however, is determined by moles of photons. It is thus important to compare lighting efficiency based on Photosynthetic Photon Flux (PPF) efficiency, with units of micromoles per joule. A dramatic example of this is a comparison of recently developed red, blue, and cool white LEDs (Table 3). The low energy of red photons allows more photons to be made with the same amount of energy (Planck's Law). Blue LEDs have a 53% higher electrical energy efficiency (49 vs. 32%) but only a 9 % higher (1.87 vs. 1.72) PPF efficiency.

LED Color	Peak Wavelength or Temp.	PPF Efficiency (µmol/J)	Electrical Efficiency (%)	Luminous Efficiency (lm/W)
Cool White	5650 K	1.52	33	111
Red	655 nm	1.72	32	47
Blue	455 nm	1.87	49	17

Table 3. **Efficiency of individual LEDs at a drive current of 700 mA (does not include power supply loss). The relationship between electrical efficiency and PPF efficiency is dependent on color. PPF efficiency is the most appropriate measure for photosynthesis.**

Table 4. Return on investment for four PPF capture assumptions

Lamp Type and Ballast	Fixture Manufacturer See Table 5 for more information	Cost of Fixture[1] ($)	Electrical Cost[2] ($/yr)	Assuming all radiation (±90°) is captured		Assuming radiation ±50° is captured		Assuming radiation ±34° is captured		Assuming radiation ±18° is captured	
				Fixtures Needed[2]	Return on investment[3] (%/yr)	Fixtures Needed[2]	Return on investment[3] (%/yr)	Fixtures Needed[2]	Return on investment[3] (%/yr)	Fixtures Needed[2]	Return on investment[3] (%/yr)
High Pressure Sodium											
400 W Magnetic	Sunlight Supply	$200	$388	2.66	-129 %	2.57	-120 %	2.55	-118 %	2.65	-129 %
1000 W Magnetic	Sunlight Supply	$275	$352	1.00	Reference	1.00	Reference	1.00	Reference	1.00	Reference
1000 W Magnetic	PARsource	$350	$313	0.94	-48 %	0.83	13 %	0.84	9 %	0.77	52 %
1000 W Electronic	PARsource	$380	$277	0.82	4 %	0.73	67 %	0.74	56 %	0.69	99 %
LED											
Red/Blue	Lighting Sciences Group	$1,200	$225	1.74	-74 %	1.08	-29 %	0.63	55 %	0.43	147 %
Red/White	Lighting Sciences Group	$1,200	$238	1.82	-77 %	1.13	-35 %	0.66	46 %	0.45	134 %
Red/Blue	Lumigrow	$1,200	$429	4.10	-107 %	2.57	-88 %	1.84	-69 %	1.57	-57 %
Red/White	Illumitex	$1,200	$263	2.84	-89 %	1.73	-60 %	1.16	-24 %	0.99	-5 %
Ceramic Metal Halide											
315 W 3100 K (Agro)	Cycloptics	$700	$250	2.25	-72 %	3.54	-107 %	6.02	-133 %	8.08	-142 %
315 W 4200 K	Cycloptics	$700	$268	2.39	-78 %	3.73	-111 %	6.30	-135 %	8.36	-143 %

[1]-Cost of fixtures as of June 2013.
[2]-Assumes 3000 hours per year operation and $0.11/kWh.
[3]-Electric rates have been discounted at a 5% per year interest rate to account for the time value of money.

Return on investment

The return on investment for supplemental lighting depends primarily on the value of the crop, but selection among options should be made based on the cost to deliver photons to the crop surface. Optimal arrangement of fixtures is critical regardless of fixture type or crop value.

We calculated a ROI for replacing 1000-W Magnetic HPS fixtures from Sunlight Supply with more efficient fixture types (Table 4). We assumed no salvage value for the older HPS fixtures that are being replaced. Similar to the values in Table 2, the best LEDs become comparable to efficient HPS fixtures at a radiation capture ratio of about 1 to 1.35 (±34°).

