Designing an optimal lighting fixture for extraterrestrial crop growth:

Integrating efficacy and photobiology

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Abstract

Extraterrestrial crop growth will require the development of technologies that provide photons to drive photosynthesis. Light-emitting diode (LED) technology is the likely technology of choice due to 1) its inherent flexibility, and 2) its high efficiency. Here we describe two important considerations for the optimization of this system: photon efficacy (µmol of photons produced per joule of input electrical energy) and spectral effects on plant growth and development. With these two considerations, we suggest the design of an LED fixture for extraterrestrial crop growth that contains a 5:10:55:30 ratio of blue, green, red, and far-red photons (respectively). This would be achieved through phosphor-converted white, 660 nm red and 730 nm far-red LEDs.

Introduction

As humans endeavor to reach out to the stars, the challenge of providing food must be considered. Currently, the caloric and nutritional demands of astronauts on the International Space Station are completely fulfilled by food delivered from Earth (with very rare exceptions). As NASA returns to the Moon and sets astronauts on Mars for the first time (NASA, 2020), growing food on these extraterrestrial surfaces provides a substantial opportunity to reduce costs, especially as human presence on these planetary and natural satellites increases with numerous return missions.

The costs associated with bringing verses growing food on extraterrestrial surfaces are primarily determined by the launch mass, often described by the equivalent system mass (ESM). ESM is calculated by the following equation (Levri et al., 2003):

$$ESM = M + V \cdot V_{eq} + P \cdot P_{eq} + C \cdot C_{eq} + CT \cdot D \cdot CT_{eq}$$

Where M is the system mass (kg), V is the volume requirement (m^3), V_{eq} is the volume mass equivalency (kg/m^3), P is the power requirement (kW_e), P_{eq} is the power mass equivalence (kg/kW_e), C is the cooling requirement (kW_{th}), C_{eq} is the cooling mass equivalency (kg/kW_{th}), CT is the crew-time requirement (CM-h/yr), D is the mission duration and CT_{eq} is the crew-time mass equivalency (kg/CM-h/y). This equation converts all system requirements into a single mass term, and in general, the enormous cost of fuel to launch the total system mass outweighs all other associated costs.

Although extraterrestrial agriculture has substantial mass associated with it (including lighting systems, growth receptacles, solar power collectors and volume requirements), investing in infrastructure for growing food on extraterrestrial surfaces will eventually reduce costs compared to extended resupply. While it is useful to determine the return on investment related to growing food in the near-term, growing food off world is an inevitable necessity as mission durations become longer and further from Earth. Prepackaged foods currently have a shelf life of 1.5 to 3 years (Anderson et al., 2018). Because prepackaged foods degrade in nutritional value with time, resupply will eventually be infeasible as missions are located further from Earth.

Additionally, fresh leafy greens (e.g. lettuce) provide psychological benefits that prepackaged foods do not (Odeh and Guy, 2017), and are only available for astronauts if they are grown. Further benefits of growing plants include natural air purification and regeneration of oxygen and water.

Despites the benefits of growing food on extraterrestrial surfaces, the thin atmospheres of the Moon and Mars result in minimal protection from both dangerous short wave radiation (wavelengths below 320 nm) and incoming meteorites. Together these factors necessitate plant growth be below ground or in a heavily armored station. But, extraterrestrial agriculture will still require photons (light) to drive photosynthesis. Unlike on Earth where sunlight drives this process, growing food in a heavily armored station requires alternative means to provide these photons.

For the past three decades, systems that use concentrating mirrors and fiber optic cables have been considered to fulfill this role (Drysdale and Sager, 1996; Drysdale et al., 2008; Nakamura et al., 2009, 2012). This technology was preferred largely due to the inefficiency of the older electric lighting technologies (e.g. fluorescent, high-pressure sodium). Light-emitting diode (LED) technology has improved rapidly over the past two decades and is now double the efficiency of the next best electric lighting technologies when operated under the right conditions (US DOE SSL program 2017; Kusuma et al., 2020). Although both technologies have similar ESM (Hardy et al., 2020), LEDs are advancing more quickly than the solar fiber optic/concentrating mirror technology, and LED-based systems are more flexible.

