Light Emitting Diodes (LED) – Applications in Forest and Native Plant Nurseries

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> *"LED lighting has a bright future in the world of horticultural lighting. —When applied in a well-designed system, no other light source can match the capabilities that LEDs have to offer"*
>
> — Bourget 2008

It was quotes like this that made us want to learn more about light emitting diodes (LED). Other than knowing that LEDs were the latest innovation in artificial lighting, we knew that we had a lot to learn. So we started by reviewing some of the basics. The following review is a brief synopsis of how light affects plants and some discussion about LED lighting. If you want more detailed information about the effects of light on plant growth, read Chapter 3 in Volume Three: Atmospheric Environment of the Container Tree Nursery Manual (Landis and others 1992).

1. The complicated nature of light

If you follow quantum mechanics, you are familiar with the relatively recent discovery that electromagnetic radiation, commonly referred to as "light", has a dual nature - properties of both waves and particles. Although scientists and philosophers as far back as Aristotle had developed theories about light, it was not until 1905 that Albert Einstein described the photoelectric effect that explained the relationship of wavelength and photons (individual particles of energy). This was just one of his most famous insights and earned him the Nobel Prize in Physics in 1921 (Nobel Media AB 2013).

Light is the most complex and variable of the limiting factors affecting plant growth, and for our purposes, there are two types: natural light (sunlight) and artificial light. Sunlight is the common name for electromagnetic radiation that originates from our sun, which is approximately 93 million miles away. The quantity and quality of sunlight differs significantly from the artificially produced light that we use in our homes and greenhouses. Managing light is particularly challenging due to its subjective nature. The sunlight that your crops "see" is much different in terms of wavelength (color) and intensity that what we humans perceive. In fact, the term "light" only refers to one small part of the electromagnetic spectrum that is visible to the human eye (Figure 1). And, to make matters even more complicated, our iris controls the diameter of the pupil of our eye and thus regulates the amount of light that we perceive from one location to another.

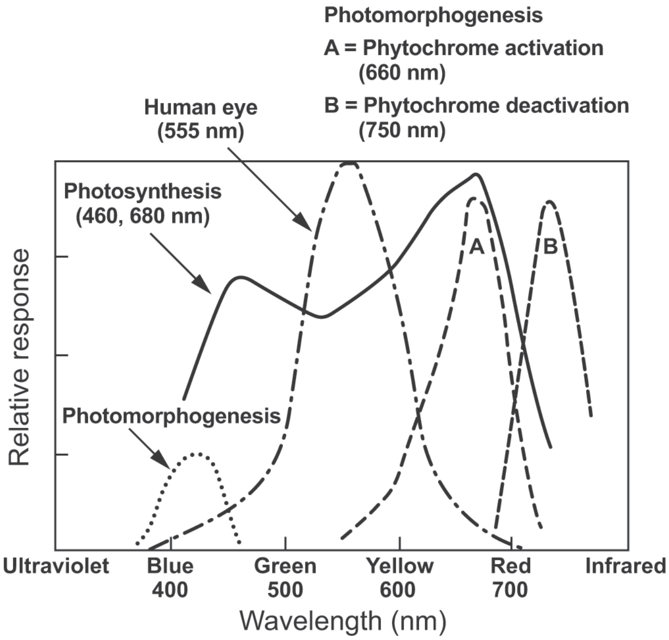

Figure 1 - Plants absorb certain wavelengths of light. Photosynthesis is fueled by blue or red light (peaking at 460 and 680 nm), whereas phytochrome is activated by red light (660 nm) and deactivated by far red light (750 nm). Phototropism and cell expansion are promoted by blue wavelengths. Contrast these responses to those of the human eye which peak in the yellow-green wavelengths (555 nm).

2. Measuring light

While the dual nature of light can be complicated in and of itself, the measurement and unit description of light only adds to the complexity and confusion. Sunlight can be measured by 3 different systems each with its own units. The unit of micromoles (μmols) per second per square meter measures the sun's energy as photon flux density per unit area, and for natural sunlight this is about 2000 μmols/s/m^2. These units are commonly used in measuring photosynthesis light energy, as described in Figure 1. In this article, we focus on artificial light that, for horticultural purposes, should be measured in terms of intensity (energy) and quality (wavelength).

