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Yield Responses to Supplemental Lighting

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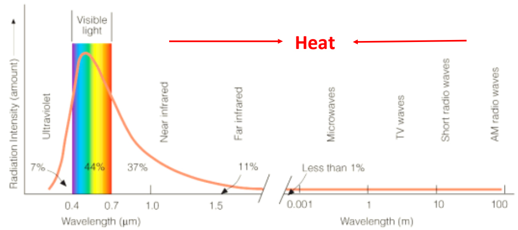
Solar radiation

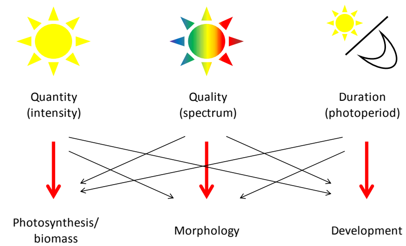
Sunlight's full spectrum ranges from 300 to 3000 nm



Plant use light from within the visible spectrum for ***photosynthesis and growth.***
Photosynthetically Active Radiation (PAR, 400 to 700 nm)

Light for plant growth and development

Three dimensions



The different properties of light interact to control growth and development

After Runkle, 2015

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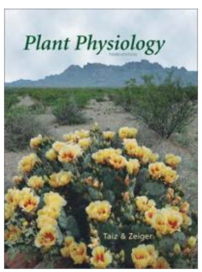
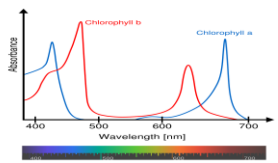
Plant Physiology

3rd edition, 2002



Chlorophyll absorbs minimal green light



After Bugbee, 2015

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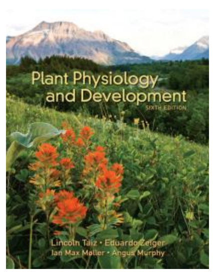
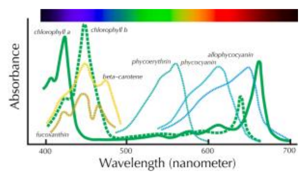
Plant Physiology

6th edition, 2015



Multiple pigments absorb nearly all radiation from 400 to 700 nm



After Bugbee, 2015

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Metrics for plant lighting

- PAR
- Photosynthetic Photon Flux
  (PPF, $\mu mol \cdot m^{-2} \cdot s^{-1}$)

The intensity of rain at any moment is like the light level you can measure with a light meter ($\mu mol \cdot m^{-2} \cdot s^{-1}$ or foot-candles)

- Daily Light Integral
  (DLI, $mol \cdot m^{-2} \cdot d^{-1}$)

Accumulated rainwater in a bucket is like the daily light integral (accumulated energy in moles/day)

Fisher and Runkle, 2004

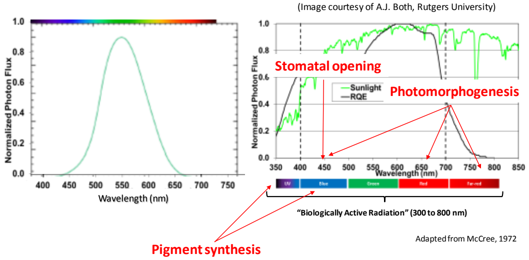
400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 h =

400 × 16 × 60 × 60 = 23,040,000 $\mu mol \cdot m^{-2} \cdot d^{-1}$ = 23.04 $mol \cdot m^{-2} \cdot d^{-1}$

Note: Lux and footcandle units should be avoided

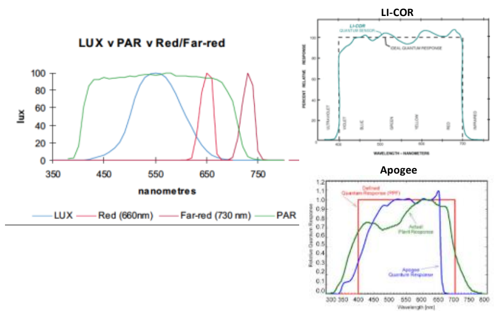
Sensitivity to light

Humans vs. plants



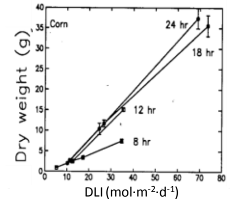
Adapted from McCree, 1972

The importance of using the right sensor



Plant responses to higher DLI

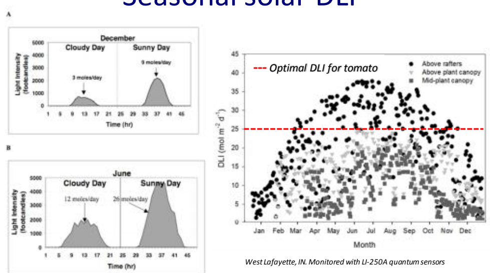
- Higher biomass production
- Smaller, thicker leaves
- More, larger flowers
- Reduced time to flower (partly due to temperature)
- Thicker stems
- More roots