LED technology

Efficiency (W per W) is not the appropriate metric to describe the performance of LEDs for plant production. Rather, photon efficacy, which is the number of photons produced per joule of input electrical energy (µmol of photons per J), is appropriate. This is because the Stark-Einstein photo-equivalence law states that one photon excites one molecule/electron. This means that photons and not energy drive photobiological processes. Although, this is fundamentally true, the photon must contain sufficient energy to excite electrons within the atoms of molecules but must not contain excessive energy to produce free-radicals. Photon efficacy is derived from the intensity of the photon flux (µmol per s) divided by the input electric power (W or J per s).

Table 1: Efficacy of 11 common LEDs that can affect plant growth and development. The LEDs are described by their peak wavelength. Efficacy decreases with increases in both temperature and drive current. The operating conditions to achieve the efficacies presented here are a junction temperature of 25 ˚C and the nominal drive current provided in the second column.

Wavelength (nm)	nominal drive current (mA)	Efficacy (µmol per J)
385	**500**	**0.9**
405	**500**	**1.6**
450	**700**	**3.0**
470	**350**	**2.7**
500	**350**	**2.2**
530	**350**	**1.9**
590	**350**	**1.1**
615	**350**	**3.1**
625	**350**	**2.7**
660	**700**	**4.3**
730	**350**	**3.8**

LEDs output a photon flux with approximately a Gaussian spectral distribution. This means they have a peak wavelength and a relatively narrow spectral bandwidth, especially compared to other electric lighting technologies. This bandwidth is often described by the full (spectral) width at half maximum (FWHM), which ranges between 9 to 35 nm depending on the type of LED (Figure 1). There are two primary types of LEDs, AlInGaP (peak wavelength between 550 to 800 nm) and InGaN (peak wavelength between 360 to 550 nm). Table 1 and Figure 1 both demonstrate the significant differences in efficacy between the available LEDs. Increasing both the junction temperature and the drive current will decrease the efficacy of the LED, while decreasing both of these parameters increases the efficacy.

Planck's equation is used to convert between efficiency and efficacy. It indicates that longer wavelength (lower energy) photons have the potential to achieve higher efficacies than shorter wavelength (higher energy) photons. This contributes significantly to the choice of LEDs to incorporate into a lighting fixture for extraterrestrial agriculture. The efficiencies of 450 nm blue and 660 nm red LEDs are actually quite similar (about 80%), but the lower energy of the red photons makes the efficacy of these LEDs about 43% higher than blue LEDs under nominal operating conditions. Thus, there is a clear benefit of including lower energy (longer wavelength) photons over higher energy (shorter wavelength) photons. It is useful then to consider how different photons drive biological responses.