Engineers measure light intensity using illumination units that reflect the sensitivity of the human eye within the

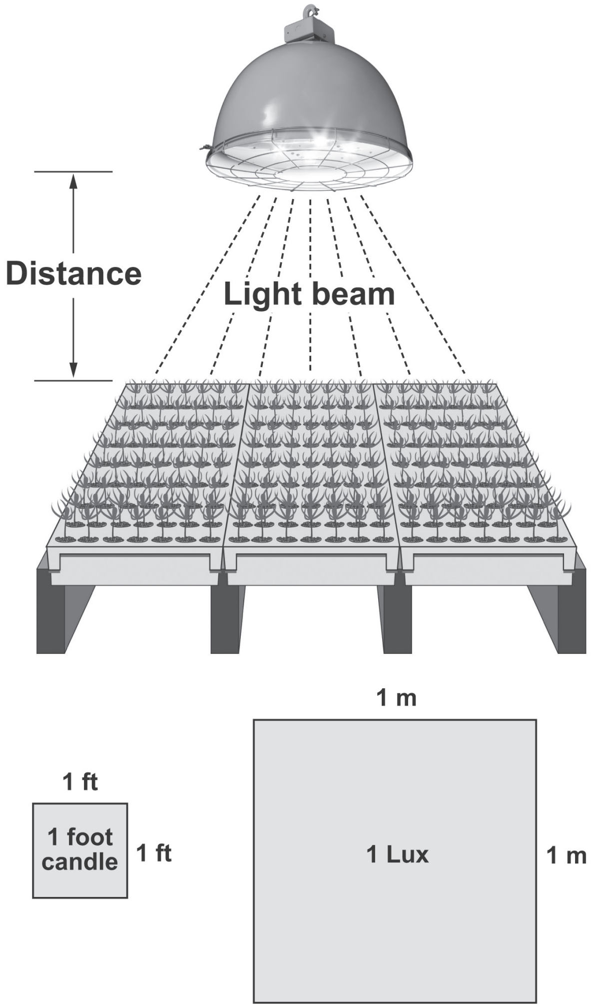

Figure 2 - Artificial lighting is measured in illumination units: the metric lux and the English foot-candle. It is critical to measure light at the crop level because illumination decreases with distance from the light source (modified from Bickford and Dunn 1972).

