Lighting up CEA Crops

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Outline

- When does supplemental lighting make sense?
- When do LED fixtures make sense over HID?
- Costs of lighting / calculator tools
- When do tunable spectra LEDS make sense?

Primary uses for horticultural lighting

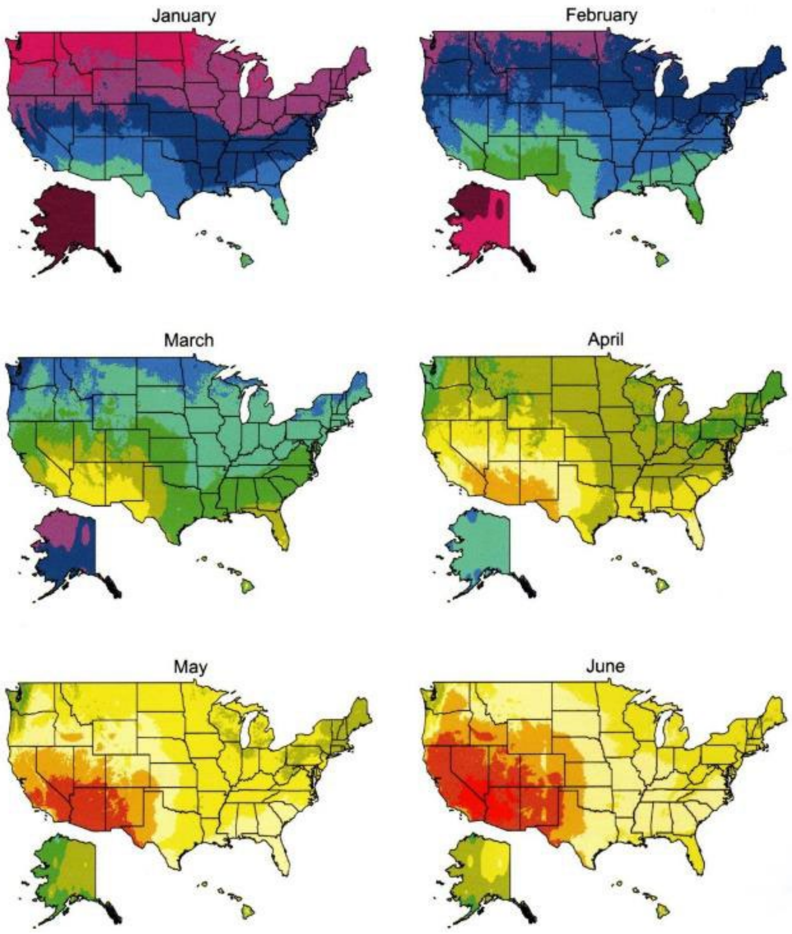
- **Photosynthetic lighting (light quantity)**
  - Supplemental (in greenhouse)
  - Sole source (indoors/vertical farm/warehouse)
- Photoperiodic lighting (light duration)
  - Flowering/Vegetative
- Light quality on plants
  - Height
  - Leaf expansion
  - Red pigmentation (lettuce)
- (Insect and disease control)

Greenhouse lighting deserves a second look

Lamp type	Photosynthetic Photon Efficacy (µmol/J)
HPS magnetic ballast 400 W (1994)	0.98
HPS magnetic ballast 1,000 W (2014)	1.16
HPS double ended electronic ballast (2014)	1.70
LED best in 2014	1.70
LED best in 2016	2.39
LED best in 2021 (reported via DLC)	3.69

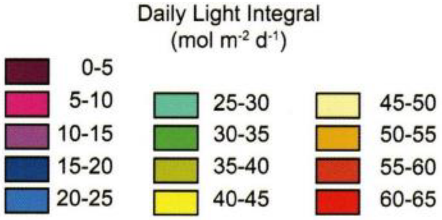
When does supplemental lighting make sense?

You live in a northern climate



Average outside DLI by month

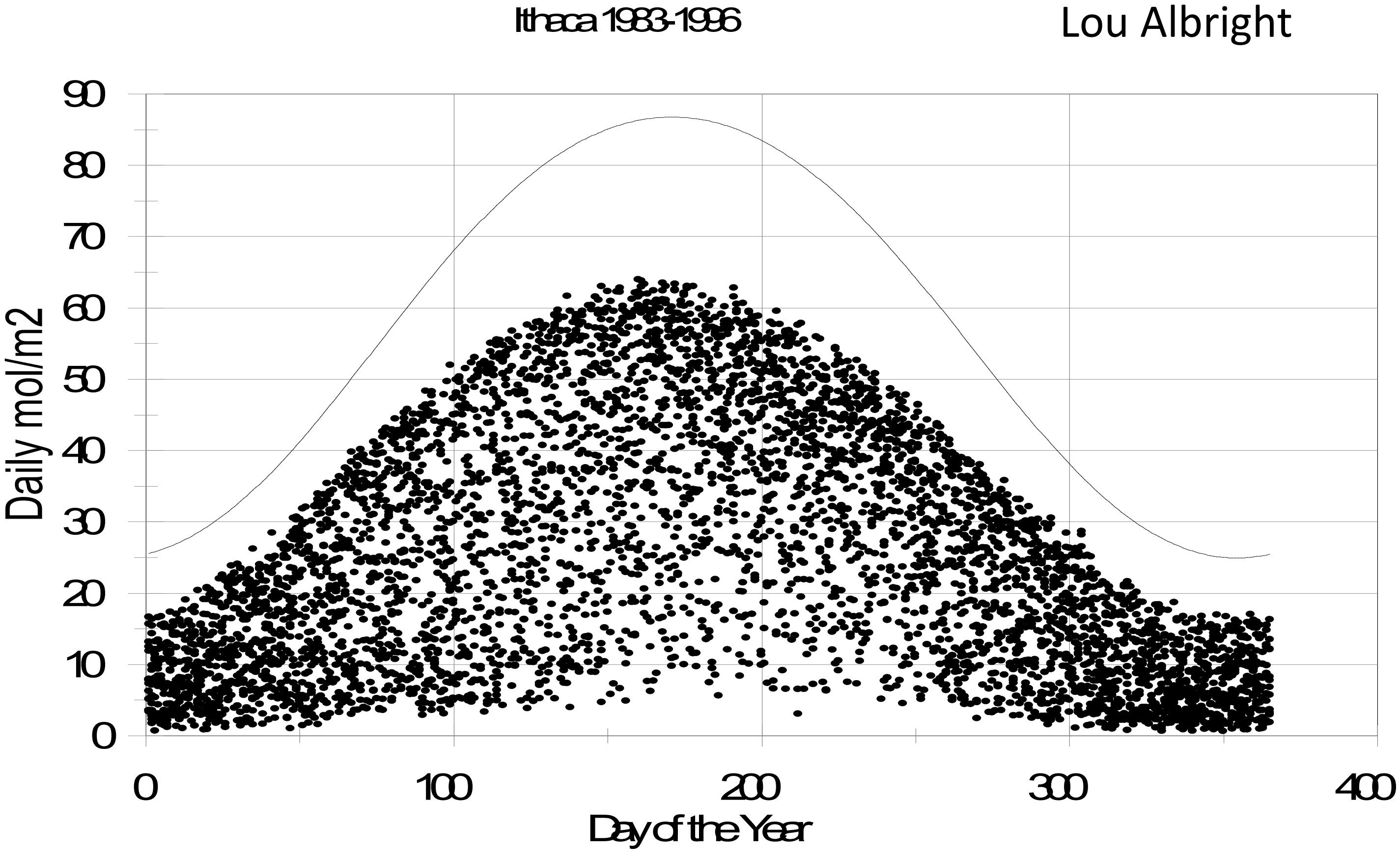
Faust and Logan (2018) HortScience 53(9):1250-1257