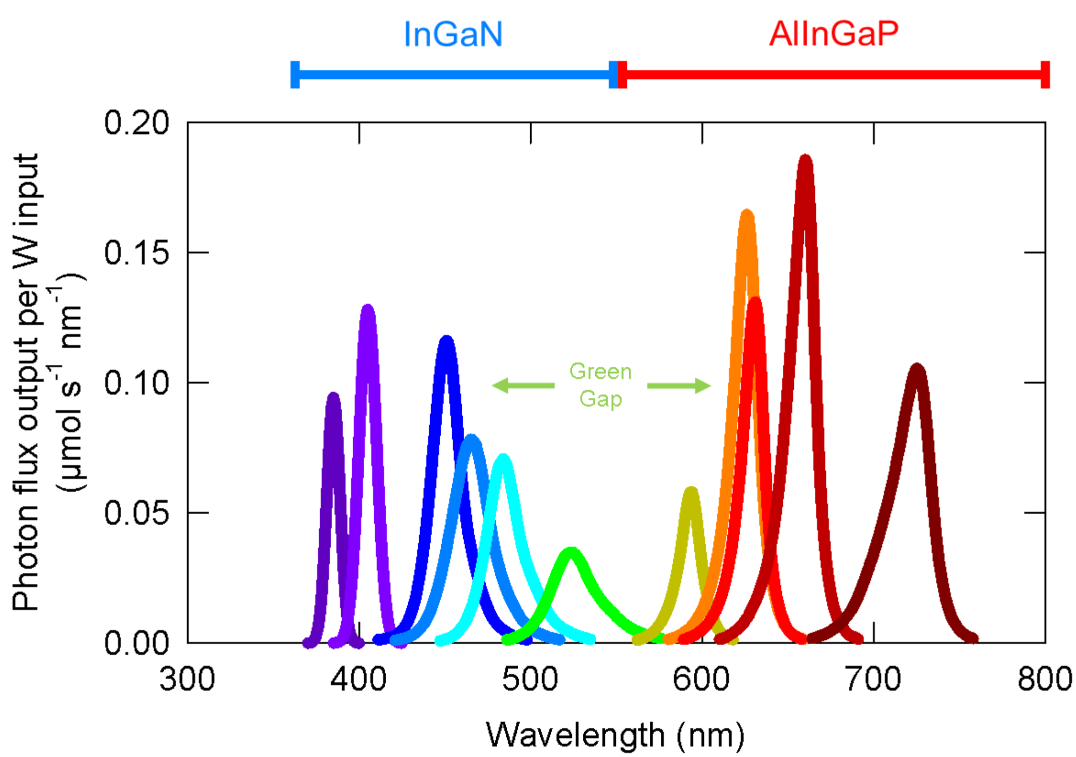


Figure 1: Photon flux (µmol per s) given one W of electrical input power for 11 narrow bandwidth LEDs. Integrating the area under the curve for each type of LED provides the relative efficacy of that LED. The curves provided here are for nominal operating conditions: 25 ˚C and drive currents described in Table 1. The blue and red bars at the top of the figure describe the semiconductor material of the type of LED. The green gap, which is the name for the relatively low efficiencies of LEDs within the green region (500 to 600 nm) of the spectrum, is shown.

Photobiology

Photosynthesis

The most important photobiological process for crop growth is photosynthesis, the process by which plants use photons to drive the conversion of CO_2 and water into sugar and oxygen. The photons that drive this process have traditionally been considered to be those with wavelengths between 400 to 700 nm (McCree, 1971, 1972). This region is called photosynthetically active radiation (PAR). Quantifying the number of photons within this region incident on a surface is called the photosynthetic photon flux density (PPFD) and has units of µmol m^{-2} s^{-1}. In general, as PPFD increases canopy photosynthesis increases, although it begins to saturate at high intensity (the specific intensity of saturation depends on many factors including species and acclimation of the photosynthetic apparatus).

Recent data suggests that this traditional definition of photosynthetic photons should be revised to include photons between 400 to 750 nm (Zhen and Bugbee, 2020a,b). This modified region is called extended photosynthetically active radiation (ePAR), and the modified term for photon intensity is called extended photosynthetic photon flux density (ePPFD). There are two important caveats to this extended definition:

1) This extended region (700 to 750 nm), is called far-red (FR) in the plant science literature. For photosynthesis, these photons must be provided in combination with shorter wavelength photons in order fix carbon. Additionally, although increasing the ePPFD increases photosynthesis, when FR photons are provided in excess of 40% of the PPFD, they deviate from a 1:1 relationship between PAR and FR in terms of photosynthetic capability (Zhen and Bugbee, 2020a).
2) Photons with wavelengths right at 750 nm likely over-estimates the bounds of photosynthesis. Zhen et al. (2019) showed that the quantum yield of photosystem II (an indicator of photosynthetic efficiency), was not increased with photons at 752 nm. Despite this, the FR LED (with a peak at about 730 nm) outputs few photons beyond 750 nm, making this defined range (400 to 750 nm) adequate for plant production under LEDs.

Although the photons between 400 to 700 nm are included in the traditional definition of photosynthetic photons, the studies that led to this definition do not necessarily show equal photosynthesis (mol CO_2 fixed per mol photon absorbed) across wavelengths.