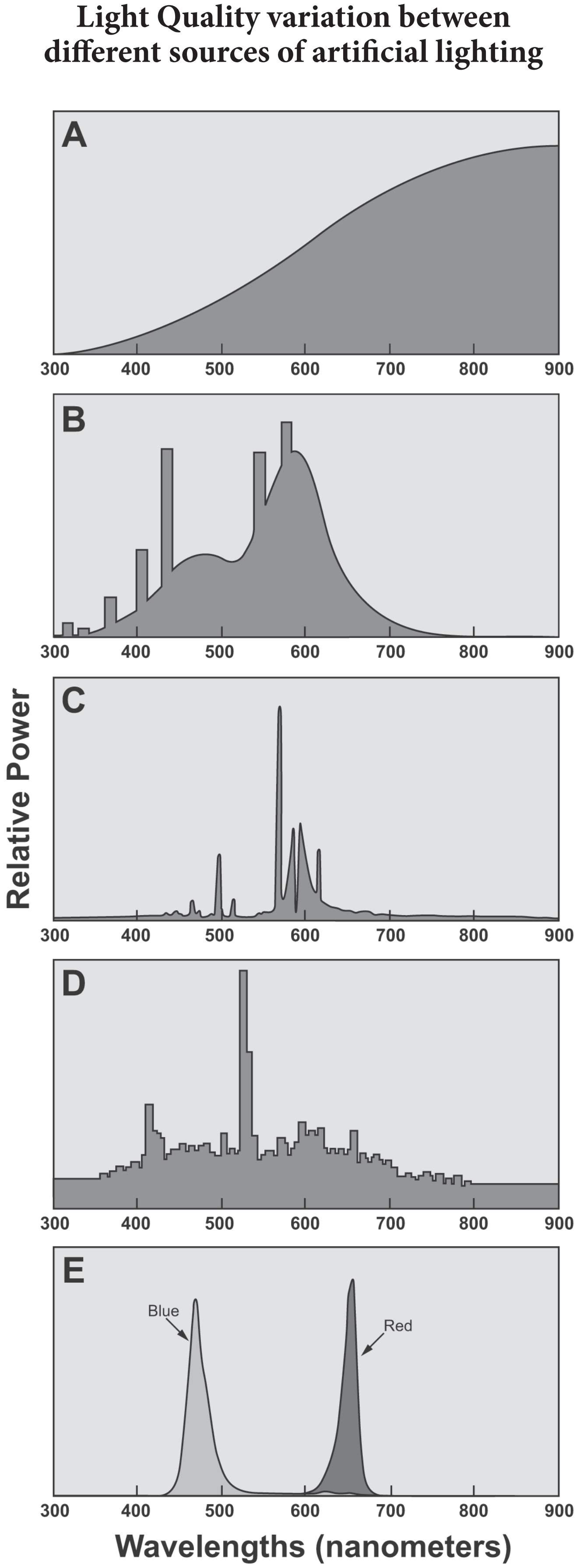

Figure 3 - These spectral energy distribution curves show the different quality of light produced by different lighting sources. Incandescent lamps produce most of their light in the red and infrared wavelengths (A), compared to fluorescent lamps that produce a more balanced output (B). Infrared wavelengths are perceived as heat, which is not only a waste of energy but requires compensatory cooling. High pressure sodium lamps produce most of their light in the yellow wavelengths (C) whereas metal halide lamps generate a more balanced "white" light (D). Light emitting diodes (LED) are unique in that each produces just one specific wavelength, such as blue and red (E) (A-D from Kaufman and Christensen 1984; E modified from Seelye and Mullan 2010).

visual spectrum (Figure 1). The standard unit of illumination is the lumen. A lumen that is evenly distributed over an area of 1 square meter is defined as 1 Lux (lx); for English units, a lumen distributed over 1 square foot is 1 foot-candle (Figure 2). An inexpensive light meter ($35+) can provide basic information on light intensity by measuring these units; because most growers of native plants rely on natural daylight for photosynthesis and usually use photoperiod lighting to extend daylength, this is adequate. The spectral quality (wavelengths) of artificial lighting varies significantly between different sources (Figure 3) and is usually measured in nanometers (nm). Fortunately, for photoperiod control, most artificial lights generate enough light to be effective (see the next section for more details). However, the light quantity and quality needed to increase photosynthesis differs considerably from that needed for photoperiod extension. If growers may want to measure the photosynthetically active wavelengths actually reaching their crops, a higher quality light meter is required ($1000+).

3. Plant responses to light

Plants respond to visible light by 2 general mechanisms that are keyed to specific wavelengths: photosynthesis that has a higher-energy requirement and photomorphogenesis that has a lower-energy requirement.

3.1 Photosynthesis

Visible light is captured by the carotene and chlorophyll pigments in leaves and, using carbon dioxide and water as raw materials, is converted into the chemical energy needed for plant growth and metabolism. Photosynthetic rates are highest in 2 bands: red light, with some activity in the blue-green wavelengths (Figure 1); these wavelengths are collectively known as photosynthetically active radiation (PAR). Conceptually, photosynthesis can be thought of as a tachometer (Figure 4A) because photosynthetic rates increase with more light up to a point that is species dependent. In forestry, this response to light levels is known as shade tolerance. Shade tolerant plants, such as dogwood, reach their maximum photosynthetic rate at 35 kilolux (klx) of illumination compared to shade intolerant (sun loving plants, such as ponderosa pine) that may continue to photosynthesize up to 120 klx.

3.2 Photomorphogenesis

The pigment phytochrome is sensitive to the ratio of red to far-red light (Figure 1) and acts as an environmental sensor to measure daylength. The phytochrome system controls several aspects of seedling phenology, such as seed germination and bud set. Although all plants in the temperate zones and higher latitudes are sensitive, tropical and subtropical species have not adapted to these changes in daylength. Blue light is important to normal morphological development, particularly in regard to branching and shoot sturdiness. Conceptually, the phytochrome system can be viewed as a light switch. Under predominantly red light, the switch is “on” and cell growth occurs as fast as the light intensity permits. However, when far-red light predominates the switch is turned “off” and growth stops as plants transition into dormancy (Figure 4B).