Integrating PPF over a horizontal surface

Accurate quantification of the integrated total PPF from a fixture must be in a room without light contamination and must capture the non-uniform output of the fixture, especially near the center. Measurements using a LI-COR quantum sensor, calibrated for each lamp with a spectroradiometer, were made 2.5 cm apart in the center and increasing to 10 cm near the perimeter. Measurements were made in three radial, straight lines below a level fixture and spatially integrated to determine total integrated PPF (Figure 5).

Lights were mounted 0.7 meters above the surface and measurements were made up to a 1.2 meter radius from the center and extrapolated farther using an exponential decay function. Light distribution can be proportionately scaled to any mounting height (e.g. Figures 1 and 2).

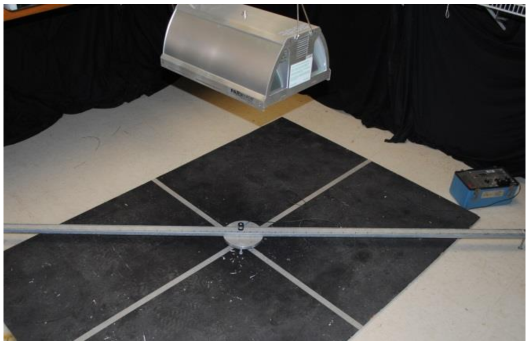

Figure 5. Set up for integrated total PPF measurement. Measurements must be made in a room without light contamination.

Independent tests indicate that the total fixture output from these measurements was nearly identical to measurements made using an integrating sphere. This technique works under the assumption that nearly all of the PPF is directed downward. Comparisons with an integrating sphere validated this assumption.

Long-term operating cost

LEDs are often promoted as having a significantly lower annual operating cost because their predicted lifetime (to 70% of the initial light output) can be more than 50,000 hours (about 10 years when used 16 hours per day). However, the LEDs in many fixtures are driven by higher amperage to achieve a higher output, which reduces their life expectancy because it increases their temperature. The radiation from sunlight warms LED fixtures and decreases their life expectancy. The cooler the LED temperature, the longer they last. Also, the power supplies in LED fixtures are expected to fail well before the LEDs themselves. Power supplies are replaceable, but changing them would increase operating costs.

Most comparisons of new LED technology are made to older magnetic-ballast HPS fixtures. The life expectancy of newer electronic-ballast fixtures, and the lamps in them, is significantly longer than fixtures with magnetic-ballasts. The lamps can now last 50,000 hours (equal to LEDs). For these reasons we did not include a differential operating cost between LED and HPS fixtures. We assumed that maintenance costs will be minimal in the first five years for all types of fixtures. The initial failure of electronic ballasts has been a problem but failure rates have decreased significantly over the past year as the circuitry has improved. LED fixtures with improved power supplies and optimized operating amperages are also becoming available. Improvements in these new technologies are occurring rapidly.

Importance of light uniformity

Light uniformity is critical in many greenhouse applications, especially in floriculture. Economically, the value of uniform plants may outweigh the cost of wasted photons. Uniformity has been well characterized and modeled with HID lights (Both *et al*., 2000; Ferentinos and Albright, 2005), but these techniques have not yet been rigorously applied to LED fixtures. Ciolkosz *et al*. (2001) showed that uniform light on the perimeter of a greenhouse requires higher fixture densities in the outer rows. This increases the wasted radiation past the edge of the lighting area. Precision luminaires or lenses can be used to apply focused lighting near edges.