Note: typical greenhouse light transmission is 50-70%

When does supplemental lighting make sense?

You produce crops during winter months



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When does supplemental lighting make sense?

You notice issues with crop quality or yield from low light

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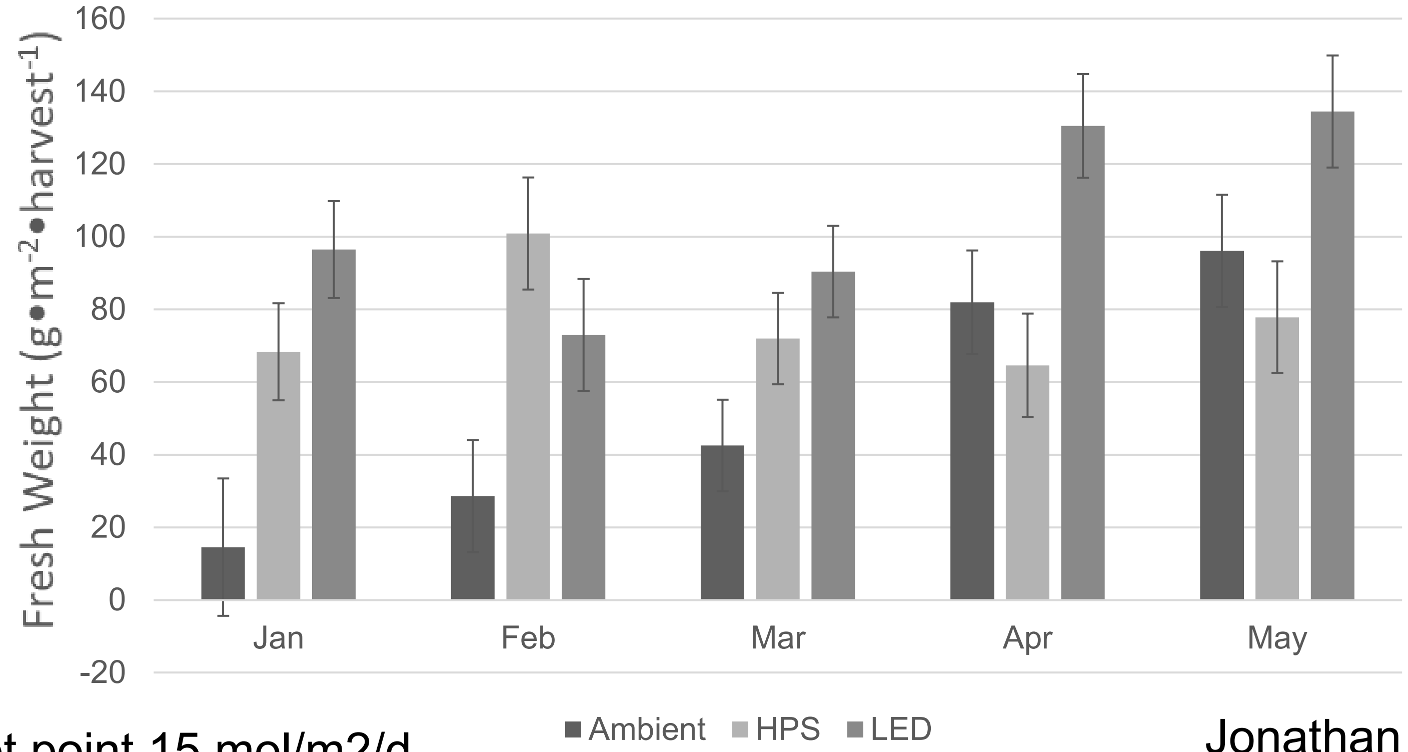
When does supplemental lighting make sense?

