Turning photons into food

The future of LEDs in agriculture

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The Martian

History of Electric lighting

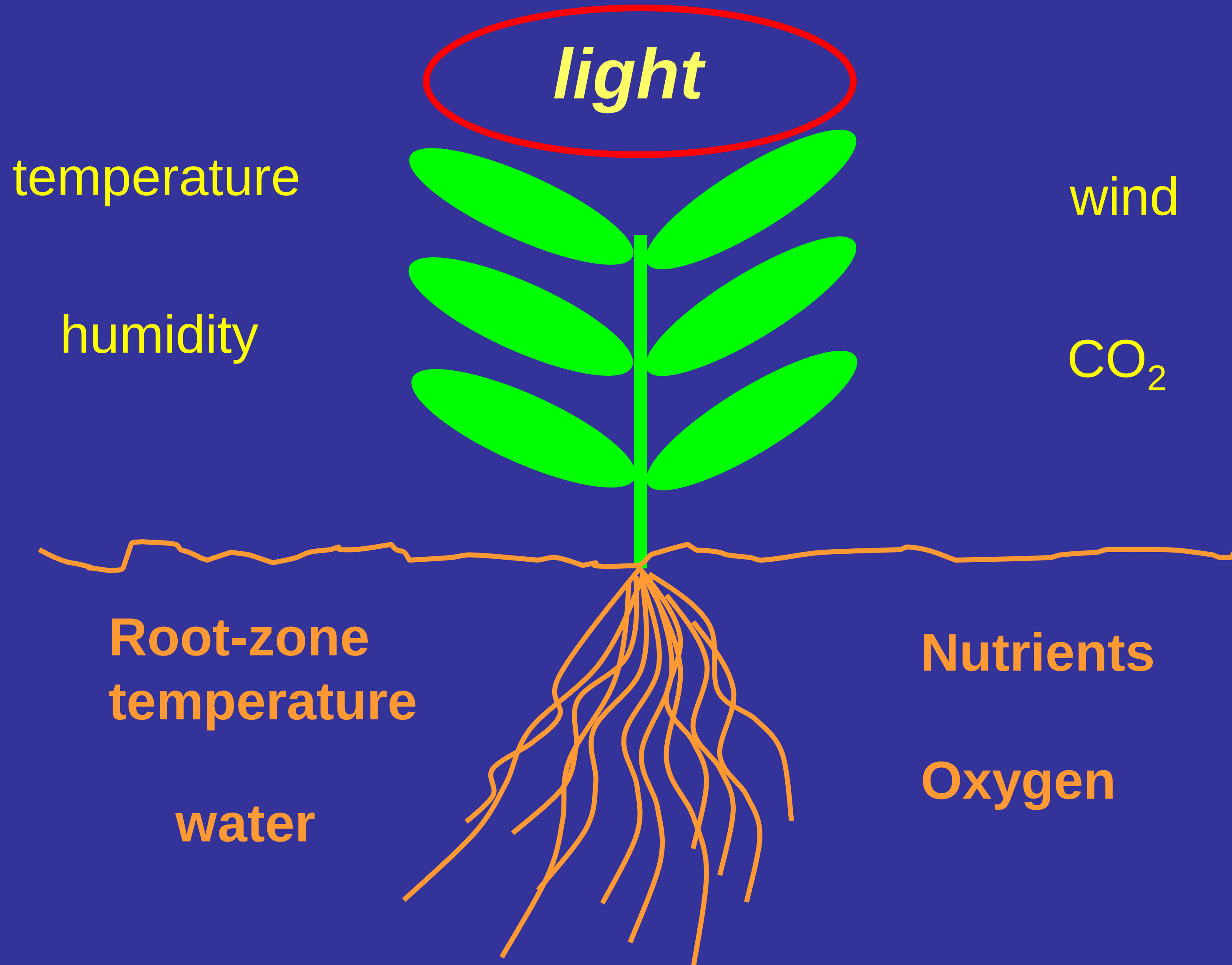
100 kW Lamp

Designed and built
by Westinghouse
to simulate full sunlight

100 years ago

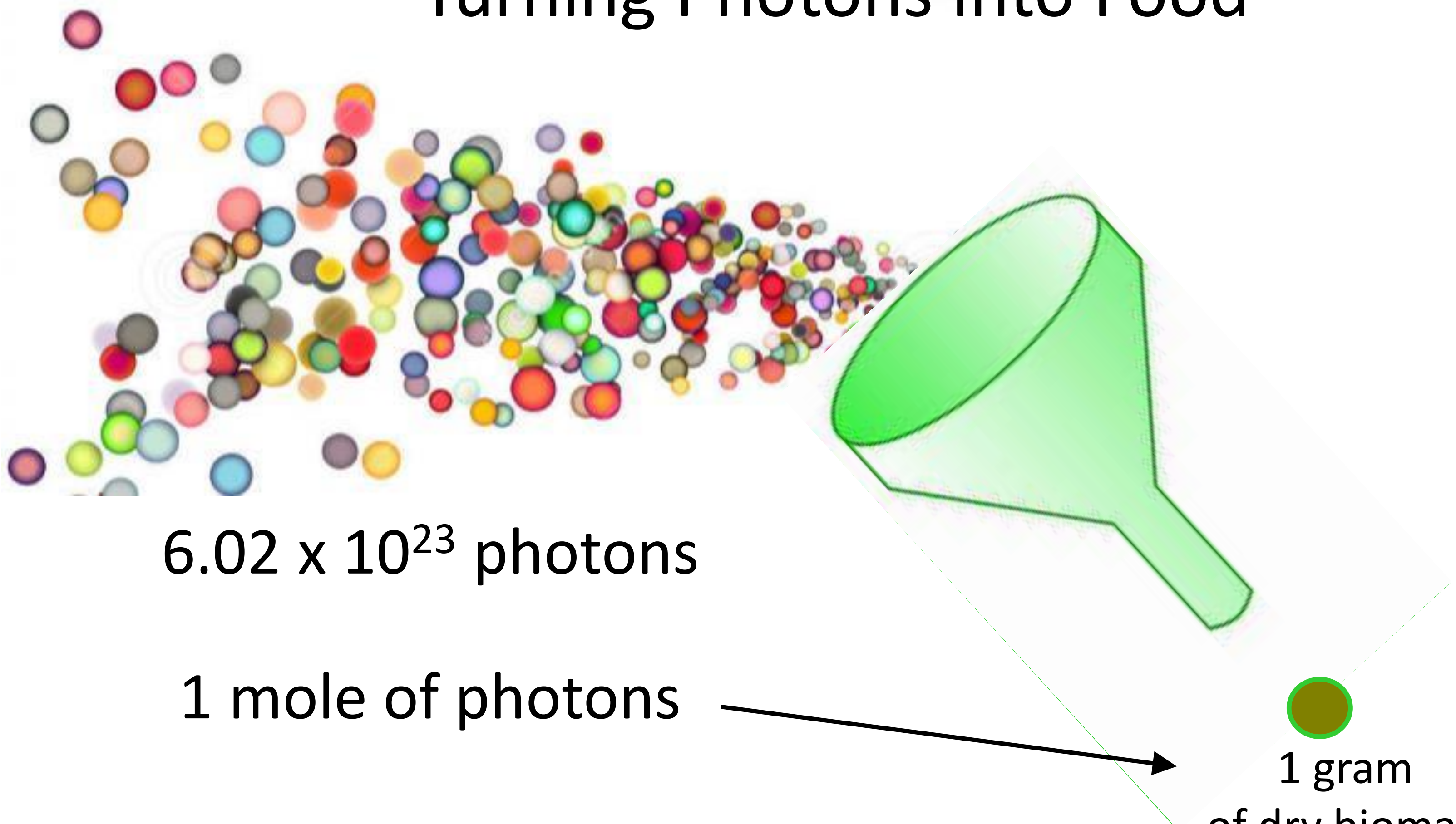
On display at the Chicago Museum
of Science and Industry