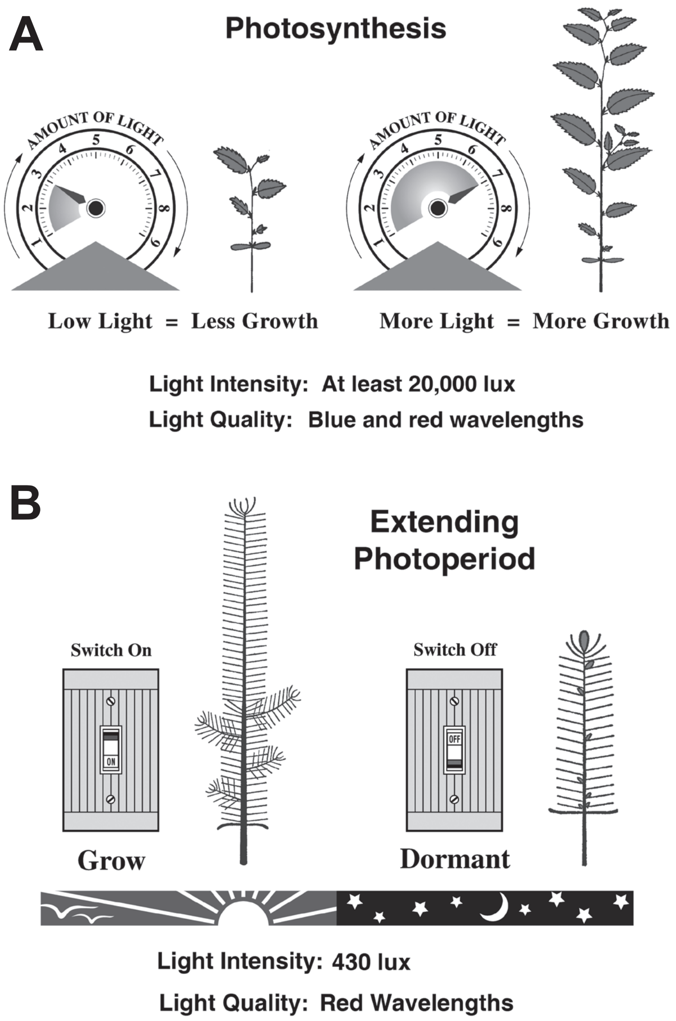

Figure 4 - Analogies are helpful in understanding the effects of light on plant growth. Shoot growth can be viewed as a tachometer - the higher the light intensity, the higher the photosynthetic rate (A). Using low intensities of red light to extend daylength is like a switch that triggers the phytochrome receptor and tricks plants into thinking it is still summer (B).

4. Types of artificial lighting used in horticulture

As we just discussed, artificial lighting is used in greenhouses to either increase photosynthesis or control photoperiod (extend daylength), but the required light intensity and quality for each are very different. A wide variety of artificial lights have been used in horticulture including incandescent, fluorescent, and high intensity discharge (HID) lights. Incandescent lighting is typically high in the red and infrared wavelengths (Figure 3A). Fluorescent lights produce more white light (Figure 3B) but the fixtures must be located very close to the crop. High intensity discharge (HID) lights, such as high pressure sodium (Figure 3C) and metal halide (Figure 3D), are more energy efficient choices. Light emitting diodes (LED) are the newest light source and can be developed to produce specific wavelengths, such as blue and red (Figure 3E). Because no semiconductors emit pure white light, most white LEDs consist of a blue light-emitting chip coated with phosphor, which causes yellow light to be emitted. This mixture of blue and yellow light is perceived as white light by the human eye. White light can also be produced by combining semiconductors of red, green and blue (RGB) into a single LED lamp (Seelye and Mullan 2010).

It is critical to note that illumination units are always measured at a standard distance from the source. We have found that the engineering specifications for artificial lighting systems are not always accurate. It is therefore important that growers make their own measurements under each bulb as well as between bulbs to make sure that the entire crop receives at least the minimum intensity. Remember, always measure light intensity at crop height (Figure 2).

4.1 Lighting to increase photosynthesis

Traditionally, HIDs, including high pressure sodium and metal halide lamps, have been used in growth chambers to supplement natural sunlight and increase photosynthetic rates (Figure 5A). Because of the large amount of electrical energy required, adding lights to increase photosynthesis is, for most reforestation and native plant nurseries, economically impractical. This conclusion, however, may need to be revisited with the advent of LED lighting that has been developed for horticulture.

Required light intensity and quality. If artificial lights are the only source of illumination, as in a growth chamber, the minimum requirement for commercial plant production is considered to be about 250 umol/s/m^2 (20

Figure 5 - High intensity discharge lights, such as these metal halide lamps, must be grouped close to the crop to produce enough light intensity for photosynthesis (A). Due to the low intensity of light required, a wide variety of different lighting systems have been used to extend photoperiod, including these incandescent flood lamps (B) (Photos from Landis and others 1992).

klx), which is about one-eighth the intensity of normal sunshine. Photosynthetic lights must also be kept on for at least 12 hours per day to generate reasonable rates of growth. Supplemental lighting is sometimes needed to compensate for cloudy weather, shading from greenhouse structures or equipment, or during the winter at higher latitudes. When 122 umol/s/m^2 (10 klx) of PAR light is added for 8 to 16 hours per day, growth rates can approach those obtained in growth chambers (ASHRAE 1989).