Warrington and Norton, 1991

"A 1% reduction in light will reduce production (harvestable yield) by 1%."

Seasonal solar DLI



West Lafayette, IN. Monitored with LI-250A quantum sensors

Affected by photoperiod × PPF

Supplemental light (SL)

- Important PAR source in Northern latitudes
- Additional DLI needed to enhance canopy photosynthesis and crop growth

Frequently perceived as too expensive!

SL for greenhouse-vegetable production

1. Installation and lamp types
2. Light intensity and photoperiod for specific crops
3. Crop management
4. Spectral composition

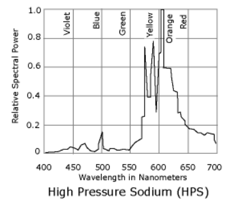
Installation

- Overhead lamps
- 3 ft above support wiring (over the canopy)
- ~100 to 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$
- Above plant rows
  - (different from Europe)
- Fewer but higher wattage (up to 1000 W) fixtures
- Turned off:
  - Solar radiation exceeds 450-600 $\mu mol \cdot m^{-2} \cdot s^{-1}$
  - DLI of 20-25 $mol \cdot m^{-2} \cdot d^{-1}$ is reached
- Consider heat contribution from SL

Note: overhead = top-lighting

Lamp types

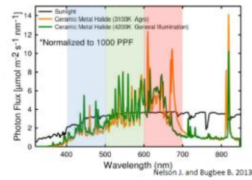
Current standard: High-pressure sodium (HPS) lamps



Note: overhead = top-lighting

- *Metal halide:*
  - Their energy efficiency is not as high as HPS lamps (1.5 vs. 1.7 $\mu mol \cdot J^{-1}$)
  - Their useful bulb life is about half as long as HPS lamps
  - "Balanced" spectrum

www.solarinnovations.com



Nelson J. and Bugbee B. 2013.

Mutual shading between/within foliar canopies

Common issue with overhead SL

Leaves under direct light

Shaded leaves

Light-Emitting Diodes (LEDs)

Alternative sources for plant lighting

- Photon-emitting surfaces are not hot
- Can be placed close to plant surfaces
- Efficiency is improving rapidly
- Potential for advances in light distribution
- Wavelength selectable

Intracanopy LED (ICL-LED) lighting

Same concept as interlighting

Other high-wire crops

Sweet pepper

Cucumber

Eggplant

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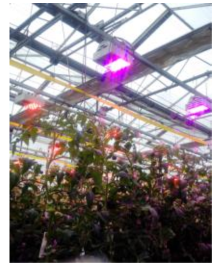
Overhead LED lighting



It all relates back to the average DLI

(received by plants)

- Specific recommendations for SL depend on the crop
- Lamp and electrical cost
- Heating requirements
- Most vegetables are day-neutral plants
  - [i.e., no particular photoperiod hastens or delays flowering (and thus, fruit production)]

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Lettuce

- *Production:*
- PPF: 250 μmol·m^{-2}·s^{-1}
  (50 to 150 μmol·m^{-2}·s^{-1} from SL)
- Photoperiod: 16 h·d^{-1}
- DLI: ~14 mol·m^{-2}·d^{-1}

Gotham Greens, Brooklyn, NY

Extending the photoperiod from 16 to 24 h can increase plant biomass by 20% and reduce production cycle by 7 days

SL can increase tip-burn incidence

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Sweet pepper

- *Production:*
- PPF: 150 to 175 μmol·m^{-2}·s^{-1} from SL
- Photoperiod: 16 to 20 h·d^{-1}
- DLI: ≥ 12 mol·m^{-2}·d^{-1}

http://www.greenhousecanada.com/business/research/harrow-shining-more-light-on-year-round-production-31099

