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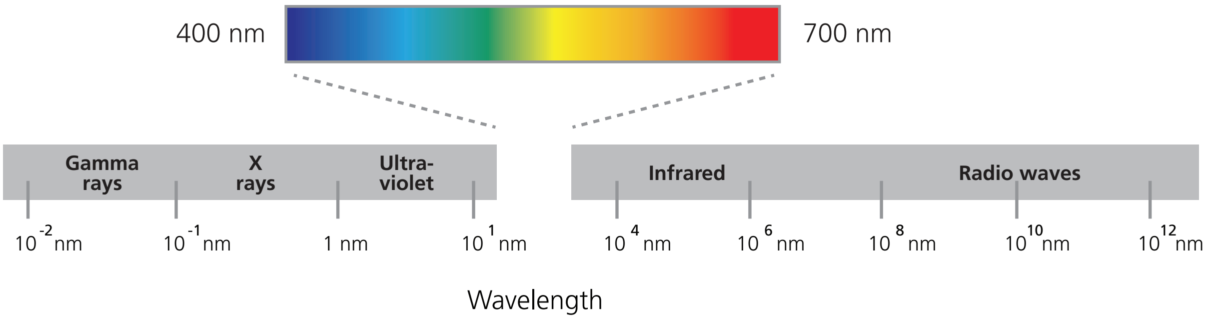
Which regions of the electromagnetic spectrum do plants use to drive photosynthesis?

Green Light: The Forgotten Region of the Spectrum.

In the past, plant physiologists used green light as a safe light during experiments that required darkness. It was assumed that plants reflected most of the green light and that it did not induce photosynthesis. Yes, plants do reflect green light but human vision sensitivity peaks in the green region at about 560 nm, which allows us to preferentially see green. Plants do not reflect all of the green light that falls on them but they reflect enough for us to detect it. Read on to find out what the role of green light is in photosynthesis.

The electromagnetic spectrum: Light

Visible light ranges from low blue to far-red light and is described as the wavelengths between 380 nm and 750 nm, although this varies between individuals. The region between 400 nm and 700 nm is what plants use to drive photosynthesis and is typically referred to as Photosynthetically Active Radiation (PAR). There is an inverse relationship between wavelength and quantum energy, the higher the wavelength the lower quantum energy and *vice versa*. Plants use wavelengths outside of PAR for the phenomenon known as photomorphogenesis, which is light regulated changes in development, morphology, biochemistry and cell structure and function. The effects of different wavelengths on plant function and form are complex and are proving to be an interesting area of study for many plant scientists. The use of specific and adjustable LEDs allows us to tease apart the roles of specific areas of the spectrum in photosynthesis. Furthermore, the synergy between photosynthesis and photomorphogenesis can be more accurately examined now. This paper focuses on photosynthesis. Photomorphogensis will be covered in the future.



The electromagnetic spectrum.

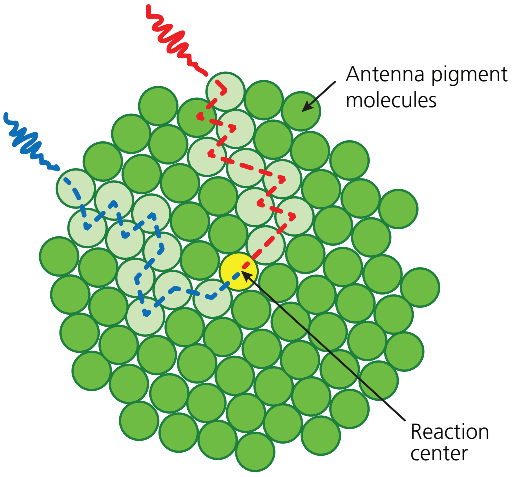
heliospectra
October 5, 2012

Photosynthetic pigments and light absorption

The first step in photosynthesis is the absorption of light by antenna pigments located within the thylakoid membrane in the chloroplasts. Photosynthetic organisms contain an assortment of pigments thereby allowing absorption of a maximum number of wavelengths. All photosynthetic organisms contain chlorophyll *a* and this is the primary light harvesting pigment. Higher plants contain accessory pigments that are also involved in light harvesting and photochemistry. These are chlorophyll *b* and the carotenoids.

An excellent and detailed description of plant pigments can be found at:

http://www.life.illinois.edu/govindjee/photosynBook/Chapter9.pdf



Light energy is absorbed by the pigment-protein complexes in the antennae and is transferred through Förster energy resonance transfer to the reaction center where light energy is converted to chemical energy. Light is collected by 200-300 pigment molecules, which are bound to light- harvesting protein complexes located in the thylakoid membrane. The energy generated by light is used in primary and secondary plant metabolism

Photosynthetic antenna where light absorption occurs.