Nine cardinal parameters



Calculating the conversion:

Turning Photons into Food



6.02×10^{23} photons

1 mole of photons → 1 gram of dry biomass

B. Bugbee and F. Salisbury. 1988.

Exploring the Limits of Crop productivity

Plant Physiology 88:869-878.

0.5 gram of yield

Theoretical economics

Cost of electricity

$$\frac{\$\,0.10}{1\text{ kWh}} * \frac{1\text{ kwh}*}{8\text{ mol}} = \frac{\$\,0.012}{1\text{ mole}} * \frac{1\text{ mole}}{0.5\text{ g}_{dry}} = \frac{\$\,24}{\text{kg}_{dry}}$$

Value of products

Wheat

$$\frac{\$\,9}{1\text{ bushel}} = \frac{\$\,0.32}{\text{kg}_{dry}}$$

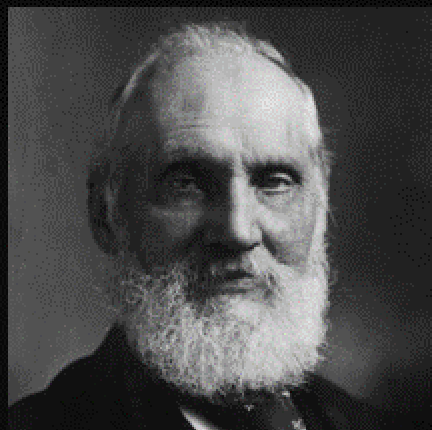
Tomatoes

$$\frac{\$\,4.54}{1\text{ lb.}} = \frac{\$\,10}{\text{kg fresh (90\% water)}} = \frac{\$\,100}{\text{kg}_{dry}}$$

Lettuce

$$\frac{\$\,4.54}{1\text{ lb.}} = \frac{\$\,10}{\text{kg fresh (95\% water)}} = \frac{\$\,200}{\text{kg}_{dry}}$$

* Nelson JA, Bugbee B (2014) Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLoS ONE 9(6): e99010.



Heavier-than-air flying machines are impossible.

~ Lord Kelvin

Theoretical economics

Potential efficiency

Cost of electricity

$$\frac{\$\,0.10}{1\ \text{kWh}} * \frac{1\ \text{kwh}*}{16\ \text{mol}} = \frac{\$\,0.006}{1\ \text{mole}} * \frac{1\ \text{mole}}{0.5\ \text{g}_{dry}} = \frac{\$\,12}{\text{kg}_{dry}}$$

Value of products

Wheat 

$$\frac{\$\,9}{1\ \text{bushel}} = \frac{\$\,0.32}{\text{kg}_{dry}}$$

Tomatoes 

$$\frac{\$\,4.54}{1\ \text{lb.}} = \frac{\$\,10}{\text{kg fresh (90\% water)}} = \frac{\$\,100}{\text{kg}_{dry}}$$

Lettuce 

$$\frac{\$\,4.54}{1\ \text{lb.}} = \frac{\$\,10}{\text{kg fresh (95\% water)}} = \frac{\$\,200}{\text{kg}_{dry}}$$

* Nelson JA, Bugbee B (2014) Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLoS ONE 9(6): e99010.

Actual economics

Cost of electricity

$$\frac{\$\ 0.10}{1\ \text{kWh}} * \frac{1\ \text{kwh}*}{8\ \text{mol}} = \frac{\$\ 0.012}{1\ \text{mole}} * \frac{1\ \text{mole}}{0.5\ \text{g}_{dry}} = \frac{\$\ 24}{\text{kg}_{dry}}$$

Value of products

microgreens 

$$\frac{\$\ 16}{1\ \text{lb.}} = \frac{\$\ 35}{\text{kg fresh (95\% water)}} = \frac{\$\ 700}{\text{kg}_{dry}}$$

Cost of electricity for
Basil under electric lights:

$$4.2 \frac{g\ basil}{mol\ photons}$$

$$2.4\ \frac{\mu mol}{J}$$

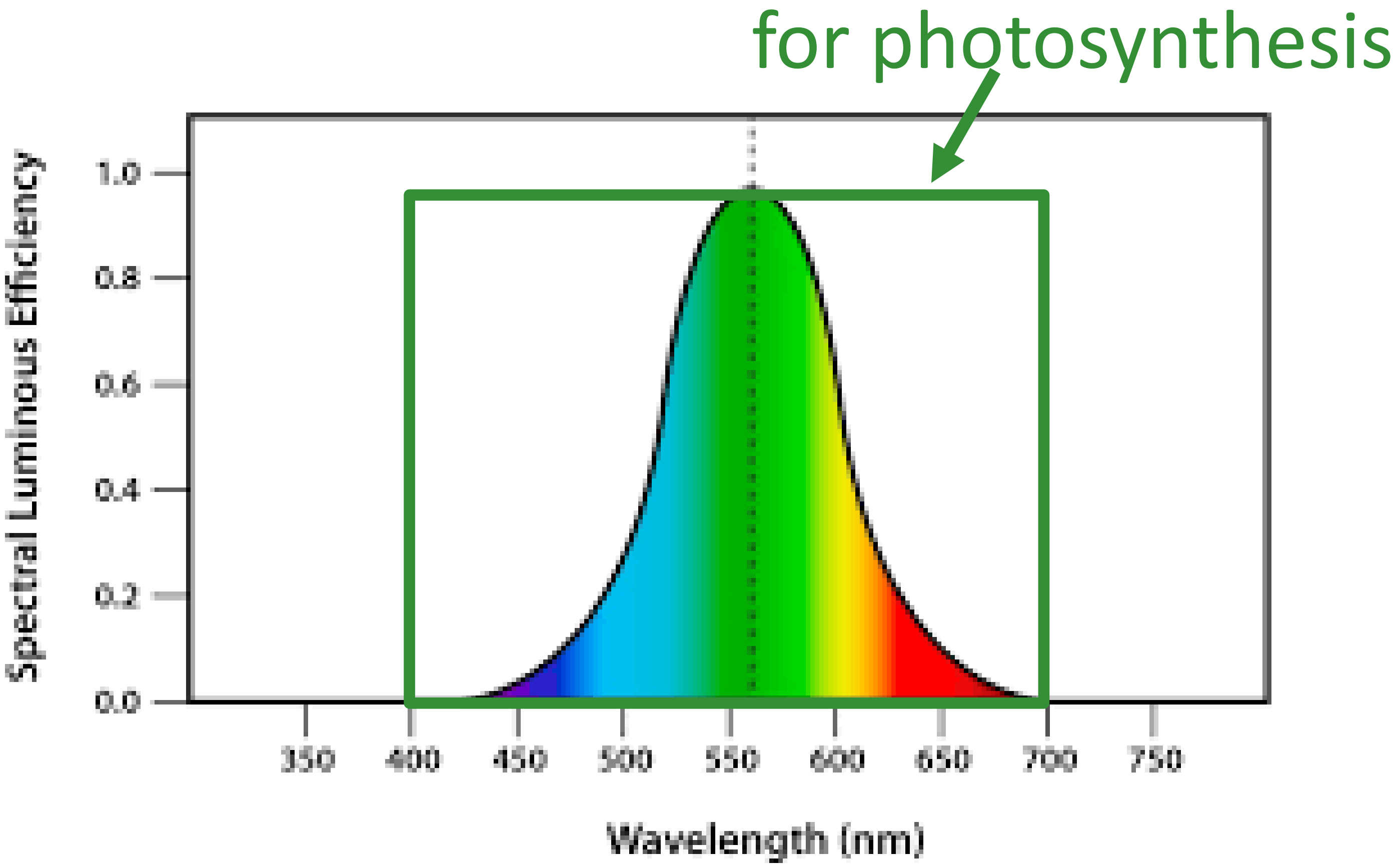
$$\frac{\$0.10}{kWh}$$

$$= \frac{\$\mathbf{0.003}}{\boldsymbol{g\ basil}} \left(\frac{\$\mathbf{0.08}}{\boldsymbol{oz}} \right)$$

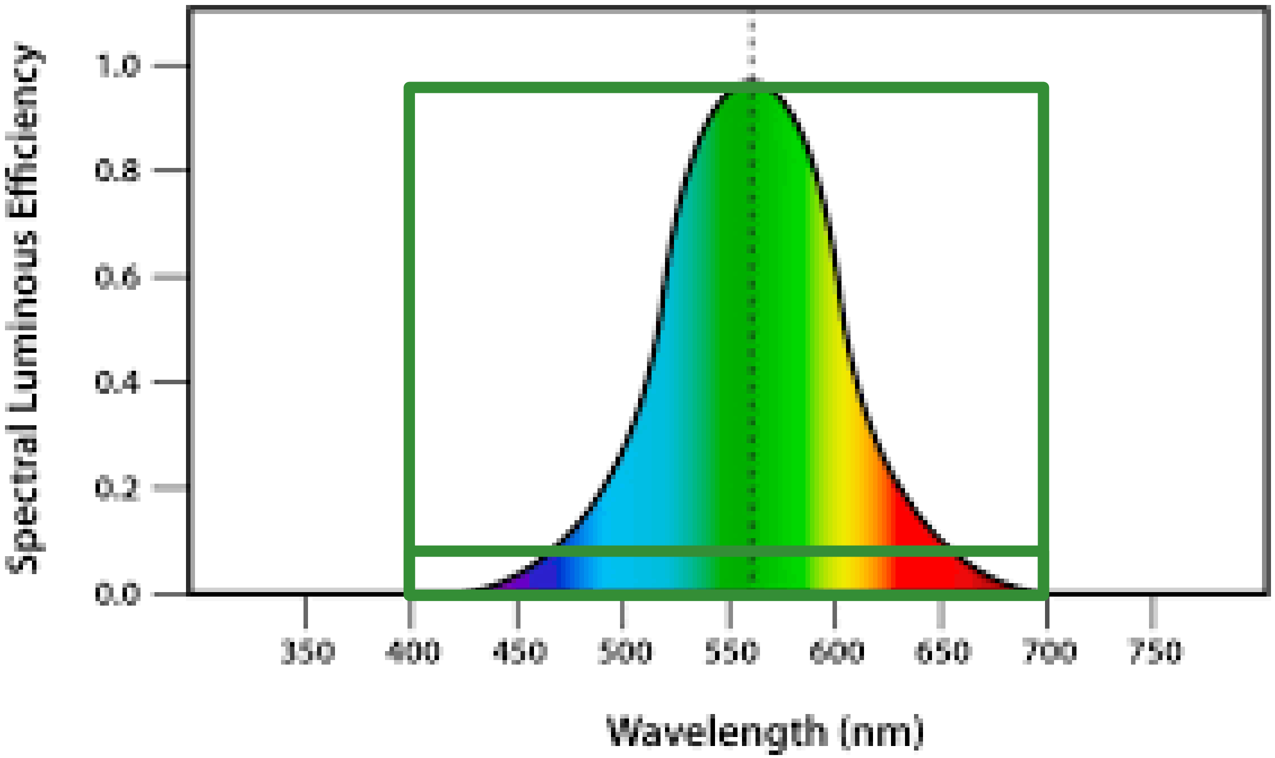
Basil from the store:

$$\left(\frac{\$\mathbf{1}}{\boldsymbol{oz}} \right)$$

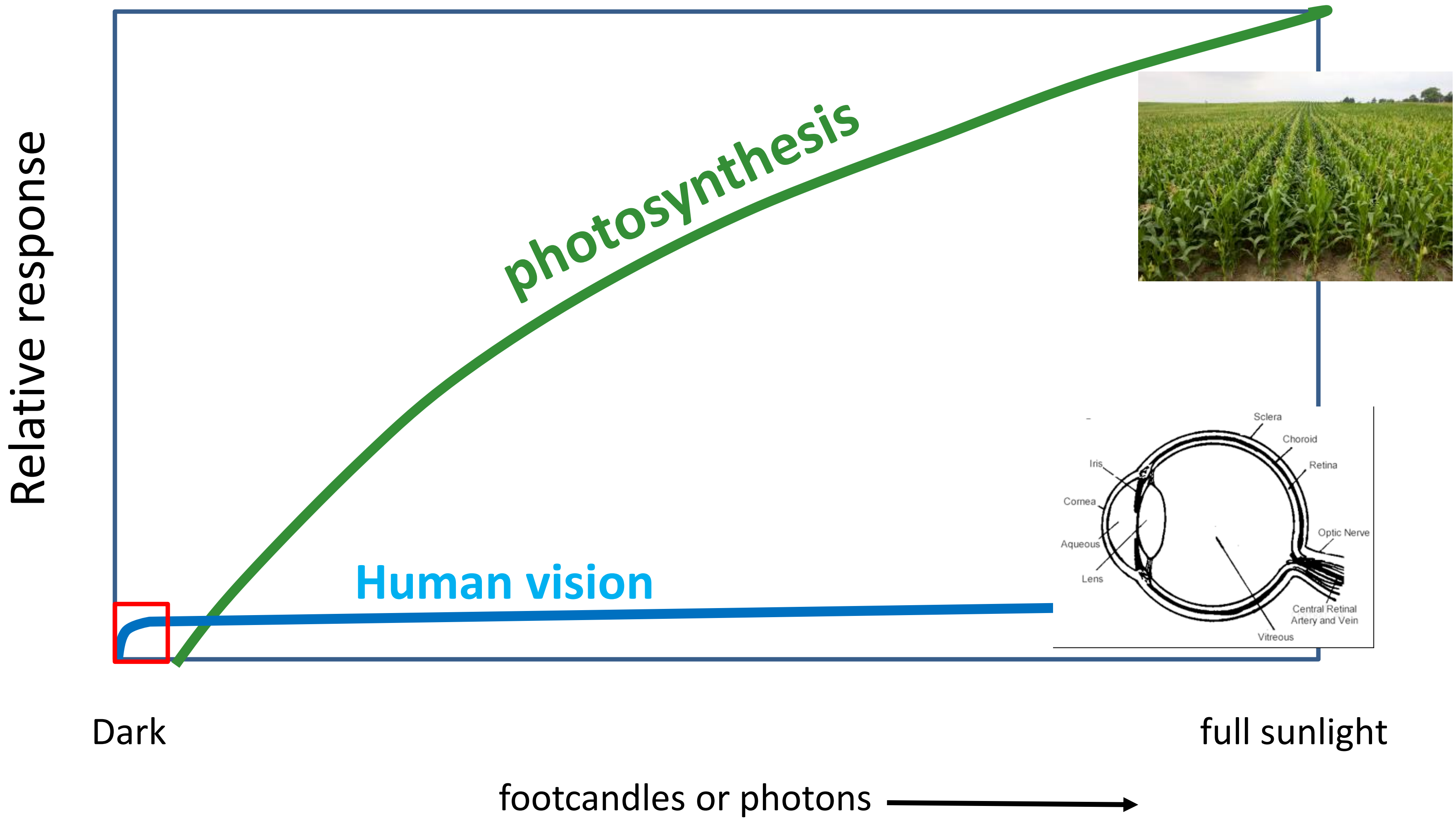
footcandles and photons



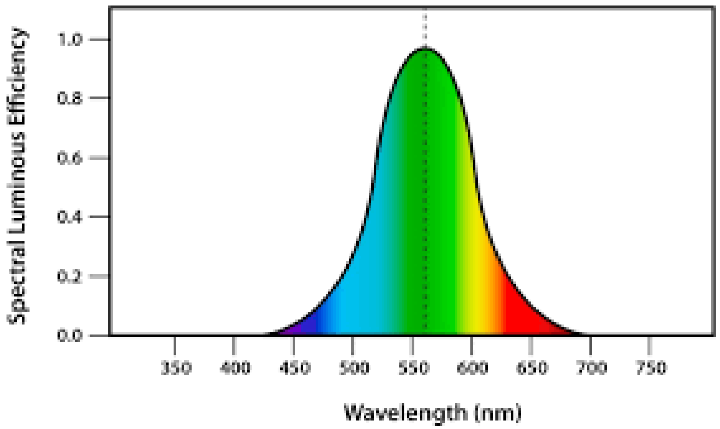
footcandles and photons

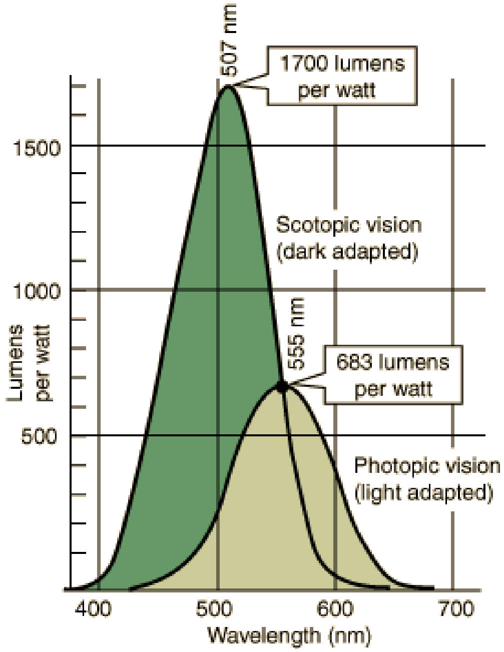


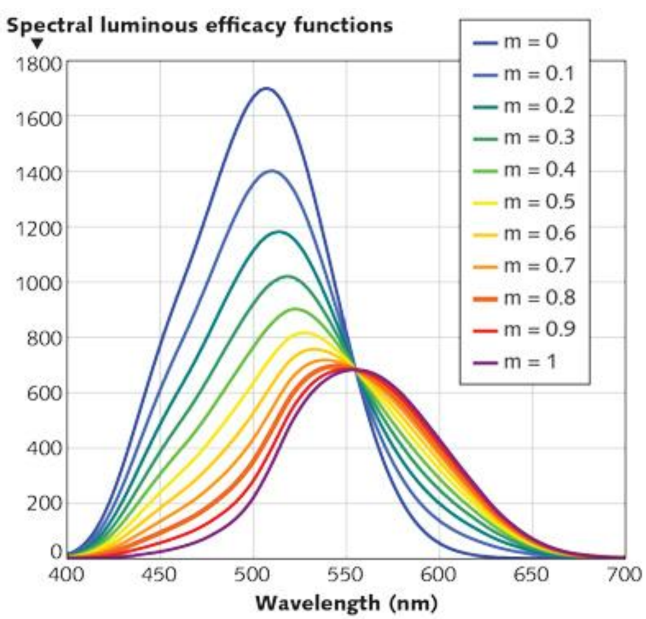
Relative response to light