You notice issues with crop quality or yield from low light

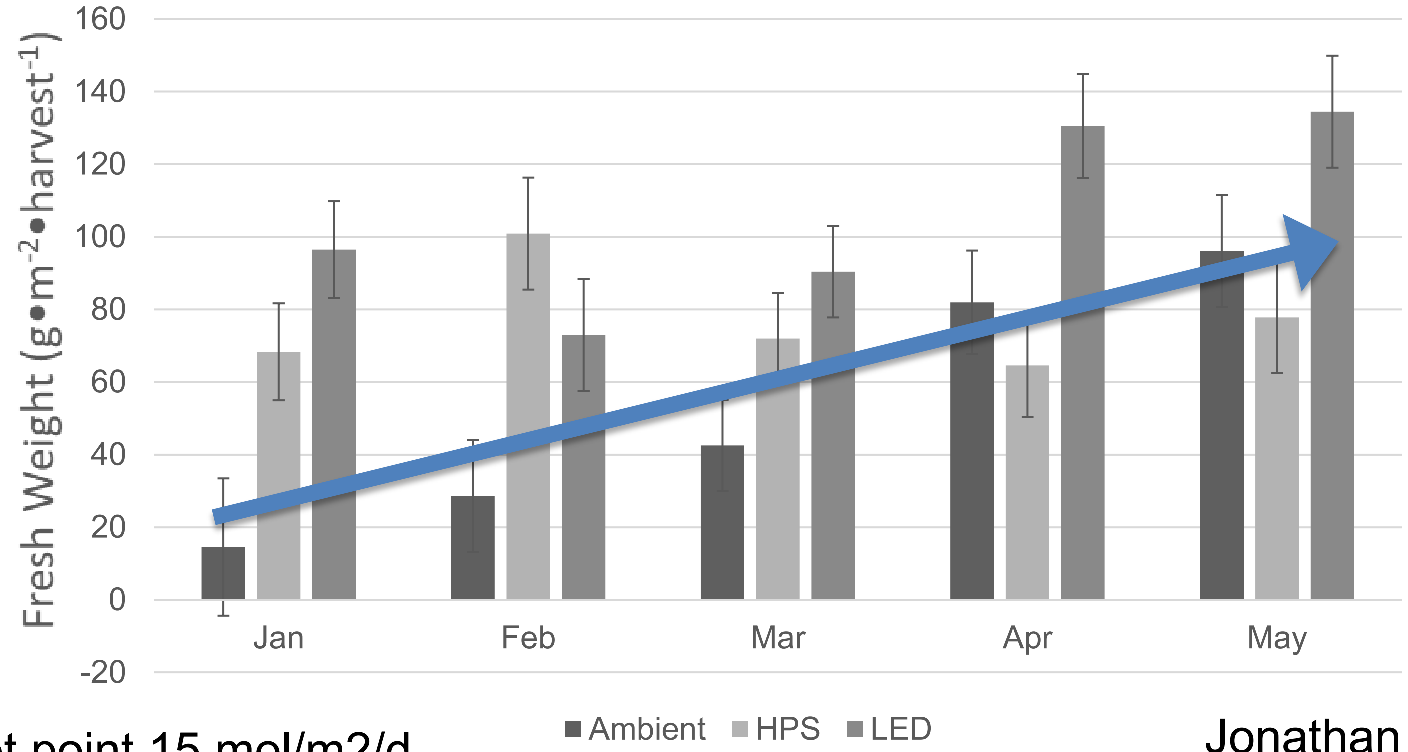
Winter lighting strawberry ‘Albion’



DLI set point 15 mol/m2/d

Jonathan Allred, Cornell

Winter lighting strawberry ‘Albion’



DLI set point 15 mol/m2/d

Jonathan Allred, Cornell

When does supplemental lighting make sense?

You wish to speed up crop turns

Pansy grown for 3 weeks under different lamps

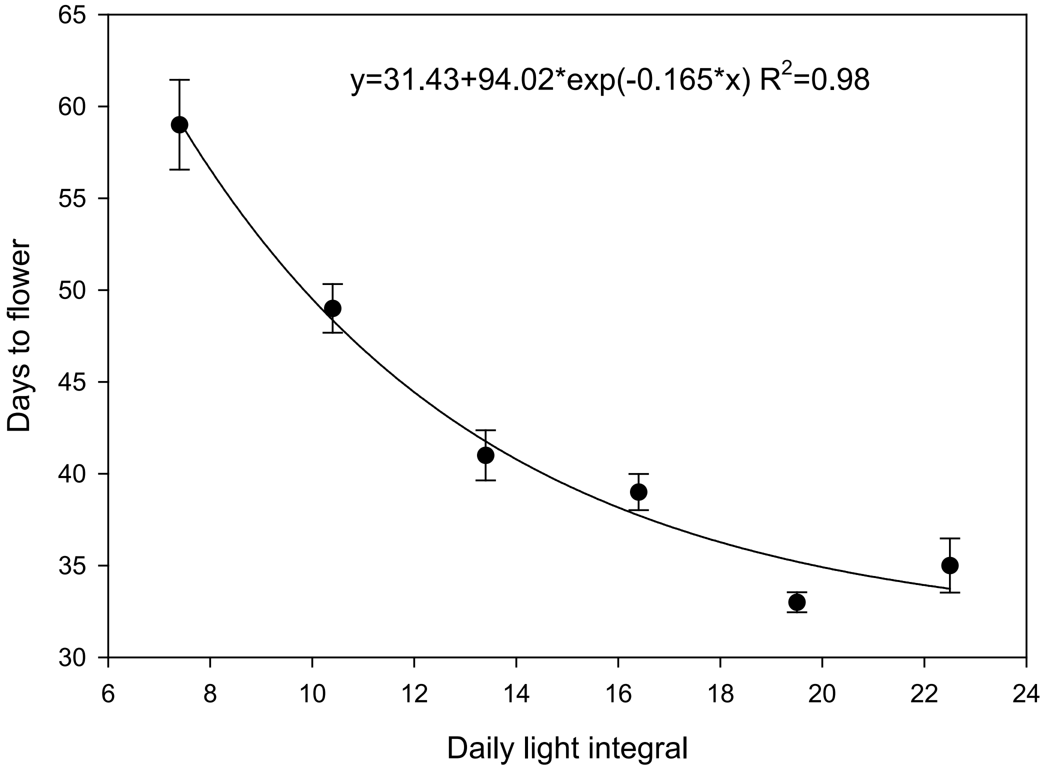
DLI ($mol \cdot m^{-2} \cdot d^{-1}$)

8	10	12.5	16	19.5	23

When does supplemental lighting make sense?

Increasing light integral decreases time to flower for Pansy ‘Crystal Bowl Supreme Yellow’ (LD)

You wish to speed up crop turns



When does supplemental lighting make sense?

High density crops (plugs, liners, seedlings)

New Guinea Impatiens ‘Harmony White’ Cuttings after 16 d of propagation

Source
Roberto Lopez, MSU

DLI ($mol \cdot m^{-2} \cdot d^{-1}$)

1.3	2.1	4.0	4.7	6.3	10.8

Marketable liners

>30 days	16 days	13 days

Root dry mass (mg)

8.0	14.5	30.0	35.5	48.5	55.5

When does supplemental lighting make sense?

