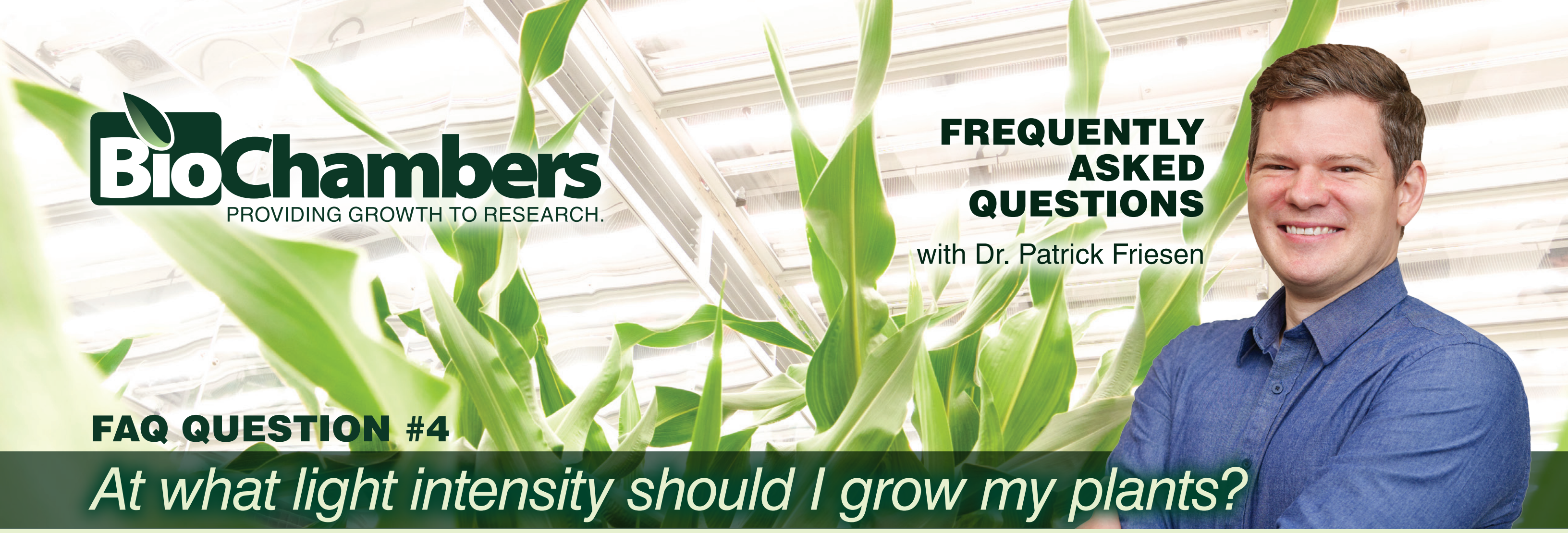

BioChambers
PROVIDING GROWTH TO RESEARCH.

FREQUENTLY ASKED QUESTIONS
with Dr. Patrick Friesen

FAQ QUESTION #4

At what light intensity should I grow my plants?

Light drives photosynthesis by providing the chemical energy required for CO_2 assimilation and growth. Light intensity for plant growth is typically measured as photosynthetic photon flux density (PPFD). The units are μmol photons m^{-2} s^{-1}, the sum of photons from 400 to 700nm wavelengths which is the currently accepted range of photosynthetically active radiation, PAR (McCree 1972). In the literature, PPFD is often called PAR, irradiance, or quantum flux (Mõttus et al 2012, Sager & McFarlane 1997). In growth chambers and rooms, PPFD is best measured with growth chamber doors closed, often at the top of the plant(s) at the height of the uppermost fully expanded leaves. It is best practice for the user to be some distance away from the sensor head, enough to ensure they themselves are not blocking or shading any of the PPFD. PPFD is measured with a quantum sensor. Not all sensors accurately measure PPFD under all electric light sources, so it is best practice to ensure you are using the correct sensor and that its calibration is up to date (Barnes et al 1993, Mõttus et al 2012). Spectrometers or spectroradiometers measure the spectrum or light quality (PFD at each wavelength), with their range often extending into the ultraviolet (< 400 nm) and far-red (> 700 nm) regions beyond PAR, in addition to also measuring total PPFD. When added to PAR (400-700nm), far-red (701-750nm) photons act equivalently to PAR photons to drive photosynthesis when included up to around 30% (of 400-750nm) in several crop species. Currently extended PPFD or PAR (ePAR, sum of photons from 400-750nm) has been proposed as another light intensity measurement to report alongside PAR (DLC, 2021, Zhen & Bugbee 2020, Zhen et al 2021).