footcandles and photons

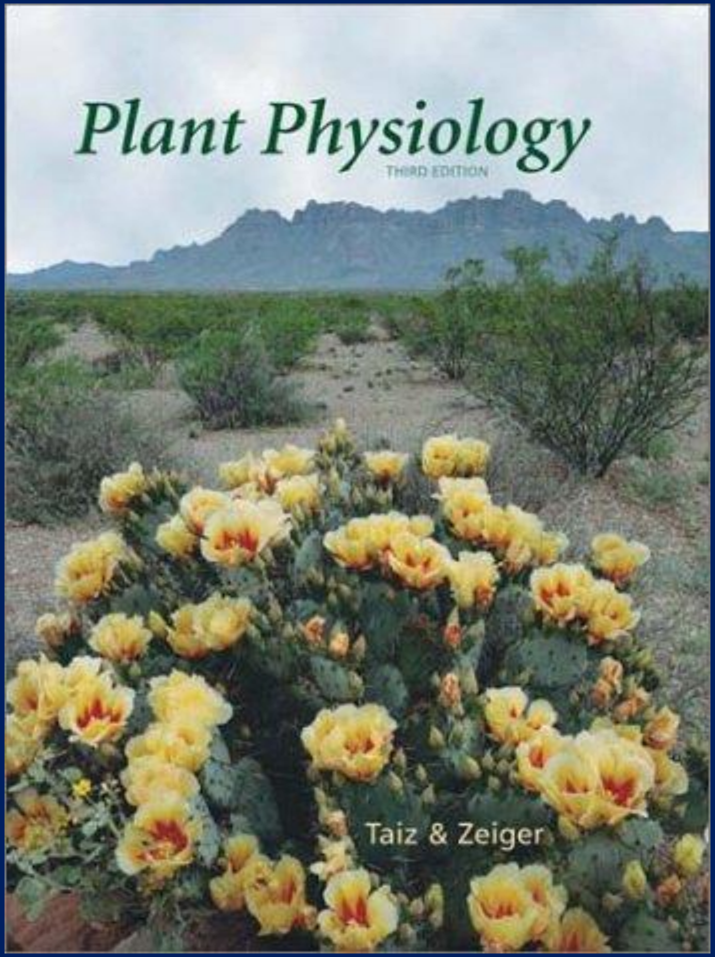




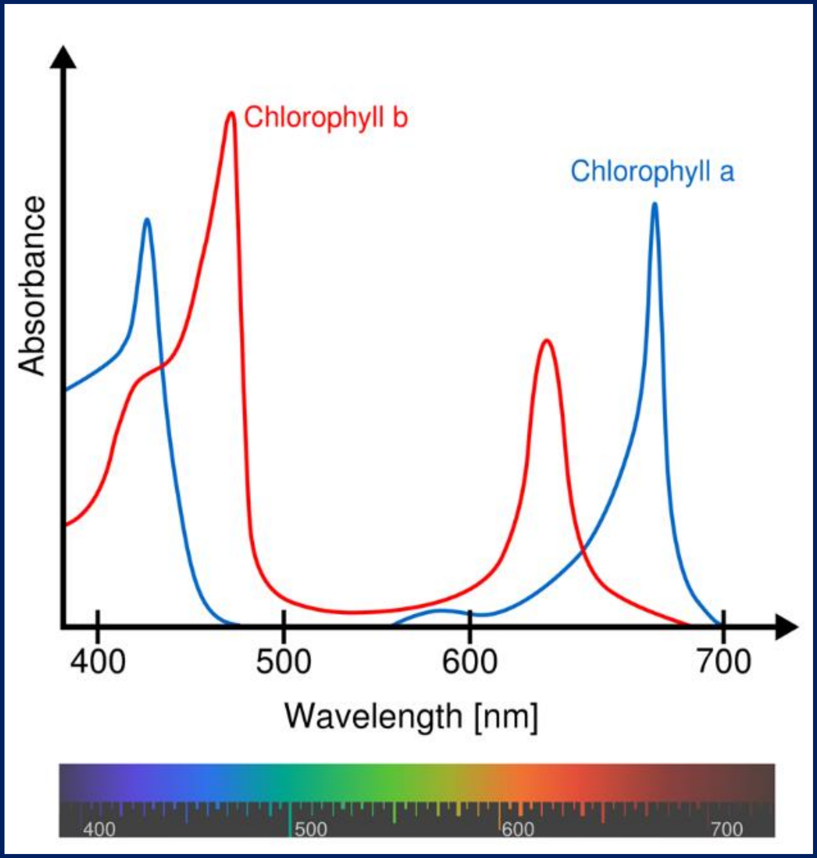


Plant Physiology

3rd edition, 2002

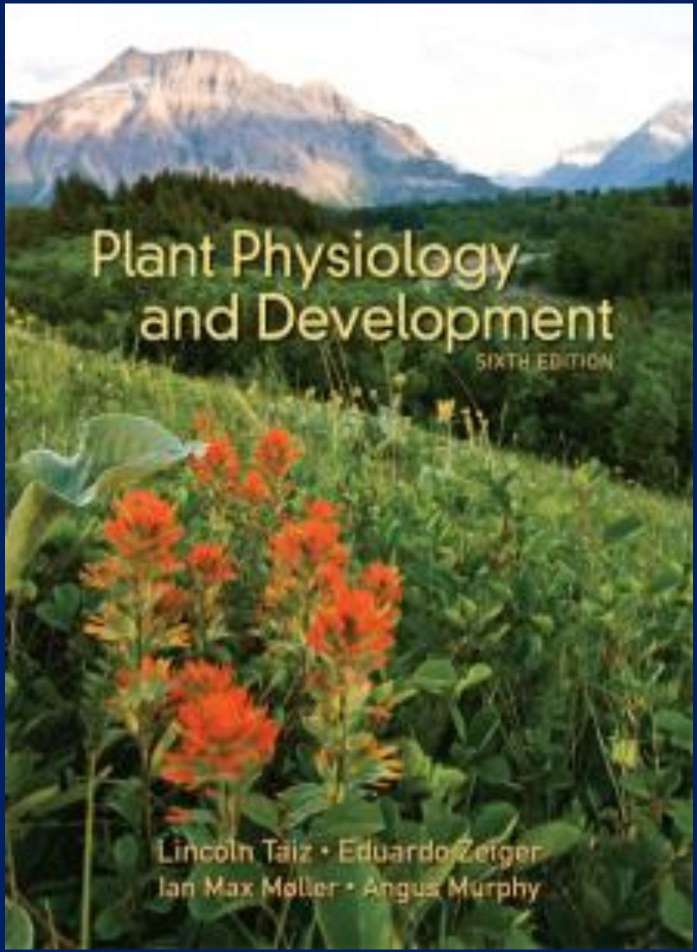


Chlorophyll
absorbs minimal green light

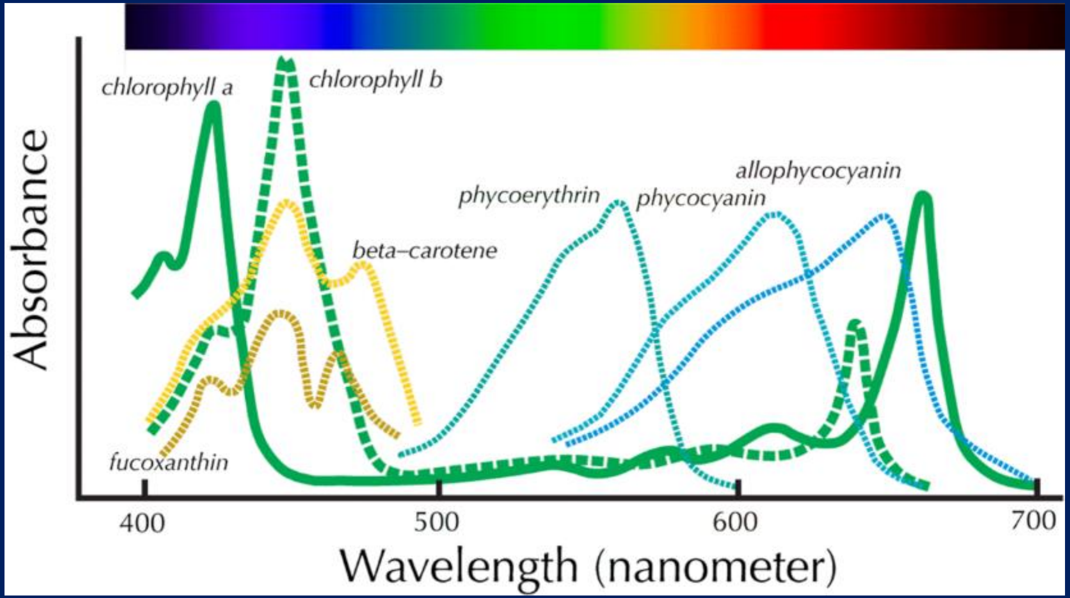


Plant Physiology

6th edition, 2015



Multiple pigments
absorb nearly all radiation
from 400 to 700 nm



Responses to blue light

High pressure sodium
5 % blue

100 g

Metal Halide
25 % blue

90 g

Dougher, T. and B. Bugbee. 2002. Effects of Blue light on plants. Photochemistry and Photobiology. 126:323-329