Because not all wavelengths are equally effective for photosynthesis, artificial lighting should be high in the PAR wavelengths bands (Figure 1): blue (460 nm) and red (680 nm) wavelengths are ideal.

Monitoring photosynthetic lighting. For high value horticulture crops, growers monitor the Daily Light Integral (DLI), which is the amount of PAR calculated as a function of light intensity and duration. Calculating DLI requires special sensors and data recorders so that light intensity and quality can be simultaneously and continuously recorded. DLI values for floriculture have been well described (Torres and Lopez 2010), but for forestry and native plant crops, are most likely non-existent.

4.2 Lighting to increase daylength

Photoperiodic lighting is much more common than photosynthetic lighting in forest, conservation, and native plant nurseries. A variety of different lighting arrangements (Figure 5B) have been effective in triggering the phytochrome response and keeping plants actively growing in the spring or fall when natural daylength becomes limiting.

Required light intensity and quality. Very low light levels are needed for daylight extension. Research trials, validated in many operational nurseries, have determined photoperiodic lighting intensity should be at least 8 µmol/s/m^2 (~430 lux), and should be increased to 16 µmol/s/m^2 (~860 lux) when the crop has a greater light requirement (Landis and others 1992). Almost any of the standard lamps can be used because they all emit light in the red wavelengths (Figure 3). A complete discussion of the most common photoperiodic lighting systems can be found in Landis and others (1992).

Monitoring photoperiod lighting. Illumination intensity should be measured at crop height with a standard light meter after sunset; to ensure that all plants are receiving the proper light intensity, take measurements beneath and between lighting fixtures.

5. LED lighting

Light emitting diodes (LED) are the newest type of artificial illumination being used in greenhouse culture. An LED is a solid-state semiconductor device that is more closely related to a computer chip than a light bulb (Figure 6A). When electricity passes through a junction constructed of different materials, visible light is emitted in a narrow wavelength (Figure 2E). LED units by themselves are very small (0.2 in or 5 mm); consequently, they are often arranged in arrays that are sealed in plastic lenses protect the units and direct the light. LED units are available as traditional bulbs that will fit standard fixtures (Figure 6B) or in linear arrays (Figure 6C) that, because they radiate no heat, can be located within plant canopies (Figure 6D). As mentioned earlier, because LEDs produce light in narrow wavelengths, they can be used to generate colors across the visible spectrum from blue to red or combined or coated to produce a more all-inclusive white light (Lighting Design Lab 2013).

LED lighting has at least 5 advantages for use in horticulture, which are described below.

5.1 Energy efficiency

As measured by radiated power output (lumens) divided by electrical power input (watts), LED units are very efficient, especially when compared to traditional incandescent bulbs. The energy efficiency of LED lights continues to improve and is projected to exceed 200 lumens per watt in the near future (Clark 2013) (Table 1).

5.2 Lifespan

The useable life of LED units is significantly longer than traditional artificial light sources used in horticulture, from 2 to 3 times better than fluorescent or HID lamps, to a 50-fold increase over typical incandescent lamps (Table 1). Unlike traditional lamps, LEDs do not “burn out”; instead, they gradually dim and should be replaced once they dim to 70% (Bourget 2008).

5.3 Custom lighting

LEDs produce light in a very narrow wavelength range (Figure 3E), so units can be designed to produce light of desired wavelengths, or combined to generate white light (van Ieperen and Trouwborst 2008). LED arrays of blue and red light that increase photosynthesis can be positioned within crop canopies where these wavelengths do not normally reach due to absorption by the upper leaves (Figure 6D).