Continuous lighting (24 h) does not improve growth/yield compared to a 20-h photoperiod

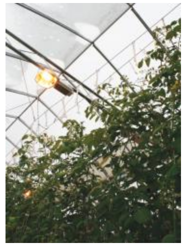
Cucumber

- *Production:*
  - PPF: 150 to 300 µmol·m^{-2}·s^{-1} from SL
  - Photoperiod: 18 to 20 h·d^{-1}
  - DLI: up to 30 mol·m^{-2}·d^{-1}

A dark period ≥4 h should be provided

Tomato

- *Propagation:*
  - PPF: 180 to 200 µmol·m^{-2}·s^{-1} from SL
  - Photoperiod: 18 to 20 h·d^{-1}
  - DLI: ~16 mol·m^{-2}·d^{-1}
- *Production:*
  - PPF: 150 to 300 µmol·m^{-2}·s^{-1} from SL
  - Photoperiod: 16 to 18 h·d^{-1}
  - DLI: 25 to 30 mol·m^{-2}·d^{-1}



Physiological injuries can be cause by long photoperiods (>16 h) during production

Crop Management

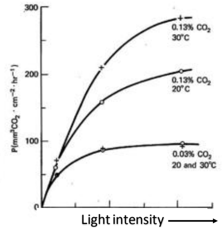
Other environmental parameters need to be considered

- To optimize use of SL, CO_2 is often enriched to 700-1000 ppm (µmol·mol^{-1})

  But…

- Optimal growing temperature for vegetable production generally increases as DLI and CO_2 concentration increase
- As light becomes more available, plants can be spaced closer together because competition to harvest light becomes less of a limiting factor

3-way environmental interactions



Cultural practices

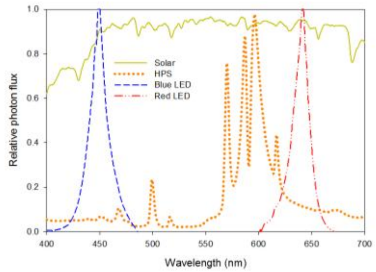
Leaf pruning (removal) and intercropping

- Usually done with high plant density
  - (12 to 15 leaves are kept)
- A similar strategy is used with cucumber
  - (highest fruit quality and greatest shelf life)
- Intercropping can optimize space and light utilization:
  - New plants are planted as older plants mature.
  - Bottom leaves of the old crop are pruned and both crops share production area for a period of 6-8 weeks.

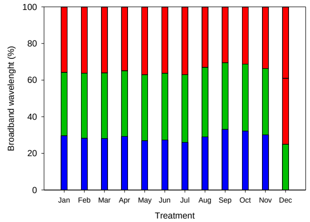
Spectral composition

importance of wavebands

Spectral composition



Broadband percentage of sunlight's blue, green, red (BGR) at noon



**Broadband definitions:*
Blue (400-500 nm)
Green (500-600 nm)
Red (600-700 nm)

The BGR percentages of midday solar PPF are similar across seasons

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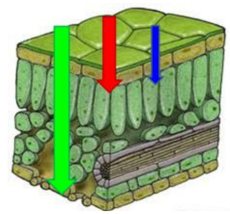
Wavebands within PAR

- Red most efficient waveband at driving photosynthesis
  - Promotes leaf expansion = increases light capture
- Blue waveband typically adds value
  - Second-most efficient driving photosynthesis
  - Reduces stem elongation/leaf expansion (?) = reducing light interception, which possibly reduces whole-plant Ps
  - Regulates flower induction (?)
  - Phototropic growth movements
  - Regulates stomatal aperture (gas-exchange)
  - Important for chlorophyll synthesis

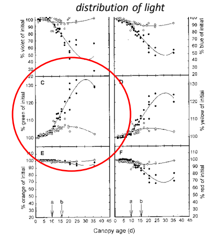
This is why most commercial LED arrays are red- and blue-biased

Green penetrates deeper into the leaf

(than red or blue)



Canopy closure affects the spectral distribution of light



Sun et al., 1998
Terashima et al., 2009

Frantz et al., 2000; after Bugbee, 2015

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Plant responses to blue light

High pressure sodium
4.4 % blue

10.0 g

Metal Halide
22.2 % blue

8.9 g

Increased blue light fraction causes
1. decreased cell expansion
2. reduced radiation capture
3. reduced growth