Increased blue light fraction causes

1. decreased cell expansion
2. reduced radiation capture
3. reduced growth

High pressure sodium
5 % blue

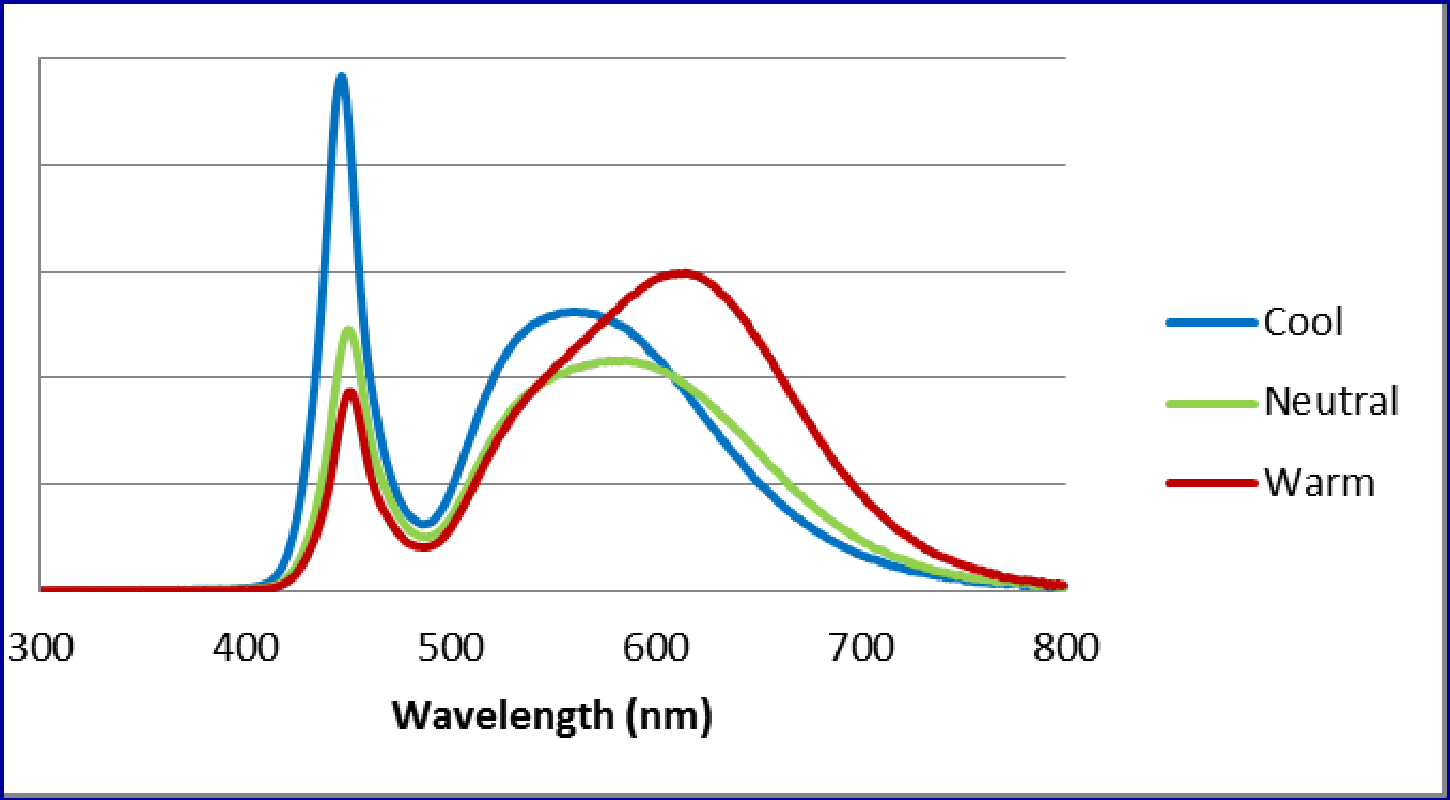
100 g

Metal Halide
25 % blue

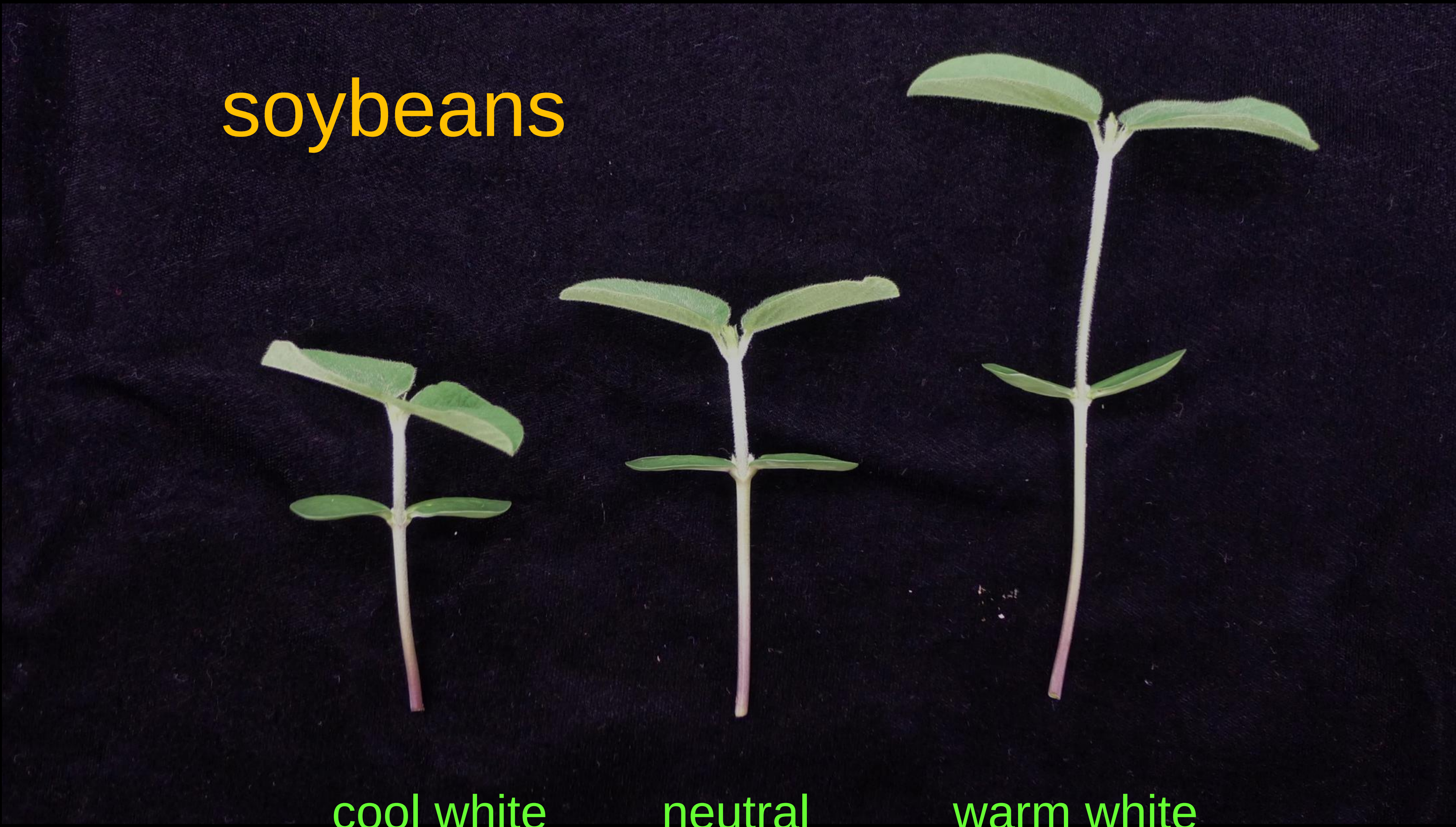
90 g

Dougher , T. and B. Bugbee. 2002. *Effect of Blue light on plants*.
Photochemistry and Photobiology. 126:323-329

studies
with white LEDs



Cope and Bugbee. 2013. Spectral Effects of Three Types of White Light-emitting Diodes on Plant Growth and Development . HortScience 48:504-509.



% blue light: 30% 20% 10%

Soybean leaves

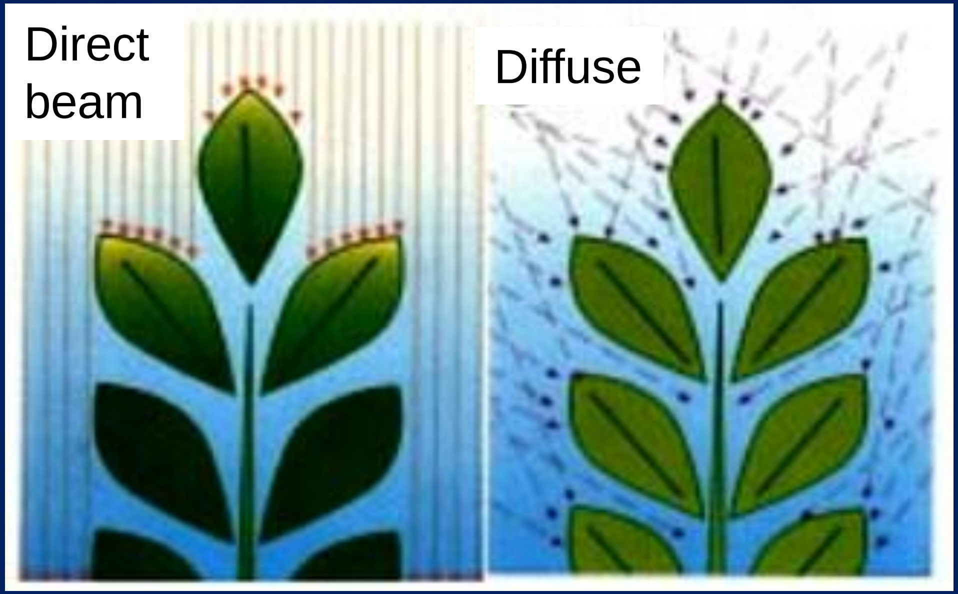
	cool white	neutral	warm white
% blue:	30%	20%	10%