Blue photons (400 to 500 nm) show lower photosynthesis than longer wavelength photons (McCree, 1971). This is primarily because blue photons are absorbed by non-photosynthetic pigments within leaves (e.g. flavonoids). These pigments are synthesized to reduce potential stress on the photosystems under high photon fluxes. The efficiency of blue photons for photosynthesis vary significantly with both wavelength and species.

At low photon fluxes, green photons (500 to 600 nm) are used slightly less efficiently than red photons (600 to 700 nm), but much more efficiently than blue photons (McCree, 1971). However, higher fluxes of green photons may increase photosynthetic efficiency to equal or (potentially) above that of red photons. This is because blue and red photons are absorbed rapidly by the chlorophyll in the top layers of leaf tissue, over-saturating the photosystems. Green photons penetrate deeper into leaf tissue resulting in more even excitation of photosystems across the whole leaf and across the whole plant canopy, which increases the photosynthetic efficiency. Although this is theoretically the case, it has been difficult to show in practice.

Red photons are efficiently used for photosynthesis, but could potentially be damaging if applied at too high intensities.

Morphology

Although only photons between 400 to 750 nm drive photosynthesis, photons between about 280 to 800 nm can affect plant development through photoreceptors. Photoreceptors are proteins with a photon-absorbing component called a pigment. When the pigment absorbs photons, it undergoes a conformational change activating the photoreceptor, which then proceeds to alter gene expression or interact with membranes. One of the most important morphological metrics that is under photo-receptor control is leaf area/leaf expansion. An increase in leaf area means that a plant can capture photons over a wider area for use in photosynthesis, resulting in overall increases in growth rate. Stem and petiole elongation are also affected by the light conditions with species-specific responses that can potentially interact with other factors, such as photon intensity. Plant photoreceptors include UVR8 (UV-B resistance 8), cryptochromes, phototropins and phytochromes.

The UVR8 photoreceptor responds to UV-B (ultra-violet B) photons (between 280 to 320 nm). UV-B photons damage plants at high fluxes because they strip electrons from molecules producing free-radicals. But, at low fluxes they act as a beneficial stressor by increasing the synthesis of secondary metabolites including anthocyanins and flavonoids (Neugart and Schreiner, 2018; Dou et al., 2019). Growing plants in the absence of UV-B typically does not induce abnormal morphology with the exception of the physiological disorder intumescence, which only occurs in specific cultivars of specific species (Kubota et al., 2017; Williams et al., 2014). LEDs that produce the UV-B photons are inefficient (at most 3%, about 0.1 µmol per J) and are therefore not an economic/practical addition to an LED spectrum. Additionally, the synthesis of beneficial secondary metabolites can also be increased by excitation of the cryptochrome photoreceptors (Wade et al., 2001). Overall, UV photons are expensive and usually unnecessary.

Blue photons excite both the cryptochrome and phototropin photoreceptors. Cryptochromes primarily modulate plant development through altering gene expression, while phototropins primarily interact with membranes (Lin, 2000). In general, increasing the fraction of blue photons decreases leaf expansion (Hernández and Kubota, 2016; Snowden et al., 2016), but growing plants in the absence of blue photons can induce abnormal morphology such as low chlorophyll concentrations and excessive elongation (Son and Oh, 2013; Snowden et al., 2016; Yorio et al., 2001). Although these abnormal symptoms often occur, leaf area and yield in the absence of blue photons have been reported to increase (Meng et al., 2020; Son and Oh, 2013; Wang et al., 2016), but decreases are also reported (Hernández and Kubota, 2016; Snowden et al., 2016; Yorio et al., 2001). The responses appear to be species and intensity specific. From these general responses, it is useful to include low fractions of blue photons, but removing blue photons entirely may be detrimental.

We have begun to investigate the tolerance of different species to low fluxes of blue photons in a background of red photons (from an LED with a peak at 660 nm) by including 0, 1, 2.5 5 and 10% blue (Figure 2). In the lettuce cultivar ‘Rex’ we observed both expected responses with decreases in leaf expansion and growth at both 0 and 10% blue compared to 1, 2.5 and 5% blue.