Light absorption by photosynthetic pigments is extremely fast. It occurs within femtoseconds (10^{-15} s) and causes a transition from the electronic ground state to an excited state and within 10^{-13} s the excited state decays by vibrational relaxation to the first excited singlet state. Photosynthetic antenna systems are very efficient at excitation transfer processes. Under optimum conditions over 90% of the absorbed quanta are transferred within a few hundred picoseconds from the antenna system to the reaction center which acts as a trap for the exciton. The exciton transferred to photosystem II results in the extraction of an electron from water that is passed along the photosynthetic electron transport chain to an excited photosystem I which subsequently reduces NADP$^+$ to NADPH which serves as an energy source for plant metabolism. A second energy source used in plant metabolism, ATP, is also produced during electron transport *via* an ATPase driven by a proton gradient. There are several alternative electron transport routes utilized by plants but these are outside of the scope of this paper.

For a more detailed look at light absorption:
http://www.life.illinois.edu/govindjee/photosynBook/Chapter10.pdf.

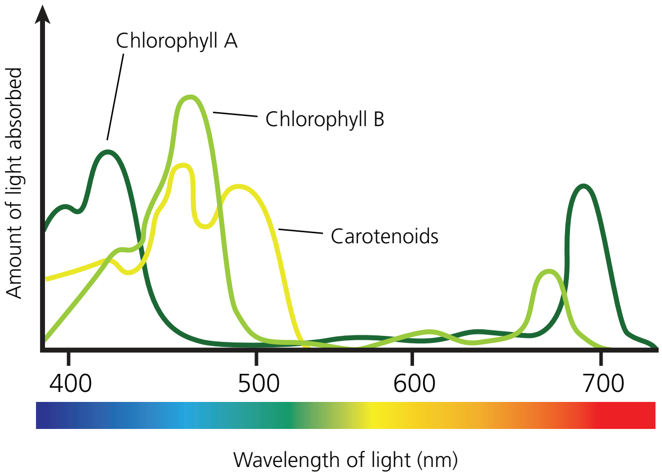
Absorption spectra versus Action spectra

Reading through the popular literature on the internet and on LED lamp websites it is obvious that there is little understanding about which wavelengths plants use for photosynthesis. It is apparent that there is confusion between what an absorption spectrum and an action spectrum are and what they represent. An absorption spectrum defines the wavelengths that are absorbed. An action spectrum defines the wavelengths that are most effective for photosynthesis. In other words, it is the portion of the spectrum that does the work. This is what is most important in plant growth and metabolism. It is important to note that light absorption and light utilization are two different phenomena.

1. What is Absorption Spectrum?

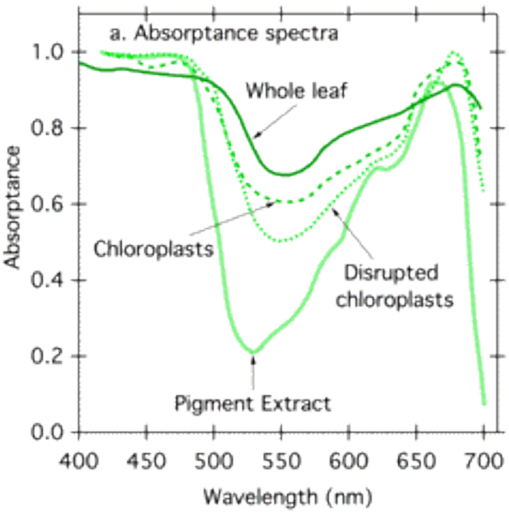
Which regions of the visible light spectrum do plants absorb light? This is different for extracted chlorophyll molecules, whole chloroplasts (where the chlorophyll resides) and plant leaves. To complicate matters, the solvent in which chlorophyll is extracted also has an effect on the absorption spectrum.

The absorption spectra of chlorophylls *a* and *b* extracts is why LED grow lamps are typically made up of blue and red LEDs. The absorption spectra of isolated pigments have been the foundation for LED selection for most LED lamps. Furthermore, it has been ignored that carotenoids play a role in light absorption and energy transfer to the photosystems.



The absorption spectra of extracted chlorophyll and carotenoids (accessory pigments). The primary light harvesting chlorophylls absorb light in the blue and red regions. Carotenoids absorb in the blue and green regions.

The absorption spectra of isolated pigments *in vitro* do not represent what the whole plant absorbing. Each pigment has a specific absorption spectrum and in living systems pigments never exist alone. They are always bound to proteins and this shifts their absorption spectrum. This is why wavebands are absorbed rather than a single wavelength. *In vivo*, the probability of a pigment absorbing light absorption depends on: 1) the specific protein that the pigment is bound to; 2) the orientation of the pigment-protein complex within the cell; 3) the forces exerted by the surrounding medium on the pigment-protein complex.