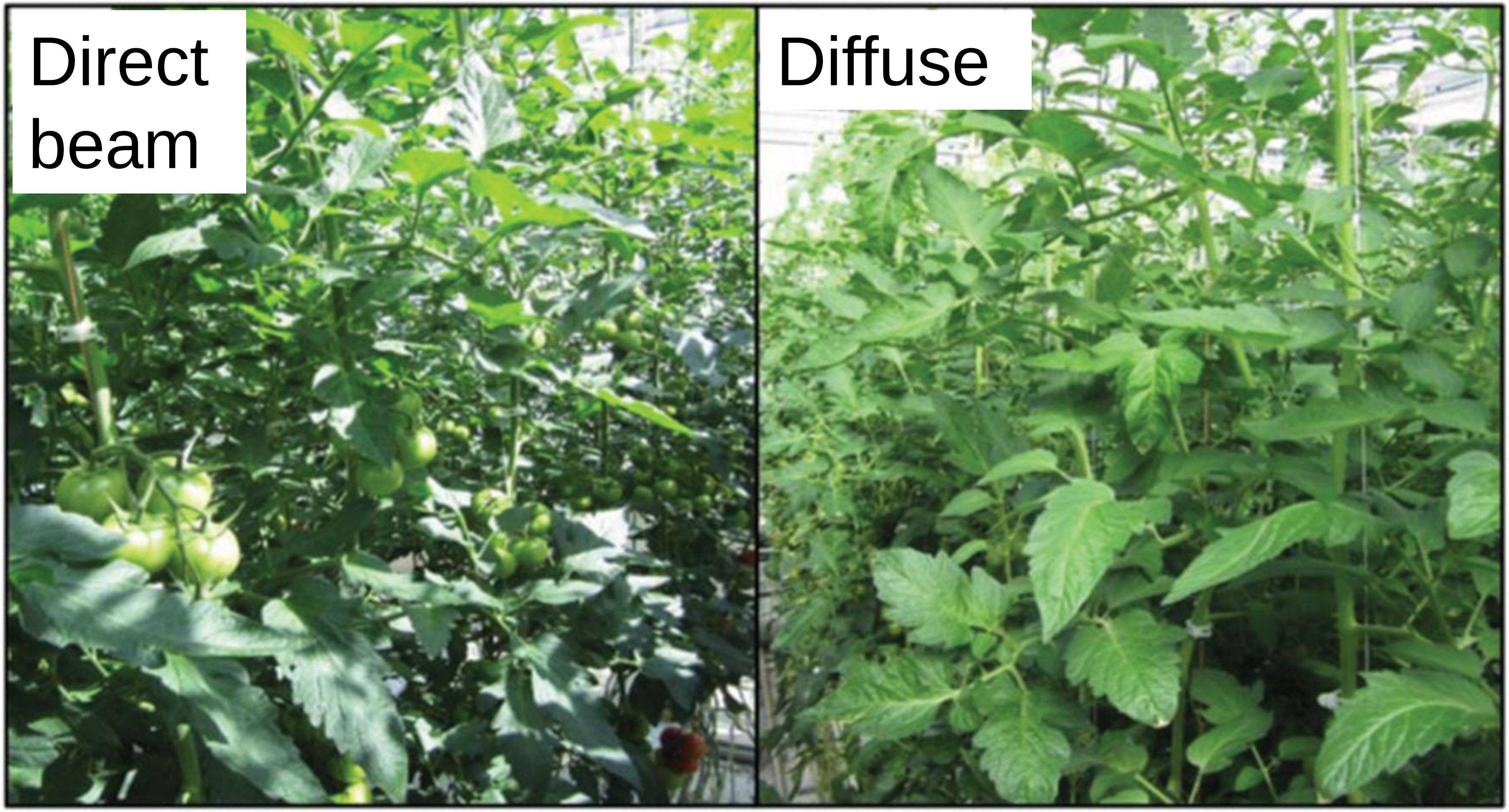
Snowden, M.C., K. Cope, and B. Bugbee. 2016.
Sensitivity of Seven Diverse Species to Blue and Green Light: Interactions With Photon Flux
PLOS ONE 10.1371

At least 7 published studies have found that plant growth is better under fluorescent than LED technologies

direct vs. diffuse light

Diffuse light
penetrates deeper into plant canopies than direct light

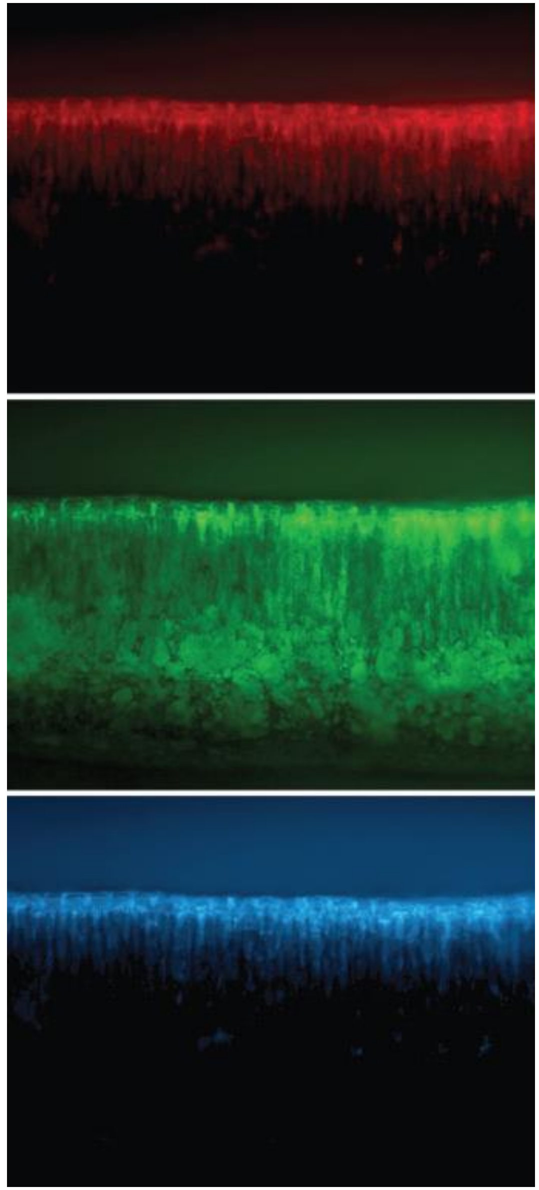



Direct beam
Diffuse

Red

Green

Blue



Craig Brodersen & Thomas Vogelmann. 2010. Functional Plant Biology. 37:403–412

Do changes in light direction affect absorption profiles in leaves?