The PPFD inside a growth chamber will depend on fixture power and photosynthetic photon efficacy, fixture dimming, distance from the fixture, fixture beam angle, and the reflectivity of the sidewalls and floor (Mõttus et al 2012, Runkle & Bugbee 2017, Sager & McFarlane 1997). The PPFD across a horizontal plane can vary inside growth chambers and rooms. Generally PPFD is greatest around the center and decreases along the sides and in the corners (Friesen 2021a, Poorter et al 2012). How much PPFD varies across the growth area (horizontal plane) at a given distance from the lights, is termed PPFD uniformity. PPFD will increase moving closer to the light fixtures, however uniformity generally decreases due to gaps between light sources.

Many plants can grow visibly healthy under a wide range of PPFD, and a PPFD that is too low or too high could depend more on photoperiod, nutrient status, growth temperatures, or light spectrum rather than plant species per se. These factors interact with each other and PPFD itself to determine the high and low PPFD extremes that can cause visible stress (eg. chlorosis). For example, the model plant *Arabidopsis thaliana* can grow under a wide range of PPFD, however is commonly grown at low PPFD (100 to 200 μmol m^{-2} s^{-1}) and moderate temperatures (18 to 23°C) in growth chambers and rooms to ensure consistent growth and plant health (Purdue 2021). However, some plants are markedly adapted to higher or lower PPFD, often referred to as obligate sun or shade plants. Photosynthetic type can also be an indicator of the PPFD required to thrive, as the photosynthetic rate of most plants with C_4 photosynthesis saturate at high PPFD (eg. *Miscanthus*, Figure 1). Many crops are obligate sun plants, whereas some tropical understory ferns are obligate shade plants, requiring higher or lower PPFD to thrive (Lambers & Oliveira 2019a). In spite of these adaptations, it appears that some sun and shade plants can grow without major adverse health effects down to a lower threshold PPFD of around 50 μmol m^{-2} s^{-1} (Pons & Poorter 2014).

A given plant species or genotype will acclimate the best it can to a given PPFD with its available resources and growth conditions. A higher PPFD generally results in higher photosynthetic and growth rates, decreased stem elongation, thicker leaves, and greater investment into roots compared to lower PPFD (Anderson et al 1995, Lambers & Oliveira 2019a, Lambers &

Oliveira 2019b, Poorter et al 2019). To fully realize the growth stimulation of higher PPFD, mineral nutrition and water supply must keep pace to feed rapidly growing plants. In addition, CO_2 concentration and temperature interact with PPFD to control growth and development. Elevated CO_2 concentrations (above current atmospheric) generally increase growth and plant size, whereas warmer temperatures (up to a given optimum) generally speed up growth and development (Lambers & Oliveira 2019a, Lambers & Oliveira 2019b).

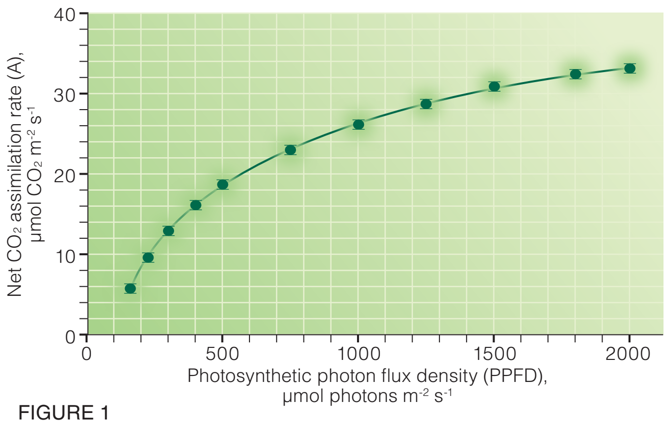

FIGURE 1

Response of photosynthetic rate (net CO_2 assimilation rate, A) to incident photosynthetic photon flux density (PPFD) of the C_4 perennial grass ***Miscanthus*** x ***giganteus***. Measurements of A were taken at 30°C and 400ppm ambient cuvette CO_2 concentration. Plants were grown in BioChambers GC-20 (TPC-19) growth chambers at 27/20°C day/night temperatures, 14hour photoperiod, and under a growth PPFD of 550 (±50) at the top of the leaves. Symbols are the mean average ± standard error, n = 6 different plants/leaves. Line through symbols is a best fit regression.

Your research and plant growth goals could influence your choice of PPFD in existing growth chambers (if adjustable), and PPFD capabilities when selecting new growth equipment. In crop science, physiology, ecophysiology, and ecology, your goal may be to grow plants that look and behave more similar to those growing outside. Historically, chamber-grown plants have received less light but warmer average temperatures than they would experience outside (Poorter et al 2016). Older lighting technologies used in growth chambers (fluorescent tubes + halogen bulbs or metal halide + high pressure sodium bulbs) could not easily achieve leaf level PPFDs as high as direct sunlight during the growing season. Recent LED lighting technologies can achieve leaf level PPFDs greater than direct sunlight at solar noon at any location on earth. Dimming capabilities at 1% intervals can be scheduled to produce bell-shaped PPFD curves similar to sunlight on a clear day (Varella et al 2011). Bell curved sunlight like PPFD may entrain the circadian system and physiology (eg. stomatal sensitivity) to be more similar to plants grown outside (Matsubara 2018). In general, more synchronous variation of PPFD and growth temperatures appears to produce plants that are closer to those growing outside (Chiang et al 2021).