Absorption spectra for pigment extracts (isolated chlofophyll), disrupted and whole chloroplasts and a plant leaf where all of the pigments remain bound to their specific proteins.
There is very little absorbance of green light (500-600 nm) in extracted chlorophyll molecules. However, as the integrity of the leaf increases we see more and more absorption in the green region.

Therefore, plant leaves do absorb green light. In this case, about 70%.

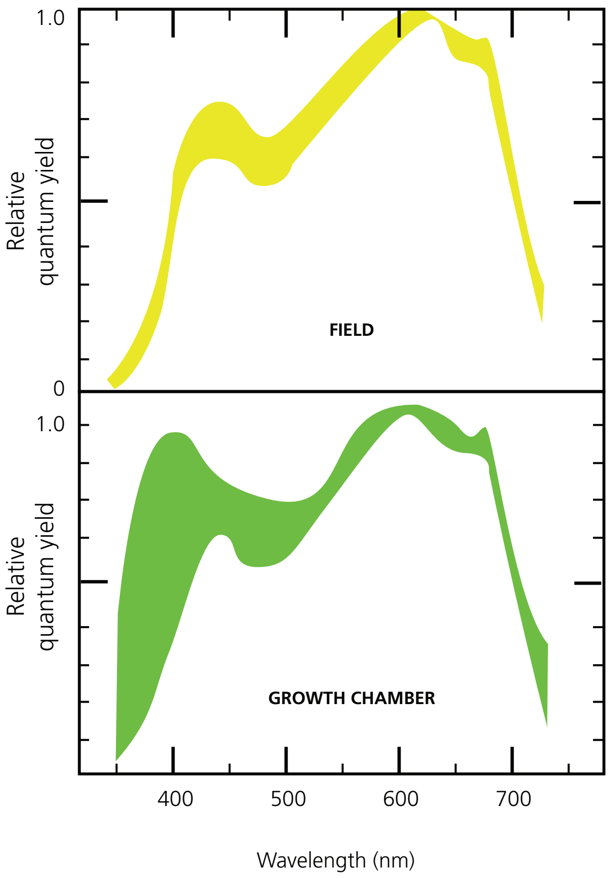
Figure reprinted with permission from Dr. Holly Gorton.(Absorptance spectra of isolated pigments, disrupted chloroplasts, intact chloroplasts, and whole leaves from spinach (Spinacia oleracea) Modified from (Moss & Loomis, 1952)). (http://photobiology.info/Gorton.html)

2. What is an Action Spectrum?

An action spectrum describes the efficiency with which specific wavelengths produce a photochemical reaction. Photosynthesis involves the harvesting of light (absorption spectrum) and the subsequent photochemical and biochemical reactions. Thus, an action spectrum describes the wavelengths that actually drive photosynthesis.

The seminal paper describing the action spectra for 22 plant species was published by KJ McCree (1972). This work was originally done in order to provide an accurate definition of PAR, which had not been previously described empirically. The action spectra described in the McCree paper plot the efficiency or quantum yield of CO_2 assimilation as a function of wavelength. Interestingly, similar action spectra were observed for the 22 plant species. However, there was slight variation between species in the blue end of the spectrum. The results from this work indicated that PAR was between 400 nm and 700 nm and that all wavelengths within this region were used in photosynthesis.

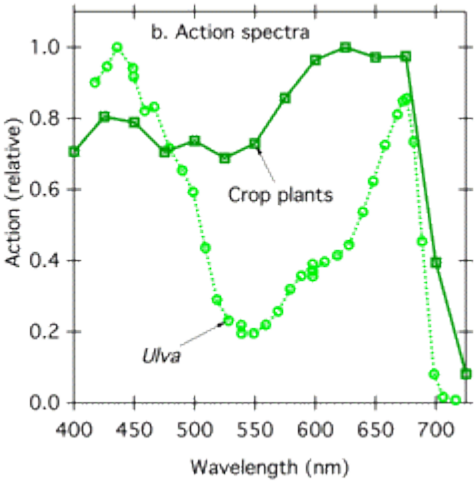
Action spectra for 22 plant species grown in the field (top plate) and a growth chamber (bottom plate).
(McCree 1972).



The areas of the spectrum that drive photosynthesis are highest in the red end (600-700 nm), followed by the blue region (400-500 nm) and lastly, the green region (500-600 nm). These data show that between 50 and 75% of the green light is used in photosynthesis.

RED > BLUE > GREEN

Thus, Green light is necessary for photosynthesis.