Ex: Argyranthemum at 73/70 Fin a double-poly greenhouse in Grand Rapids, MI

High density crops (plugs, liners, seedlings)

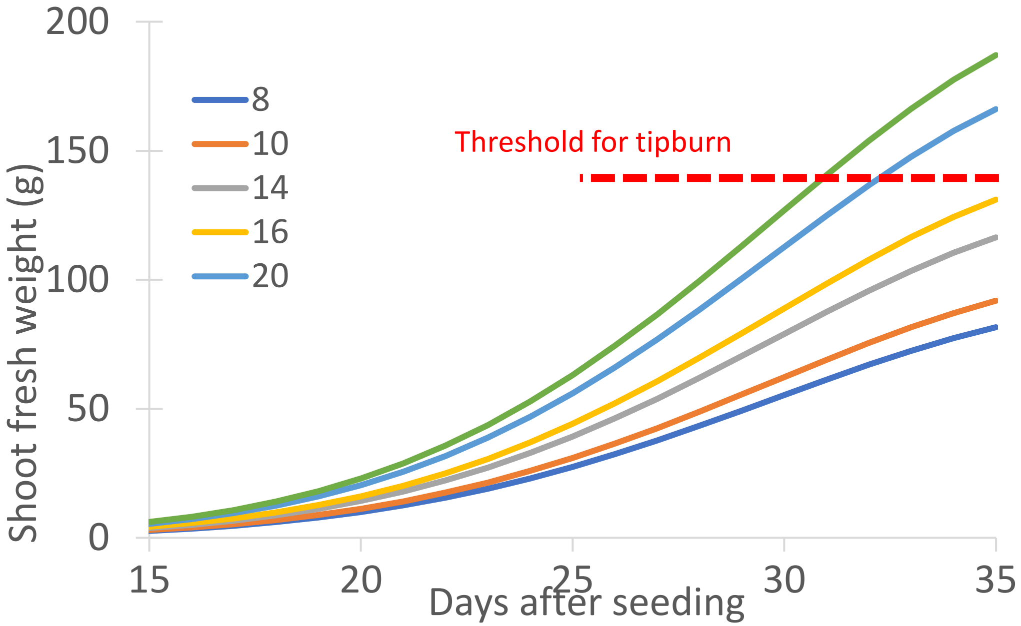
	Prop. DLI (mol m^{-2} d^{-1})	Heating cost ($/sf)	Lighting costs ($/sf)	Total heat + light cost ($/sf)
No suppl. Light	7	$1.28 (5 weeks)	$0	$1.28
Suppl. Light	12	$0.75 (3 weeks)	$0.03 (2 weeks)	$0.78

Heating with natural gas
15 x 400 W HPS lamps (75 µmol m^{-2} s^{-1}) for 18 hr

Source: Roberto Lopez, MSU

Head Lettuce

- 12 to 17 mol·m^{-2}·d^{-1} if vertical airflow fans are installed
- Greater light → increased incidence of tipburn
- Lower light → longer crop turn or lower biomass
- Photoperiod: continuous lighting (24 hr) can be used



'Ostinata' lettuce fresh weight response to DLI
Adapted from A.J. Both, 1997

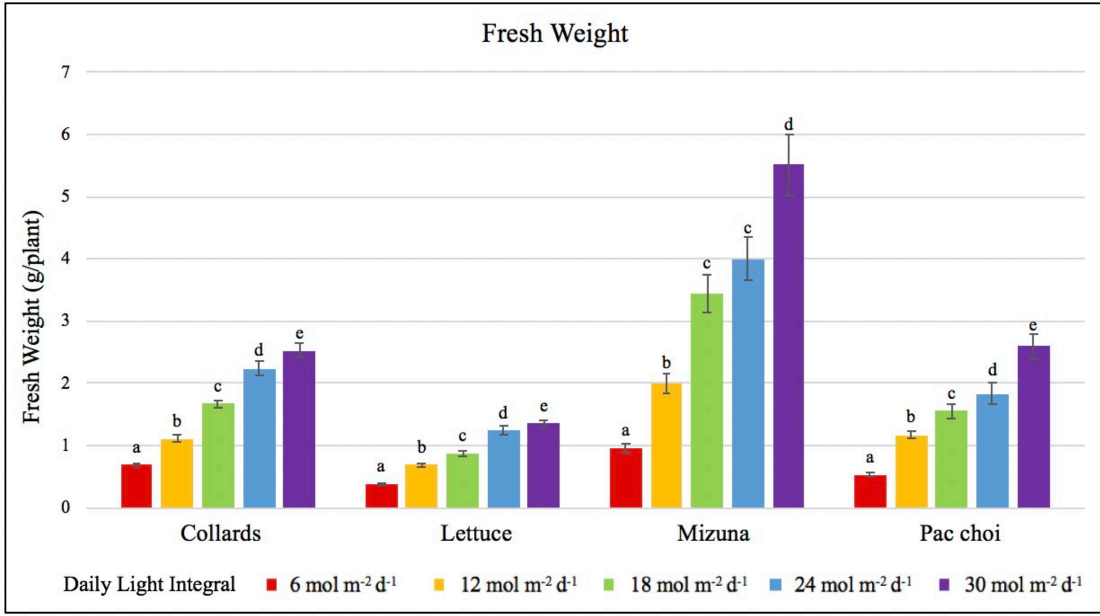
Lettuce


Symptoms of low light

Symptoms of high light

Baby Leaf Greens

- 18 to 30 mol·m^{-2}·d^{-1} (depending on crop)
- Not sensitive to tipburn at young age
- Lower light → longer crop turn or lower biomass
- Photoperiod: depends on species