In other species (data not shown), the low fractions of blue induced excessive stem elongation. Stem elongation results in lodging in

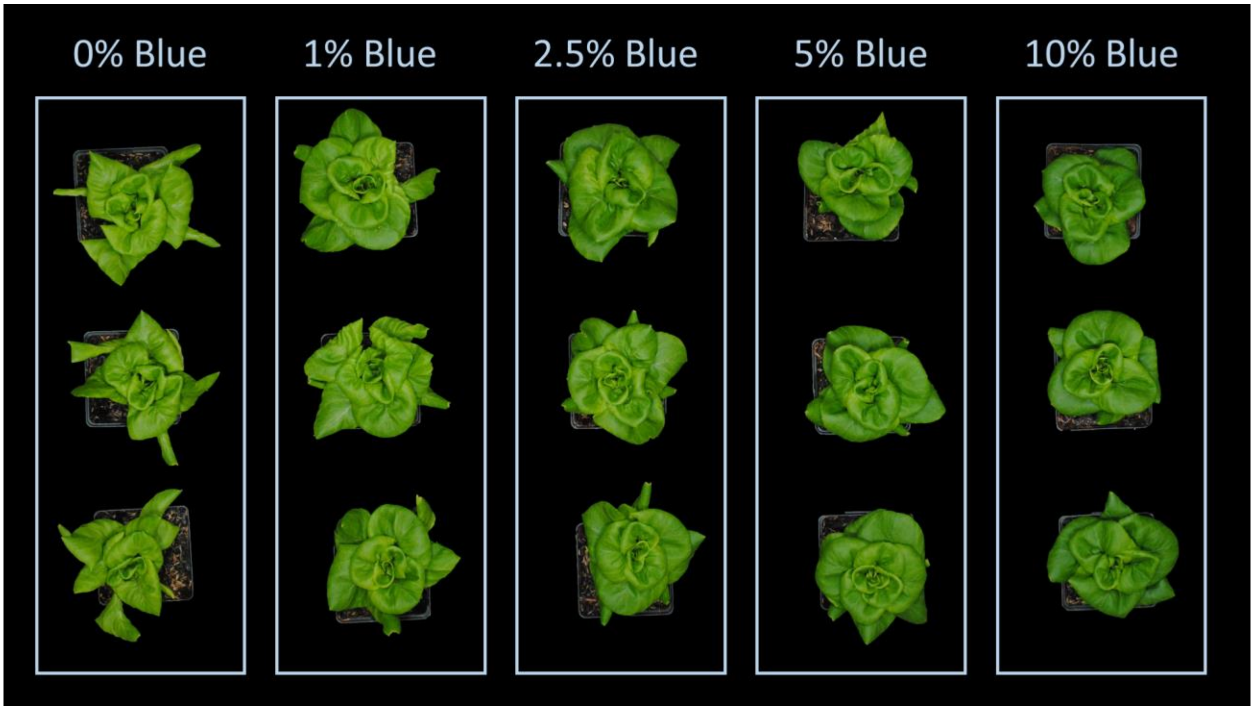


Figure 2: Lettuce (cv. Rex) grown under low fractions of blue photons in a red background. Three representative plants under each percent plants are shown. Both blue and red photons drive photosynthesis (with different efficiencies), and they both activate photoreceptors that can play critical roles in plant development. But, because blue photons (at 450 nm) have 47% more energy in each photon than red photons (at 660 nm), it is beneficial to minimize these photons to increase system efficiency.

some species (bending of stems under excessive weight without proper structure) and increased biomass partitioning to the stems, meaning it is partitioned away from the organ of interest depending on the crop species (e.g. fruits, seeds and leaves).

Blue photon-activated-cryptochromes also contribute to the transition from vegetative growth to reproductive growth, and therefore the absence of blue photons could obstruct this transition. Further research is required to determine the thresholds of photon fluxes for normal plant growth and development. For the most part, 5% blue appears to be adequate for many species (Figure 2, Dougher and Bugbee, 2001).