But it makes plant shape more similar to sunlight

Dougher and Bugbee, 2002; after Bugbee, 2015

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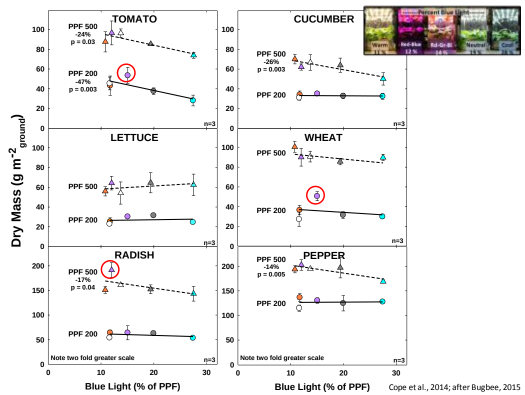
Phosphor-coating effect

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

Cope and Bugbee. 2013; after Bugbee, 2015



Cope et al., 2014; after Bugbee, 2015

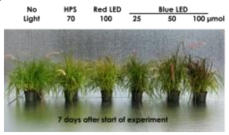
Manipulating plant characteristics I
blue light

Effects of different supplemental light qualities on baby leaf lettuce phytochemicals and growth (Comparisons with white light control)

Parameters \ Supplemental light quality	UV-A	Blue	Green	Red	Far red
Anthocyanins	+ 11%	+ 26%	NS	NS	- 40%
Carotenoids	NS	+ 12%	NS	NS	- 14%
Chlorophyll	NS	NS	NS	NS	- 11%
Ascorbic acid	NS	NS	NS	NS	NS
Phenolics	NS	NS	NS	+ 6%	NS
Biomass	NS	NS	NS	NS	+ 28%

NS = No significant difference by ANOVA at P≤0.05 (Li and Kubota, 2009)

Currey and Lopez, 2014



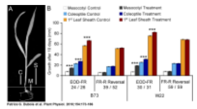
Owens and Lopez, 2015

Runkle, 2015

Potential to improve quality (phytochemical content) of crops, and control morphology and/or flowering

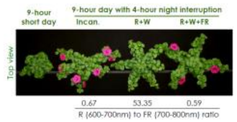
Manipulating plant characteristics II
red/far-red light

Morphology



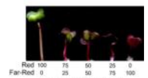
Li and Kubota, 2009

Flowering



Runkle, 2015

Anthocyanin content



Carvalho and Folta, 2014

Potential to control morphology (stem elongation/leaf expansion), quality, and for photoperiodic control

Early-generation
commercial LED arrays

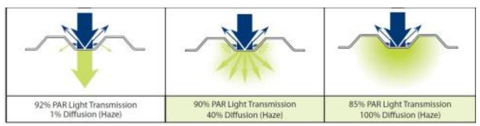
- Because initial capital investment is high, present commercial LED arrays tend to have:
  - Limited spectral choices
  - Fixed-color ratios
  - Modest output intensities (low LED density)
  - Passive heat sinking
  - Limited light-distribution geometry
- Limited capability to determine optimum light recipes for specific crops

(Re)-discovering the solar spectrum
From previous and ongoing sole-source lighting research

- Adding green to overhead red + blue light promotes growth
- Adding far-red
  - Promotes stem elongation
  - Promotes flowering in some photoperiodic classes
  - Prevents intumescence growth in some species

- Adding UV
  - Prevents intumescence
  - Promotes pigment and phytochemical accumulations
- Are white LEDs the answer?
  - Are blue LEDs + phosphor
  - Electrically inefficient (<50% as efficient as blue LEDs)
  - Lack FR, UV

Alternative to greenhouse SL
Improvements in glazing technology



Effect of direct and diffuse light in the greenhouse

Diffuse light penetrates deeper into plant canopies than direct light

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Summary

- Typical PPF = 100 to 150 μmol·m^{-2}·s^{-1}
- Typical photoperiod = 8 to 16 h·d^{-1}
- Typical DLIs from SL = 2.9 to 8.6 mol·m^{-2}·d^{-1}
  - 20 mol·m^{-2}·d^{-1} is a general target DLI from most fruiting vegetables
  - 10 mol·m^{-2}·d^{-1} is the minimum acceptable DLI for many vegetable crops
- Benefit of SL is greatest when sunlight intensity is low
- Consider alternative technologies

Questions?

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