Baby leaf greens yield increased up to 24-30 mol·m^{-2}·d^{-1}

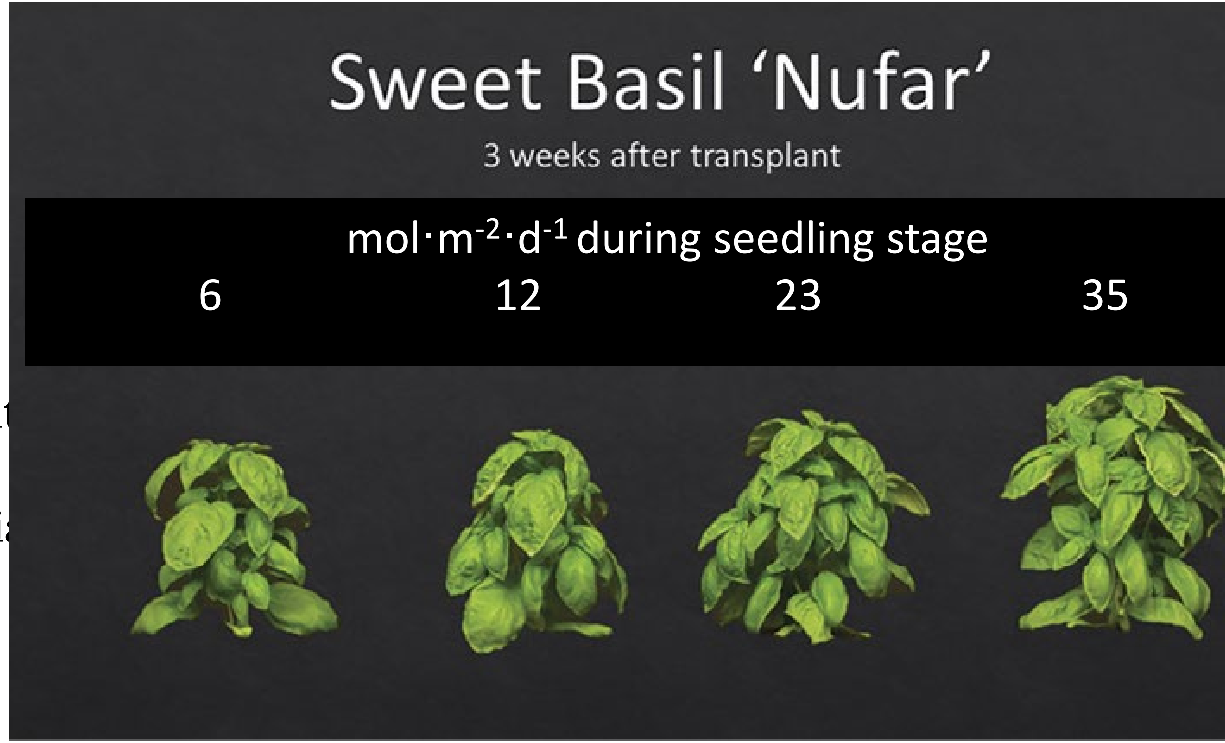
Collards

Lettuce

Photos & Figure: Charles Gagne, Cornell University

Herbs

- 12 to 20+ mol·m^{-2}·d^{-1} (depending on species)
- Need for more research
- Photoperiod: depends on species
  - Long day
    - Cilantro, dill, peppermint, spearmint
  - Short day
    - 'Blue Spice' basil, Stevia
  - Day neutral
    - 'Genovese' basil, oregano



Walters and Lopez, Produce Grower Magazine

Vine crops

Cucumbers

- Minimum: 15 mol·m^{-2}·d^{-1}, Optimum: 30+

Tomatoes

- Minimum: 20 mol·m^{-2}·d^{-1}, Optimum: 30+

Sweet Peppers

- Minimum: 15 mol·m^{-2}·d^{-1}, Optimum: 20+

Photoperiod: all day-neutral plants for flowering

- Tomatoes and peppers require a 6-hour dark period
  - Continuous light causes physiological disorder (leaf chlorosis, smaller plant size and yield)

What type of light?

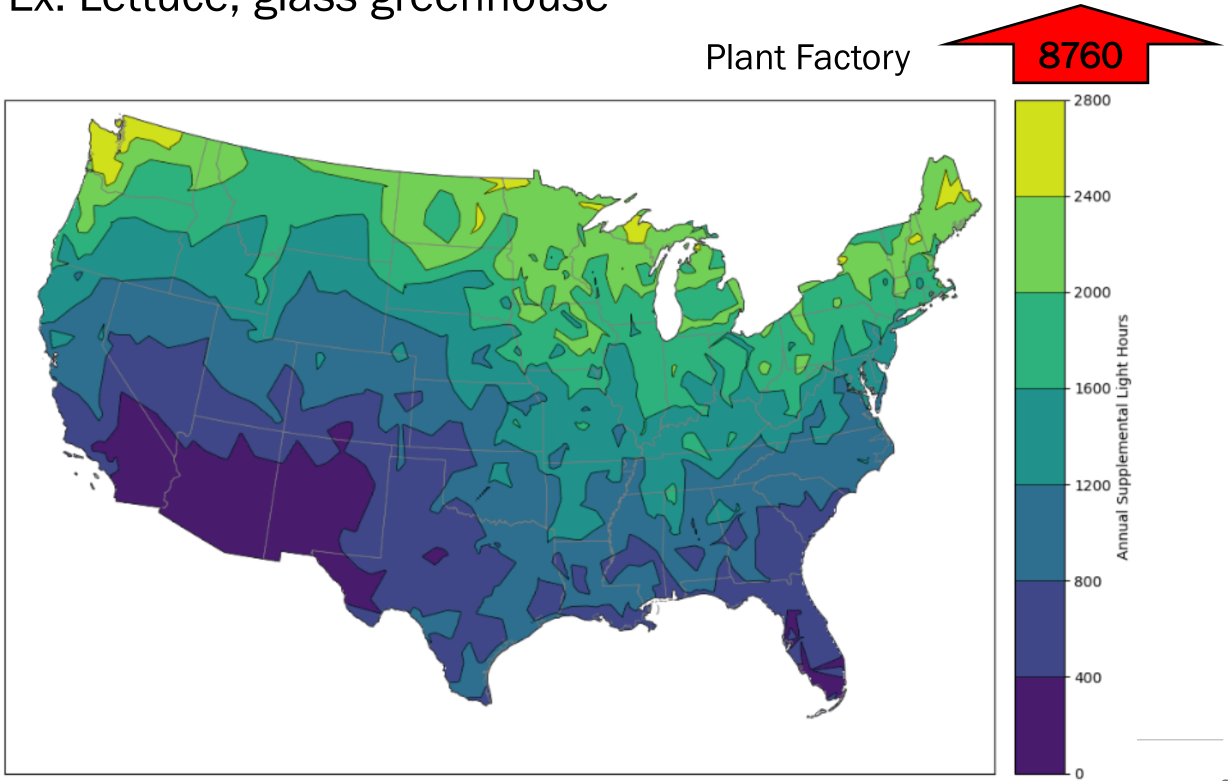
When do LED fixtures make sense over HID?

Lighting for several hundred hours per year

Examples

- year-round vegetable production in northern climates
- sole source lighting

Ex: Lettuce, glass greenhouse



Katherine Rogers and Kale Harbick

DLI target: 17 $mol \cdot m^{-2} \cdot d^{-1}$ Fixtures provide 200 $\mu mol \cdot m^{-2} \cdot s^{-2}$ PPFD

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When do LED fixtures make sense over HID?