There is good evidence that cryptochrome activation is reversed by green photons (Bouly et al., 2007), meaning that green photons can induce elongation. Similar to the potential beneficial effects of green photons on photosynthesis, beneficial effects of green photons on morphology are theorized, but not necessarily well demonstrated. Plants often appear to develop normally in the absence of green photons (Hernández and Kubota, 2016; Snowden et al., 2016), and substituting red photons for green photons has often been shown to minimally affect plant development (Son and Oh, 2015).

Phytochrome photoreceptors absorb across wavelengths from 300 to 800 nm, but they are most sensitive to the red and FR regions. Phytochromes act in a similar manner to cryptochromes, altering development primarily by modulating gene expression. While cryptochromes are thought to be activated by blue photons and deactivated by green photons, phytochromes are activated by red photons and deactivated by FR photons. This means that red

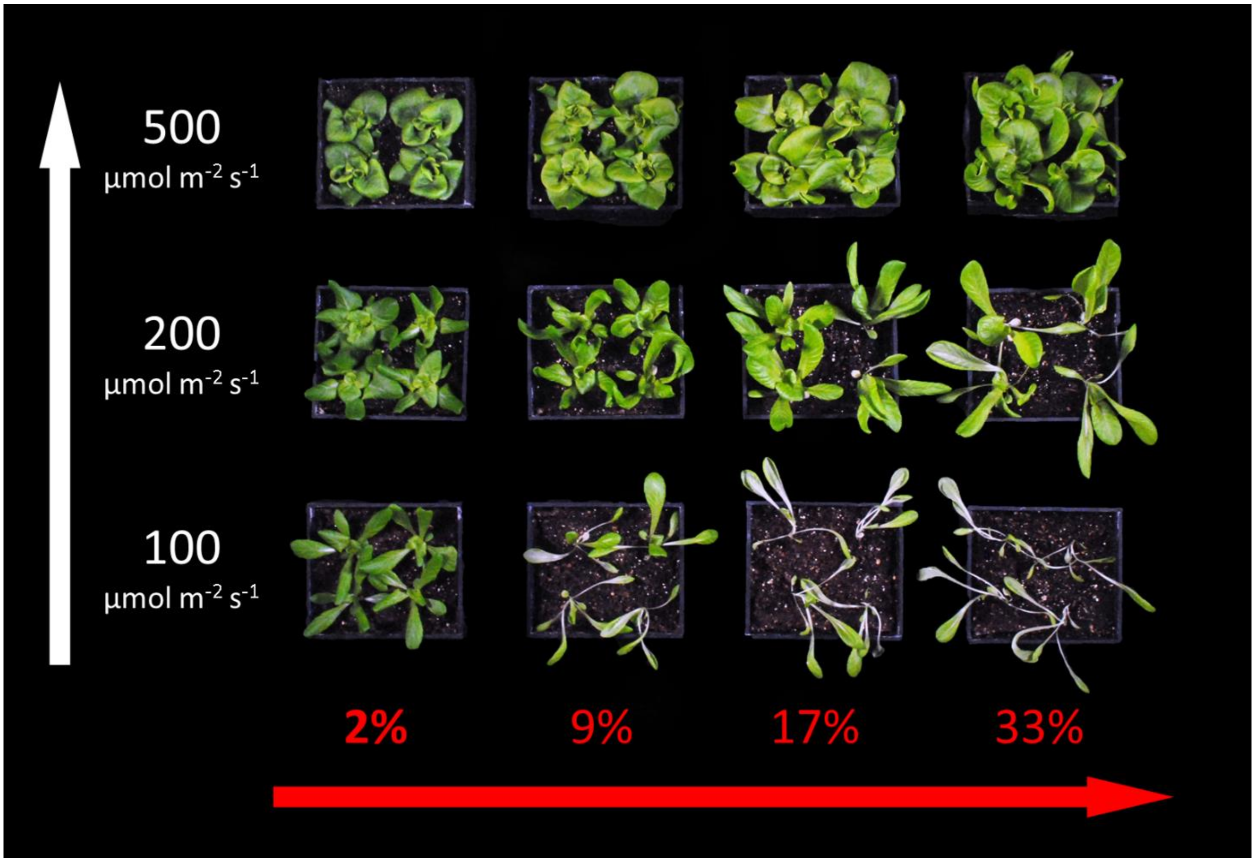


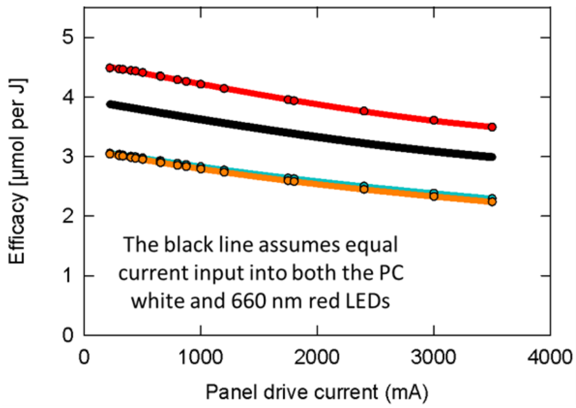
Figure 3: Interactions between far-red and photon intensity on leaf expansion in 'Rex' lettuce. Increasing the percentage of FR increased leaf expansion at high photon intensities, but decreased leaf expansion at low photon intensities. This study maintained a constant ePPFD within a set of treatments (100, 200 and 500 µmol m^{-2} s^{-1}), and reduced PAR while increasing FR.

photons tend to reduce plant elongation, while FR tends to promote elongation. This response of plants to FR is well studies, and photons within this region can have substantial effects on plant growth and development. We investigated interaction between FR and photon intensity in the lettuce cultivar 'Rex', and found that FR beneficially increased leaf expansion at high photon fluxes, but decreased leaf expansion at low photon fluxes (Figure 3).

Synthesis of efficacy and photobiology

Decreasing the drive current below the nominal current listed in Table 1 will increase the efficacy of the LED for two reasons: 1) decreasing the drive current inherently increases efficiency, and 2) this increase in efficiency will reduce internal heating, reducing the temperature, which increases efficiency. At the same time, decreasing the current through the LED will decrease the photon output, meaning that achieving high photon fluxes with high efficacies will necessarily increase the cost of the LED fixture. This is an issue for economical plant production under LEDs on Earth, but this cost is relatively small for NASA, especially when viewed through the lens of ESM.