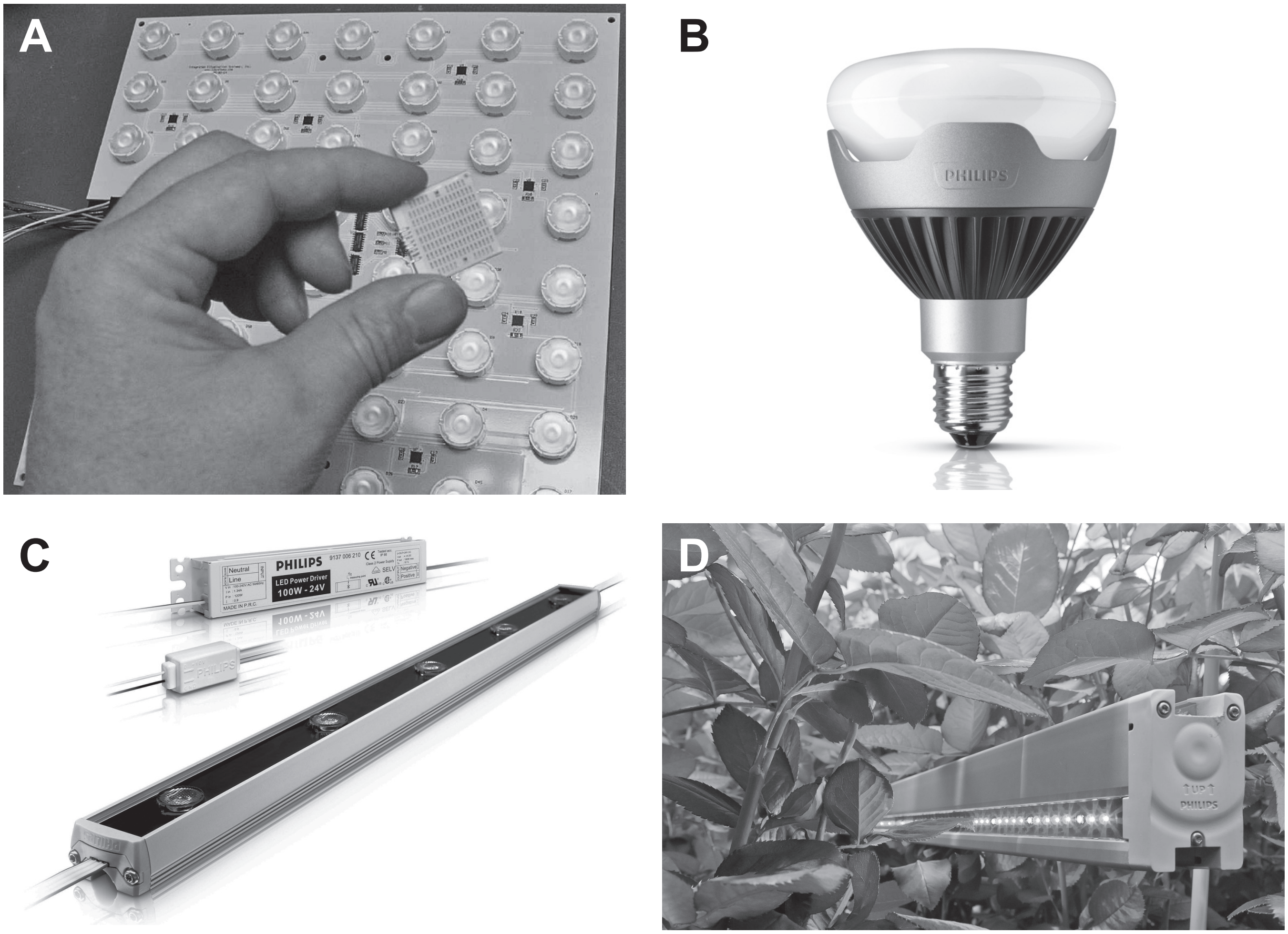

Figure 6 - Light emitting diodes (LED) are the newest form of artificial lighting used in horticulture and are more like computer chips than light bulbs (A). LED units can be housed in traditional bulbs that will fit standard fixtures (B) or arranged in arrays designed to produce light of specific wavelengths (C) that, because they do not radiate heat, can be located within plant canopies (D) (A from Morrow 2008; B-D courtesy of Philips Electronics 2012).

Table 1 - Energy efficiency and lifespan of common light bulbs compared to light emitting diode units (Bartok 2012).

Illumination source	Energy efficiency (Lumens per watt)	Average lifespan (hours)
Incandescent	15 to 18	1,000
Tungsten - halogen	15 to 20	2,000
Compact fluorescent	50 to 65	10,000
T-12 fluorescent	30 to 40	15,000
T-5 fluorescent	90 to 110	20,000
Metal halide	90 to 100	15,000
High pressure sodium	90 to 100	24,000
Light emitting diodes (LED)	60 to 90 *	50,000

* LED efficiencies continue to improve and are predicted to reach 260 to 300 lumens per watt in the coming decades (Clarke 2013).

5.4 Radiant heat

LEDs produce almost no radiant heat and so can be positioned close to plants, ensuring maximum light interception (Seelye and Mullan 2010).

5.5 Plant productivity

The current literature contains very little research on using LEDs for forest or native plant crops. Recent preliminary research trials in Finnish conifer nurseries, however, show that LED lights (Vayola B100, spectra G2) performed similarly to high-pressure sodium lights and were sufficient to prevent bud formation in Norway spruce and Scots pine (Riikonen 2013). In horticulture, LED intracanopy lighting produced 75% more tomato fruit biomass compared to overhead high pressure sodium lighting (Gomez and others 2013).