Light quality

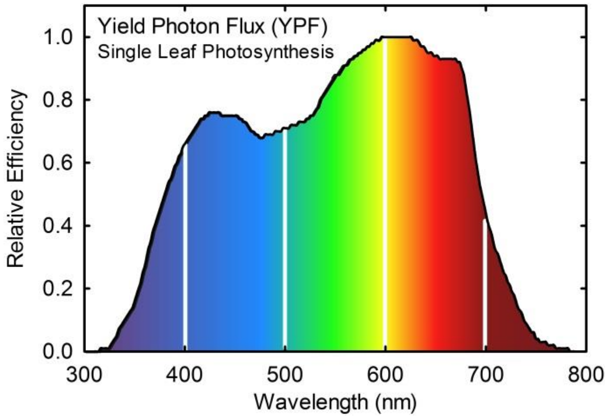

Figure 6. Effect of wavelength on relative photosynthesis per incident photon for a single leaf in low light (McCree, 1972).

Light quality (color) has a small effect on photosynthesis and a large effect on plant morphology (plant shape). The combination of these two parameters results in plant growth. A high fraction of blue light typically decreases leaf expansion rate, which decreases radiation capture and plant growth. Reduced growth under high blue light is often misinterpreted as a direct effect on photosynthesis, but it is primarily an indirect effect mediated by reduced leaf expansion and radiation capture. The detrimental effect of blue light is often minimal after canopy closure.

Many exaggerated claims have been made for increased plant growth associated with the light quality of LED fixtures. Perhaps our best estimate of the effect of light quality on photosynthesis comes from the Yield Photon Flux (YPF) curve, which indicates that orange and red photons between 600 to 630 nm can result in 30% more photosynthesis than blue or cyan photons between 400 and 540 nm (Figure 6). This curve, however, was developed from single leaves in short term studies in low light. Longer-term studies with whole plants in higher light indicate that blue and green wavelengths are more valuable than indicated by the YPF curve (see for example: Cope and Bugbee, 2013; Johkan et al. 2012; http://cpl.usu.edu/files/publications/poster/pub__2576523.pdf).

In any case, HPS lamps have a high output between 580 and 600 nm and a low output of blue light. They are thus equal to or better than the best LED fixtures based on the YPF curve.

The most PPF efficient colors of LEDs are blue, red, and cool white, respectively (Figure 7), so LED fixtures generally come in various combinations of these colors. Ultraviolet (UV) radiation is absent in typical LED fixtures. Sunlight has 6% UV, and standard electric lights have 0.3 to 1% UV radiation. The lack of UV causes disorders in some plant species (e.g. Intumescence, Morrow and Tibbitts, 1988) and this is a concern with LED fixtures. LED systems also have minimal far-red radiation (710 to 740 nm), which decreases the time to flowering in several short-day species (Craig and Runkle, 2013). Green light (530 to 580 nm) is low in most LED fixtures and these wavelengths better penetrate through leaves and are more effectively transmitted to lower plant leaves. The lack of these wavelengths, however, should be minimal when LEDs are used in greenhouses, because most of the radiation comes from broad spectrum sunlight.

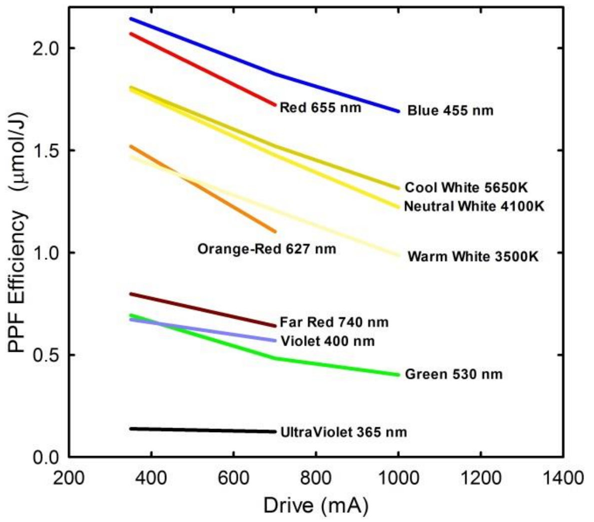

Figure 7. Effect of drive amperage and color on PPF efficiency of LEDs. Data for Philips Lumileds LEDs (April 2013), courtesy of Mike Bourget, Orbitec.