Incorporating LEDs into a lighting system introduced further decreases in efficiency, but with careful design, these decreases can be minimized. We have worked with the LED manufacturer Luminleds, to develop LED fixtures with high efficacy (Figure 4 and Figure 5). These



LED fixtures incorporated phosphor converted (PC) white LEDs and red LEDs. Although these

Figure 4: Current droop (as current increases efficacy decreases) of the LED panels developed by Lumileds as a demo extraterrestrial lighting fixture for crop growth. 4000 and 6500 K LEDs have similar efficacies under the conditions here.

LED fixtures represent the state-of-the-art, improvements can be made that consider both the lower energy of longer wavelength photons (in conjunction with good efficacy), and considerations of the limits of photobiology.

Because higher photon fluxes result in faster growth rates, the optimal spectrum presented here assumes high photon intensity. There is a tradeoff between photon intensity and volume requirements (Wheeler, 1990), but we do not consider this.

In general, the lower limit of blue photons generally appears to be about 5%, although more research is required to determine this threshold across species. Additionally, potential interactions with photon intensity are need to be determined. Green photons could be beneficially, but studies generally show minimal response to green photons. Furthermore, the LEDs that produce green photons directly have a poor efficacy (Table 1 and Figure 1). This may improve over the next few decades, but currently, green photons are produced by phosphor conversion (white LEDs, used in Figure 4 and Figure 5). The phosphor conversion process incorporates a material called a phosphor on a (450 nm) blue LED. The phosphor absorbs blue photons and re-emits them at longer wavelengths. This conversion process is not 100% efficient, and the maximum efficacy is determined by the underlying blue LED, which inherently have a lower potential efficacy.

Despite these issues, the green color of plants is only visible under a spectrum that contains green photons. This has many potential psychological benefits for astronauts, which ought to be considered. These visual considerations are related to color rendering index, and further investigation is required. At present, 10% green photons would allow visualization of the green color of the plants, and could potentially increase photosynthesis and leaf expansion.