5.6 Actual comparison of commercial LED lamps

We were curious to run our own tests on currently-available lamps, and purchased 3 different flood lamps with a 120 watt rating (Table 2). The first thing we noticed was “sticker shock” due to the much higher cost of the LED lamps — more than 4 times as much as the other bulbs. The price of LED lamps has continued to decrease. One report states that the top-rated LED lamp from Home Depot dropped about 50% in just a few months. Philips says it will introduce a $10 LED 60 watt rated light bulb by the end of the year (Janeway 2013). Based on the label information of estimated lifespan and yearly energy costs, annual operating cost for the compact fluorescent and LED lamps rated about the same, but the incandescent lamp was more than 3 times more costly to operate.

We decided to test the 3 lamps (Figure 7A) in the same fixture and immediately noticed that, although each had a 120 watt rating, the LED lamp was noticeably brighter. Illumination readings were taken 5-ft (1.5 m) directly under the lamps and our results confirmed our observations: the LED lamp produced 4,726 lx, the incandescent 561 lx, and the compact fluorescent 301 lx – an 8-fold and 15-fold difference, respectively. Another striking pattern we noticed was the horizontal light distribution perpendicular under each lamp. While the LED was brightest directly under the lamp, the light

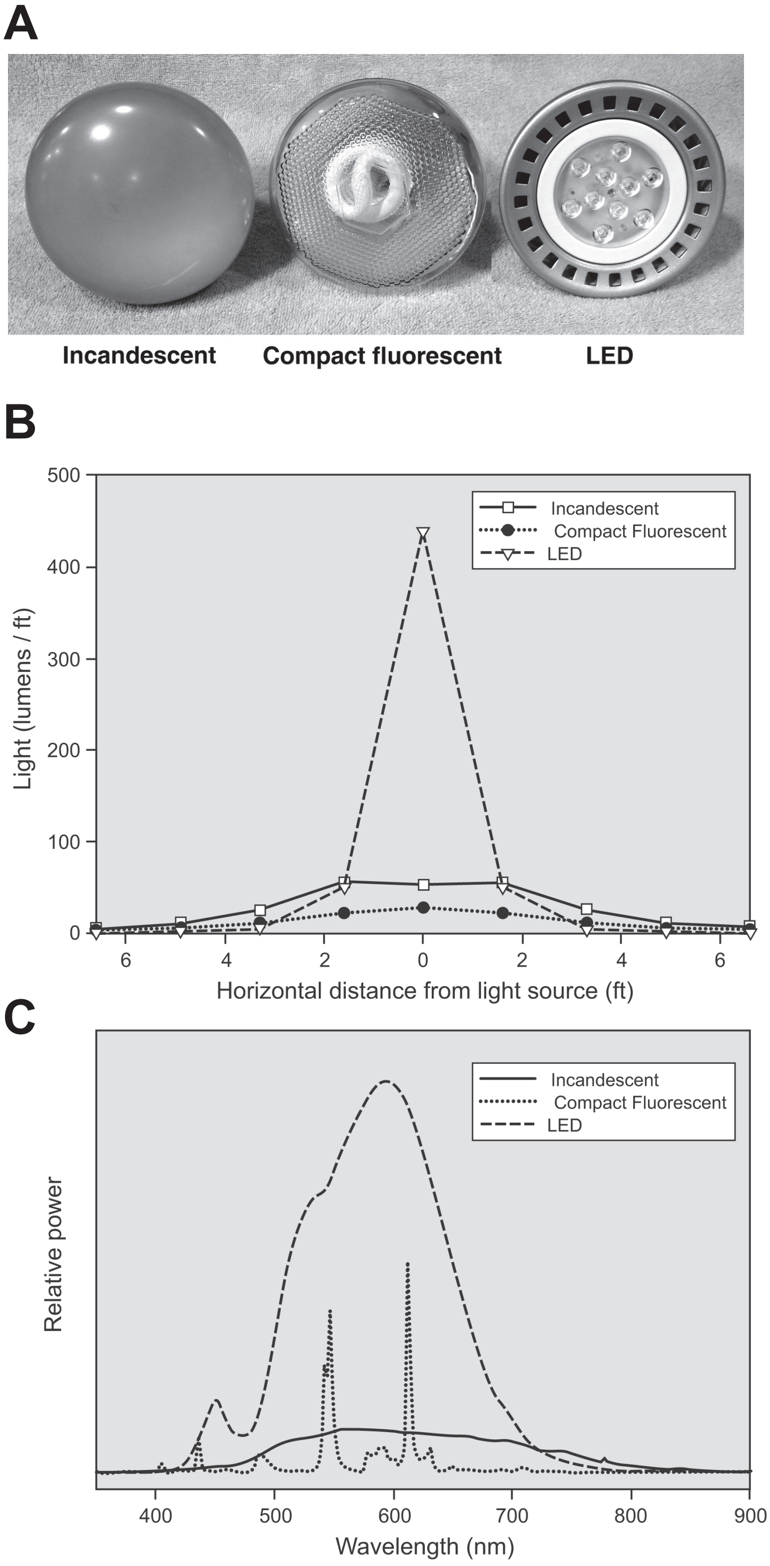

Figure 7 - Light intensity of 3 commercially available 120 watt-rated lamps (A: incandescent, compact fluorescent, and LED) measured 5 ft (1.5 m) directly below, and at 4 horizontal distances perpendicular from this point (B). Relative spectral energy distributions also differed among the three light sources (C).

Table 2 – Comparison of commercial 120 watt-rated flood lamps currently available.

	Incandescent	**Compact Fluorescent**	**LED**
Manufacturer	Philips	EcoSmart	Philips
Type	EcoVantage, Bright Light, Dimmable, Indoor BR40 [a] Flood	Soft White PAR38 [b] Flood	Soft White, Dimmable, PAR38 [b] Flood
Label Specifications			
Equivalent wattage	120	120	120
Actual wattage	70	23	19.5
Label Brightness (lumens) [c]	1225	1290	1100
Color temperature (K) [c]	2810	2700	2700
Estimated life (y) [c]	2.7	9.1	22.8
Estimated yearly energy cost [c]	$8.43	$2.77	$2.35
Purchase price [d]	$9.97	$10.27	$42.97
Annual operating cost [e]	$12.12	$3.90	$4.23
Toxicity	None	Mercury [f]	None
Disposal	Trash	Recyclable [g]	Recyclable [h]

[a] BR40: bulged reflector, 40/8ths of an inch wide, or 5 inch diameter.
[b] PAR38: parabolic aluminized reflector lamp, 38/8ths of an inch wide, or 4.75 inch diameter.
[c] Per manufacturer's package. Estimated life assumes 3 h use per day. Estimated yearly energy cost assumes 3 h use per day and $0.11 per kWh.