Published recommended PPFD values are not as common as daily light integral (DLI, mol photons m^{-2} day^{-1}) values for a given plant species. The DLI is how much light plants receive in a day, analogous to a rain gauge for a rainfall event. In growth chambers, for traditional ON/OFF light schedules, the DLI is the product of PPFD and photoperiod (Friesen 2021b). If plants can acclimate to a given PPFD, then DLI, through photoperiod adjustment, is often a better predictor of overall plant growth. DLI also better expresses plant growth when your PPFD is variable, for example, when re-creating conditions outside in the field (Poorter et al 2019). Outside, PPFD perpendicular to a clear sky in an unobstructed location will produce bell-shaped curves with a peak at solar noon (Varella et al 2011). These peak PPFD values vary with latitude, and can be over 2,200 μmol m^{-2} s^{-1} at the equator during the equinoxes, and 1,800 to 1,900 μmol m^{-2} s^{-1} at 50°N latitude on the summer solstice. At higher latitudes, the seasonal range in peak PPFD increases, with a peak of only 500 to 600 PPFD at 50°N latitude at the winter solstice (Apogee Instruments 2021). In reality, cloud cover and shading often create a dynamic PPFD environment for a given leaf over the course of its life.

The PPFD of all electric lights will decline with age (usage time). LED lighting generally maintains its initial PPFD output longer than older electric lighting. How the PPFD of an electric light source declines with usage time is given by its L rating. An L_{70} = 50,000 hours indicates the light source will have 70% of it's initial PPFD output after 50,000 hours of use, operating at a specified temperature (here usually 20-25°C). Temperature negligibly affects PPFD output of most LED lighting over the short-term, but continual operation under higher temperatures may hasten the PPFD decline of LED lighting. The PPFD output of exposed fluorescent tubes declines considerably below 25°C chamber temperatures if tubes are not fitted with heat retaining sleeves.

Our growth chambers and rooms can be organized by their PPFD capabilities:

Maximum PPFD Capabilities	Growth Chamber/Room Series	PPFD range typically used for…
Ultra Low: <50 PPFD	Seed Germination (SG)	Germinating seeds of many different plants.
Low: 100 to 600 PPFD	Tissue Culture (TC) Short Plant (SP) Flex (FX)	Tissue culture and micropropagation and growing Arabidopsis. Growing many other plants to early growth stages, such as leafy greens.
Medium: 600 to 1000 PPFD	Flex (FX) Low Temperature (LT)	Growing a wide variety of medium sized plants including many crop plants.
High: 1000 to 2200 PPFD	Tall Plant (TP) Flex (FX)	Growing taller crop plants and young trees, especially those that thrive under high PPFD (eg. Corn, other C_4 crops, sunflowers, hemp).

Questions to ask yourself when deciding what PPFD to grow your plants under:

- Do you need to match PPFD to another study for experimental purposes?
- Do I want to increase PPFD to make my plants grow faster and invest more into roots?
- Do I want to adjust PPFD to have some control over growth rate, in order to synchronize plant growth and development with some other process, action, or event?
- Will I be moving plants into another growth environment and want to best match PPFD to seamlessly continue growth and avoid potential stress?
- Do I want to re-create more outside like conditions by re-creating a bell shaped PPFD curve and synchronize variation of PPFD and growth temperatures?

When considering PPFD specifications, pay close attention to:

a) The vertical distance from the lamp canopy the measurements were taken.

b) The distance between measured grid points over a horizontal plane at the given vertical distance.

For example, here is the light intensity specification for our TPC-19:

Intensity: 1500 µmol m^{-2} s^{-1} PPFD measured at 150mm (6”) from the lamp canopy at 25°C and averaged on a 150mm (6”) grid.

Light Intensity Control: Two channel dimmable system. PhysioSpec Indoor broad spectrum LED modules are on one dimming channel and PfrSpec far-red spectrum LED modules are on the second dimming channel. For each channel, users program a percentage setpoint within the dimmable range from 10% to 100% via the controller.

Here are some resources with recommended growth PPFD for a variety of plant species:

https://www.controlledenvironments.org/wp-content/uploads/sites/6/2017/06/Plant_Info_Table-1.pdf

https://fluence.science/wp-content/uploads/2018/11/Fluence-Photobiology-Guide-2019.pdf

https://media.osram.info/media/img/osram-dam-15178492//OSRAM_OS_A4_Horticulture_2020-11-06_EN.pdf

Other lighting resources:

https://www.apogeeinstruments.com/videos-and-tutorials/

https://www.canr.msu.edu/floriculture/uploads/files/sole-source-lighting.pdf

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