Red photons from 660 nm LEDs would make up the bulk of the spectrum, as these photons efficiently drive photosynthesis. As discussed previously, FR was not beneficial when added in excess of 40% of PPFD (about 30% when considered a percentage of ePPFD). Additionally, This fraction of FR benefits leaf expansion at high photon fluxes (Figure 3). FR photons are the lowest energy photons that can be considered photosynthetic, meaning they have the potential to have the highest efficacy. Horticultural applications have driven research and development into increasing the efficiency/efficacy of 660 nm red LEDs. This has resulted in a higher current efficacy of 660 nm red LEDs compared to 730 nm FR LEDs, but advancements in FR LED are not far behind and could catch up in the near future. Nonetheless, FR LEDs have the second highest efficacy under nominal conditions of all the LEDs described in Table 1.

Altogether, we suggest that the optimum spectrum for extraterrestrial crop growth would contain 5% blue, 10% green, 55% red and 30% far-red. This would be achieved with a

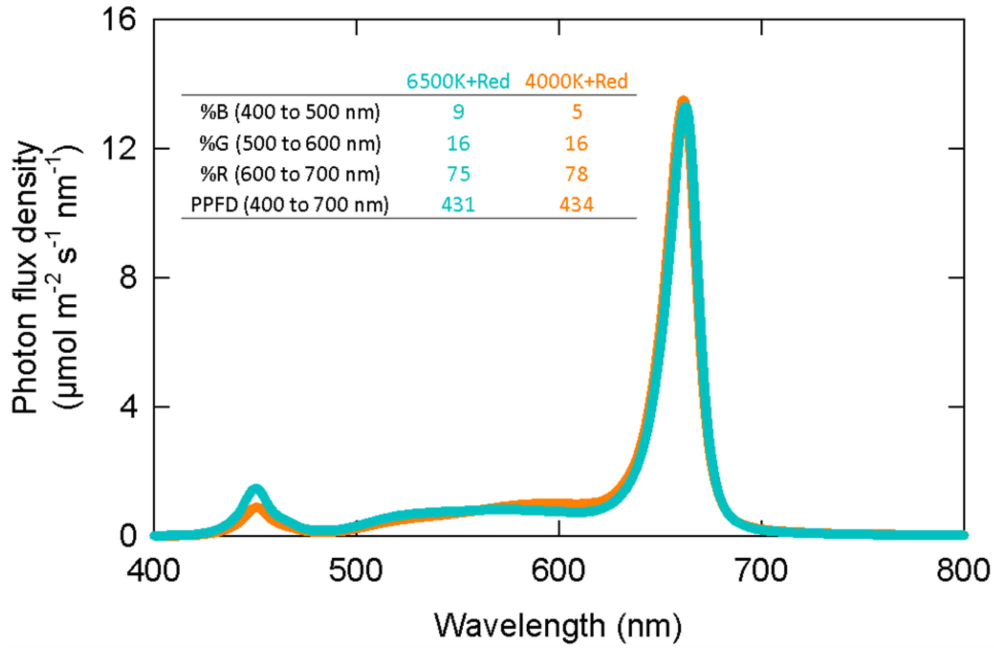


Figure 5: The spectrum of the demo LED fixture developed in partnership with the company Lumileds. The spectrum suggested here would be very similar, but with added FR photons at 730 nm.

combination of PC white LEDs, 660 nm red LEDs, and 730 nm FR LEDs. With current technology, this fixture could be built with an efficacy approaching 4.1 µmol per J (under the right operating conditions). Assuming continued improvements in LED technology (to about 90% efficiency); the LED fixture could achieve an efficacy of approaching 4.8 µmol per J. The next best electric lighting technology, high-pressure sodium, has an efficacy of 1.7 µmol per J, meaning this LED fixture would drive plant growth with nearly 3 times less energy.

In addition to high potential efficacy, this spectrum would efficiently drive photosynthesis, and the low (but not absent) blue, moderate green, and high FR would all result in rapid leaf expansion, meaning higher rates of photon capture and faster growth.

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