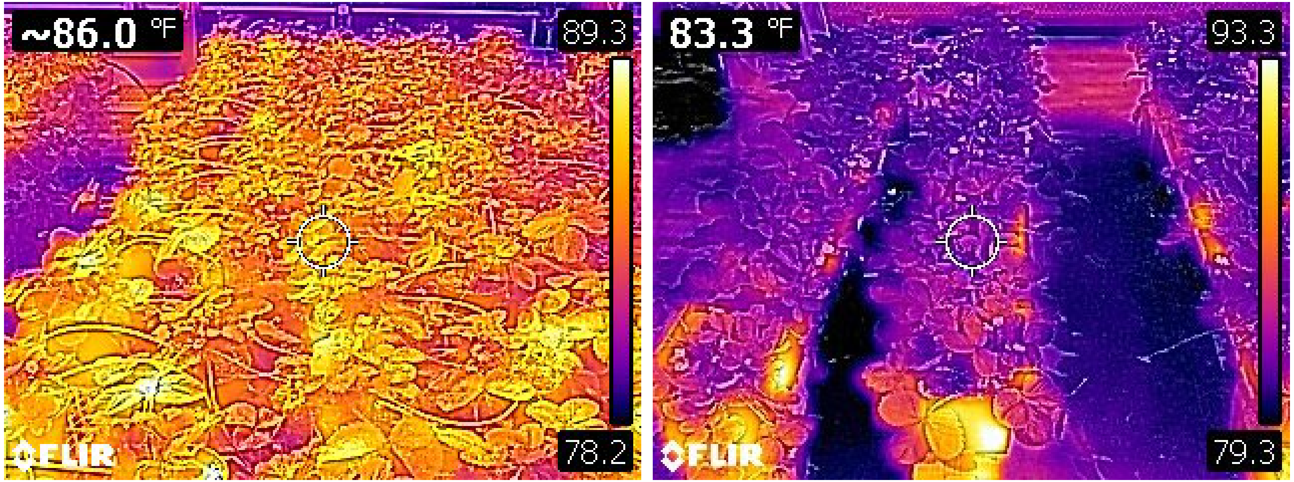
Electricity costs are expensive

State	Cost (¢/kWh)
Hawaii	32.1
Rhode Island	22.7
Massachusetts	22.5
Alaska	21.8
Connecticut	21.5
New Hampshire	**20.0**
California	18.3
New York	17.3
Maine	17.3
Vermont	16.7

Costs per kWh vary from 8.8₵ (OK) to 22.7₵ (RI)
Residential prices
U.S. average is 13.2₵

When do LED fixtures make sense over HID?

Need to add light during warm cloudy days (and don't want to add additional heat to canopy)



Thermal images of strawberry plants under supplemental HPS lighting (Left) and ambient solar irradiance (right)

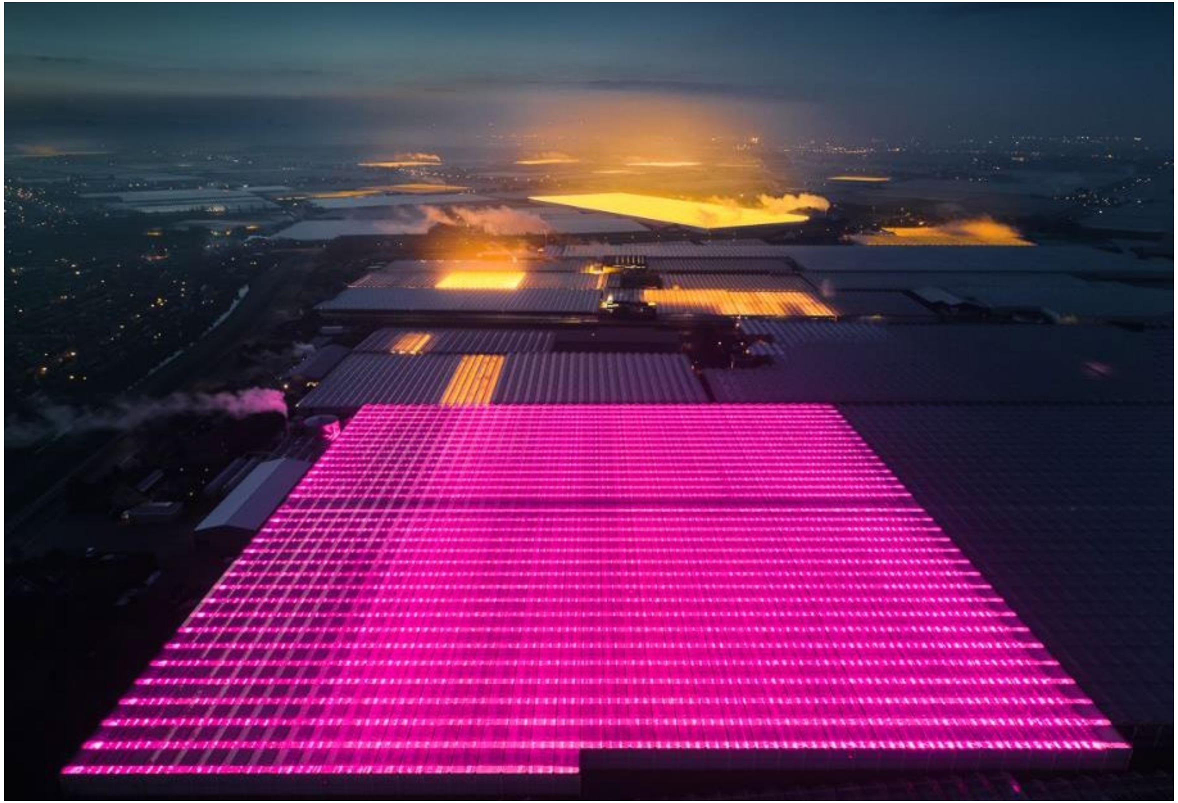
When do LED fixtures make sense over HID?

Not relying on HIDs to fulfill greenhouse heating requirements

- Some greenhouses account for waste heat from HID and reduce boiler size accordingly
- LEDs still provide some waste heat

When do LED fixtures make sense over HID?

Limitations to electrical grid – adopting LEDs may help you expand without adding electrical capacity



https://www.thisiscolossal.com/
Photo by Tom Hegen

Selecting a lighting fixture

- **Photosynthetic photon efficacy**
  - Typical units µmol/j
  - Note: umol/j × 3.6 = mol/kWh
- **Initial cost ($/fixture x # of fixtures)**
- Lifespan (often reported to 70 or 90% output)
- Bulb replacement cost
- Installation cost
- Shading of fixture
- Uniformity of light plan
- Wavelength/light quality?

Which LEDs meet energy efficiency and reliability criteria?

DLC Horticultural Lighting Qualified Products List (QPL)

- Fixtures registered with DLC meet several minimum requirements
- Fixtures design for North American AC line voltage
- Many utility companies use this list to decide if a fixture qualifies for energy efficiency incentives
- Specification revised every 2 years to become more rigorous

https://www.designlights.org/horticultural-lighting/

Which LEDs meet energy efficiency and reliability criteria?