[d] Retail price for single bulbs at local "big box" home improvement store.
[e] Annual operating cost = (Purchase price/estimated life) + (estimated yearly energy cost).
[f] Contains mercury.
[g] See US EPA website for more information: http://www2.epa.gov/cfl/recycling-and-disposal-after-cfl-burns-out#cantrecycle (accessed 29 May 2013). Local options may be available.
[h] Varies: May be recycled where purchased (including online companies) and at some local recycle centers.

intensity diminished exponentially as distance increased horizontally from beneath the light source (Figure 7B). We also measured the spectral distribution of each light source to show relative differences in wavelength emittance, which demonstrates the high quality white light from the LED lamp (Figure 7C).

6. Summary

So, what is the bottom line? Should you run right out and replace your existing lighting systems with LED lights? For the applications commonly used in forest and native plant container nurseries, we see some immediate applications. LED lights come in standard sizes and illumination units that can be easily substituted in existing lighting fixtures in offices and other workplaces. LED bulbs are available with screw bottoms or as long tubes to replace fluorescent bulbs. We have found a range of LED lights at our local home improvement stores.

For the high intensity lighting needed to increase photosynthesis, LED lights in the blue and red wavelengths would increase growth rates but, because they may have to be situated close to the crop, they could interfere with irrigation. For germination rooms, however, LED lighting would be much more efficient than standard fluorescent lights, would generate significantly less heat, and would not be subject to corrosion by the high humidity levels.

For the low intensity red light needed to extend photoperiods, LED lights would be as effective, use less energy, and last longer than traditional lamps. A major limitation as found by our rudimentary testing found that LED did have limitation in the area they illuminate (rapidly decreasing light intensity as the distance below the source increases). Before switching to LEDs, be sure that light coverage is adequate and confirmed with a light meter (at crop level). LED bulbs are available in screw bottom for traditional fixtures or as long tubes to replace fluorescent bulbs. Nurseries using high intensity discharge lamps would have to weigh the costs of replacing the fixtures as well as the lamps.

LED lighting is rapidly changing, with improving efficiencies improving and decreasing costs, so growers should keep an eye on this exciting new technology.

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