Novel applications of LEDs

Although far-red LEDs are not as electrically efficient as other wavelengths (Figure 7), they can be used for precise management of plant characteristics such as stem length or flowering times (Craig and Runkle, 2013; Yang et al., 2012). LEDs are also being studied for supplemental intra-canopy lighting where the radiation capture can be close to 100% (Frantz et al., 2000; Massa et al., 2008; Gómez et al., 2013). Another advantage of LEDs is that they can be rapidly cycled without lamp degradation. This allows for precise timing of supplemental lighting, which can be useful on partly cloudy days. Recent studies indicate that rapidly cycled LEDs can deter aphid predation (Bob Morrow, Orbitec, personal communication).

Thermal radiation

LED fixtures produce heat from the back of the fixture rather than from the front. This characteristic allows them to be positioned close to the plant canopy, which can be useful in some applications. However, the thermal radiation from the front of other fixtures (e.g. HPS) is useful in warming the plant canopy and the greenhouse air temperature can thus be cooler. Additional thermal radiation on the plants is valuable on cool days and detrimental on hot days.

Improved electrical efficiency reduces the cooling load in a greenhouse, which increases the value of efficient fixtures when cooling is required. The ability to rapidly cycle LED fixtures can be used to stabilize the heat load in a greenhouse, which can improve temperature control and increase the lifetime of cooling system equipment.

Effect of fixture shadow

All fixtures block radiation from the sun, and the shadow is proportional to the size of the fixture. For the same PPF output, LED fixtures block more sunlight than HPS fixtures. We did not include the effect of the shadow in this analysis, but this effect favors the higher wattage HPS fixtures. In the long-term, LEDs can take advantage of innovative design options like mounting along greenhouse support structures, which provides light without extra shading. Long narrow LED fixtures may be preferable to rectangular fixtures because the duration of the shadow is shorter.

Cost of electricity

Commercial electric rates vary by region, ranging from $0.07 in Idaho to $0.15 in New York, with residential rates averaging $0.02 higher, and industrial rates $0.02 lower. *As electricity becomes more expensive, improved lighting* *becomes more valuable.* See http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_05_a for a summary of current electric rates by state and region.

Conclusions

LED technology is becoming a viable supplemental lighting option in greenhouses, but the use of LED fixtures must be coupled with precision delivery of photons to be a cost effective option for photosynthetic lighting.

We define the term electrical use efficiency as photons delivered to the crop surface per joule of electric input to the lighting system. This is influenced by many factors but the easiest change is to manipulate the spacing of fixtures to improve photon capture.

Manufacturers are working to improve all types of lighting technologies and the cost per photon will change as new technologies, and new prices, become available. The prices in Table 1 were current as of June 2013. The principles described in this paper, however, can be used to make informed decisions for all types of lighting systems once the efficiency, light distribution, and cost are known.

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Lamp Type and Ballast	Fixture Manufacturer	Model Number
High Pressure Sodium		
400 W Magnetic	Sunlight Supply	Sunstar
1000 W Magnetic	Sunlight Supply	Sunstar
1000 W Magnetic	PARsource	GLX
1000 W Electronic	PARsource	GLX
LED		
Red/Blue	Lighting Sciences Group	Purple
Red/White	Lighting Sciences Group	Vivid White
Red/Blue	Lumigrow	ES 330
Red/White	Illumitex	NeoSol NS
Ceramic Metal Halide		
315 W 3100 K (Agro)	Cycloptics	All-Bright
315 W 4200 K	Cycloptics	All-Bright w/ 4200k lamp

Table 5. Fixture manufacturer and models used in this comparison. The ES 330 fixture from Lumigrow was recently discontinued.