DLC Horticultural Lighting (version 2.1), minimum requirements:

- Photosynthetic Photon Efficacy (PPE) ≥ 1.9 µmol/j
- Photon Flux Maintenance (Q_{90}) ≥ 36,000 hours
  - i.e. # of hours until light output is degraded to 90% of original output
- Driver lifetime ≥ 50,000 hours
- Fan lifetime ≥ 50,000 hours
- Warranty: fixtures ≥ 5 years; lamps ≥ 3 years

https://www.designlights.org/horticultural-lighting/

Design Lights Consortium

TESTED PHOTOMETRIC PERFORMANCE	
Tested Photosynthetic Photon Efficacy (400-700nm)	3.46 µmol/J
Tested Photosynthetic Photon Flux (400-700nm)	1821 µmol/s
Tested Photon Flux Blue (400-500nm)	196 µmol/s
Tested Photon Flux Green (500-600nm)	103 µmol/s
Tested Photon Flux Red (600-700nm)	1522 µmol/s
Tested Photon Flux Far Red (700-800nm)	9 µmol/s

Tested Performance Criteria

Tested Photosynthetic Photon Flux (µmol/s)	1480 - 5000
Tested Photon Flux Blue (µmol/s)	1460 - 5000
Tested Photon Flux Green (µmol/s)	380 - 5000
Tested Photon Flux Red (µmol/s)	1940 - 5000
Tested Input Wattage	0 - 2000
Tested Photosynthetic Photon Efficacy (µmol/J)	3.1 - 5
Tested Power Factor	0.88 - 1
Tested Total Harmonic Distortion	0 - 0.24
Tested DC Photon Efficacy (280-800nm)	1.8 - 5

DLC QPL LISTED®

https://www.designlights.org/horticultural-lighting/

Solid State Lighting | Horticultural Lighting | Lighting Controls | Current Efforts | News and Ev

Clear All Filters

Manufacturer +

Listing Status +

Listed Products

Technical Requirements Version Number +

Product Function +

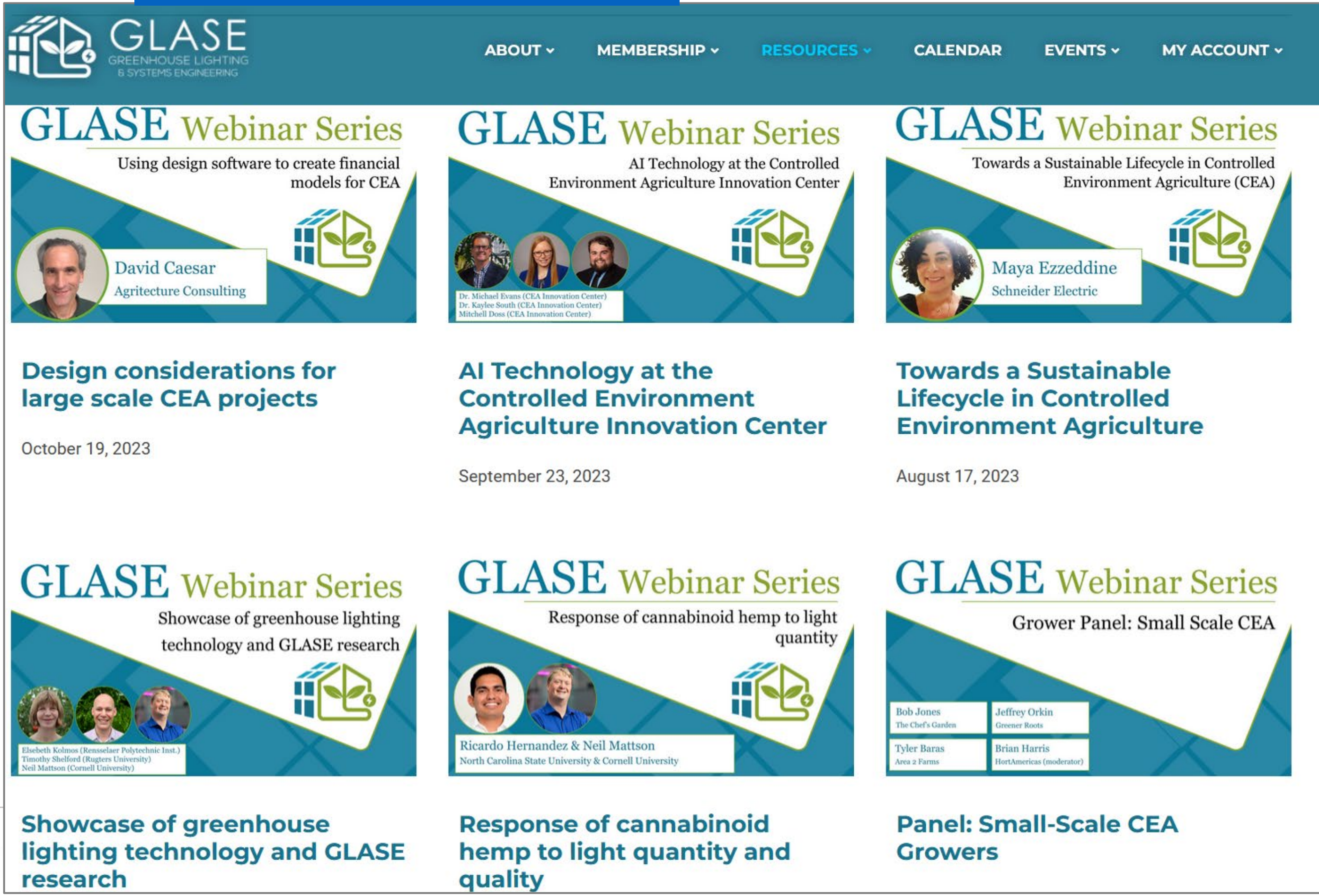
Product Categories +

State Compliance +

H-PLS0JDZ	VR-2X-I-x-xx-xxx-xx-x	Fluence Bioengineering Inc.	Fluence Bioengineering	VYPR 2x PhysioSpec Indoor
H-0WNDYAR	HT-02 Uniformity Pro 320W	FGI	Forever Green Indoors Inc	FGI Uniformity Pro 320
H-ZI8J8X3	HT-02 Uniformity Pro 640W	FGI	Forever Green Indoors Inc	FGI Uniformity Pro LED
H-AMU5JMO	ZK2-ML600-[SP01,SP02]/D	SANANBIO	Fujian Sanan Sino-Science Photobiotech Co., Ltd	625W LED grow light
H-S0O25G3	ZK2-TL300-[SP01,SP02]/D	SANANBIO	Fujian Sanan Sino-Science Photobiotech Co., Ltd	300W LED grow light
H-CNRSSYT	ZK2-TL600-[SP01,SP02]/D	SANANBIO	Fujian Sanan Sino-Science Photobiotech Co., Ltd	600W LED grow light
H-R0A9JR4	GEHTL-HPPB4-(2,3)NX1	GE Current a Daintree company	GE Current, a Daintree company	ARIZE ELEMENT L1000

www.glase.org

- Lighting research
- Webinars
- Newsletter
- Annual short-course



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Lighting Approaches to Maximize Profits