The action spectra for higher plants and a green alga (*Ulva*)
(http://photobiology.info/Gorton.html)

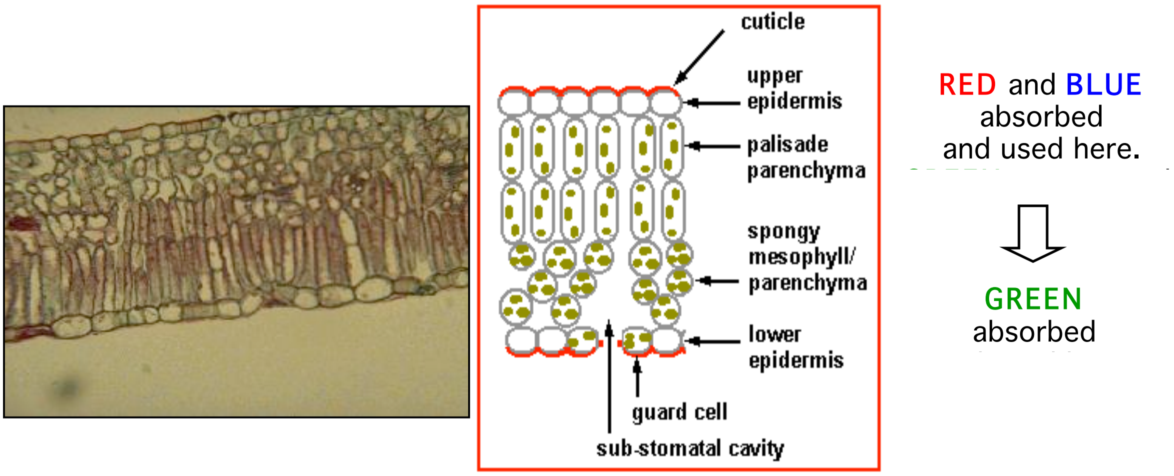
The action spectrum for higher plants presented here (b) is an average of the data presented in the McCree (1972) paper. On average, over 70% of the green light was used in photosynthesis.

Crop plants have been bred for uniformity and thus have similar action spectra. Algae and other photoautotrophic organisms have evolved differently.

Figure reprinted with permission from Dr. Holly Gorton. (Photosynthetic action spectra for the green alga Ulva (two cell layers) (Haxo & Blinks, 1950) and higher plants (multiple cell layers). The curve for higher plants represents the average of action spectra obtained for 22 crop plants (McCree, 1971/1972) recalculated on a photon basis.).

The Role of Green Light in Photosynthesis.

It is clear that green light is a player in photosynthesis along with the other portions of the spectrum. How and where does this occur? Blue and red light are absorbed preferentially at the adaxial (upper) side of leaves and are more efficient at driving photosynthesis in this region compared to green light (Sun et al. 1998; Nishio, 2000; Terashima et al., 2009). As a consequence, green light is transmitted deeper into the leaf and is more efficient than either blue or red light at driving CO_2 fixation at the abaxial (lower) sides (Sun et al. 1998; Terashima et al., 2009). Indeed, on an absorbed quantum basis, photosynthetic efficiency or quantum yield for green light is similar to that of red light, and greater than that of blue light in the deeper layers of a leaf (Terashima et al. 2009).



RED and BLUE absorbed
and used here.

GREEN absorbed

Figure reprinted with permission from Mr. Michael Knee.

Transverse section of a lilac leaf (left panel) and schematic of the internal structure. Light is absorbed by pigments within the various layers of cells. The different cell layers have different absorbance properties. (hcs.osu.edu/hcs300/anat3.htm).

Conclusions

Typical absorption values of green light (550 nm) range from 50% in lettuce to 90% in evergreen broadleaf trees. As observed above in the action spectra, the entire light spectrum is used to drive photosynthesis. It appears as though green light is not a safe light and that green light is required for optimum whole plant photosynthesis. Recent studies have determined that green light is more photosynthetically efficient than red or blue in the deeper layers of leaves. The experiments we have performed at Heliospectra support the importance of green of green light for optimal plant growth and have found that the amount of green required is species dependent. The Heliospectra LED selection differs from most other LED plant growth lamps and this was based on full understanding of photosynthesis and plant physiological processes.

References

McCree, K.J. (1972). The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agric.Meteorol. 9 : 191-216.

Nishio, J.L. (2000). Why are higher plants green? Evolution of the higher plant photosynthetic pigment complement. Plant, Cell & Environment 23(6): 539–548.

Sun JD, Nishio JN, Vogelmann TC. 1998. Green light drives CO2 fixation deep within leaves. Plant and Cell Physiology 39, 1020–1026.

Terashima I, Fujita T, Inoue T, Chow WS, Oguchi R (2009) Green light drives leaf photosynthesis more efficiently than red light in strong white light: revisiting the enigmatic question of why leaves are green. Plant Cell Physiol 50: 684–697

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October 5, 2012