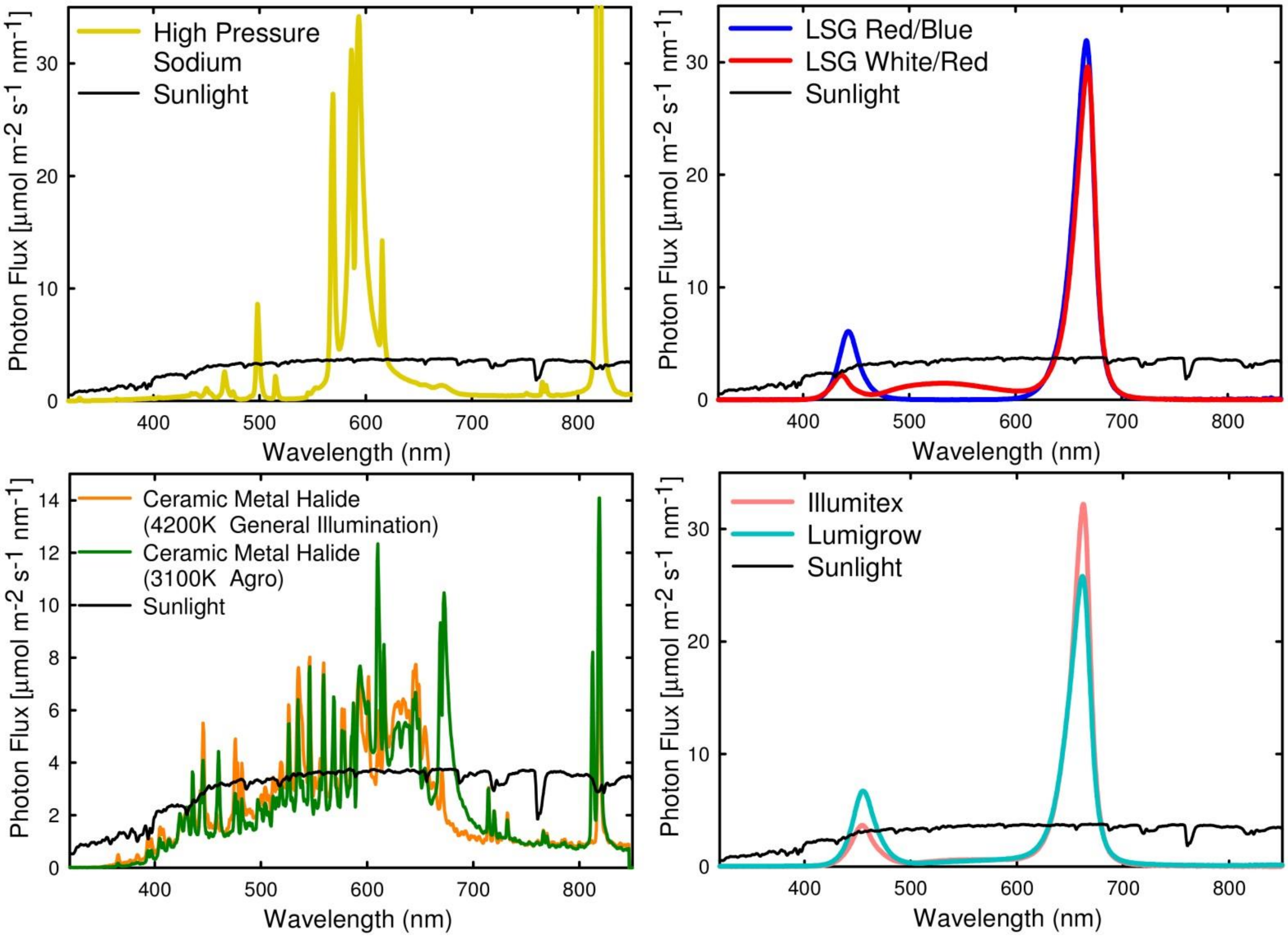

Figure 8. Spectral output for the fixtures in this comparison. All photon flux data are normalized to 1000 PPF to show relative differences. Note the change of scale for the ceramic metal halide lamps. These lamps have a more spectrally uniform output without tall peaks. The scale has been reduced to better see the differences between the two CMH lamp types. The sunlight trace (black line) in each graph is included to provide a reference.