USDA

NIFA

United States Department of Agriculture

National Institute of Food and Agriculture

This work is funded by USDA-NIFA-SCRI Award Number # 2018-51181-28365
Project ‘Lighting Approaches to Maximize Profits’

hortlamp.uga.edu

lighting/

LAMP Lighting Calculators

- 'Unlimited lighting' calculator
- 'Unlimited lighting' calculator in EXCEL
- 'How large should my lighting system be' calculator
- 'How often will I reach my target DLI' calculator
- 'How many fixtures do I need?' calculator
- DLI Interactive Maps - United States

https://uga-lighting-calc.shinyapps.io/supplementalcalc/

SupplementalCalc | Home | Add Location | Add Greenhouse Design | Required Supplemental Lighting | FAQ | Quit

Lighting Approaches to Maximize Profits

Welcome to our 'How large should my lighting system be' calculator!

With this calculator, users specify on how many days of year they want to be able to reach the target DLI (expressed as a percentage of 365 days). After entering what percentage of days you want to reach the target DLI, the calculator will determine the required lighting capacity, and provide a graphical summary of the lighting conditions you can expect in your greenhouse. This lighting system also estimates the demand charge, associated with the use of the lighting system. This calculator is particularly useful for the design of new lighting installations.

https://uga-lighting-calc.shinyapps.io/supplementalcalc/

Enter Greenhouse Location

Location Name
(Enter a unique identifier for your Location)

Grand Rapids, MI

Zip Code
(5 digits)

49501

Electricity Rate ($/kWh) ?

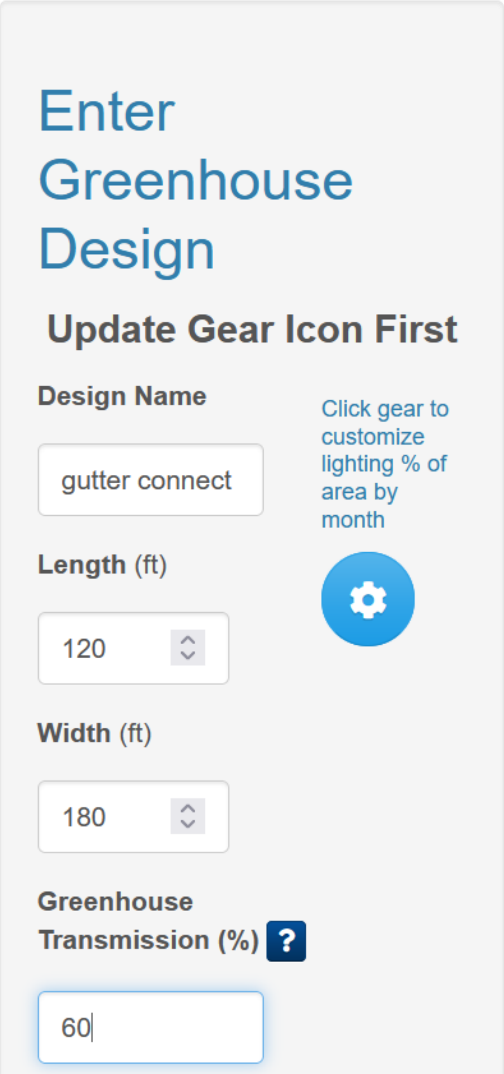
$0.105

Save

Step 1

Enter:

- Location name
- Zip code
- Electricity rate

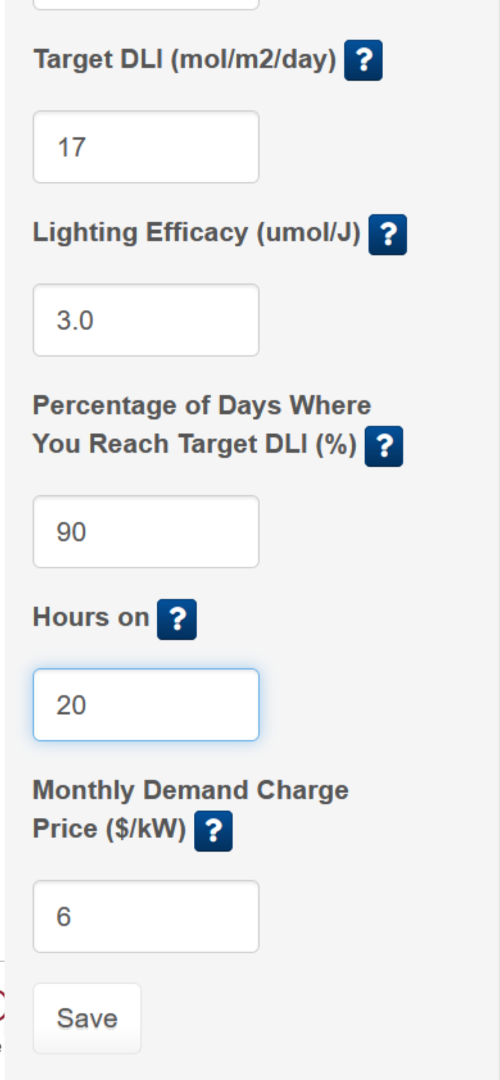


Enter Greenhouse Design

Step 2A

Enter:

- Length
- Width
- Transmission % (typically) 45-70%



Step 2B

Enter:

- Target DLI
- Lighting efficacy (typically 1.2 – 3.0+ µmol/J)
- Percentage of day where you reach target DLI
  - Is 100% necessary? Requires greater installation
- Hours on, ex:
  - Lettuce can be lit continuously
  - Fruiting crops require 4-6 hr dark period
- Demand charge for electricity ($/kW)
  - Based on highest usage in a single 15-minute period during the month

Results

Required Supplemental Lighting

Location

Grand Rapids, MI

Design

gutter connect

Update | Adjust | Reset

Download Results

Download Adjusted Results

Press the Update Button to view results

WARNING: Press the Adjust Button to adjust the supplemental DLI capacity AFTER clicking on the chart

Press the Reset Button to revert changes

Monthly Area Lighting %

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Annual Lighting Cost

$ Per ft2	$ Per acre	$ Total Design
1.435	62,519	31,001

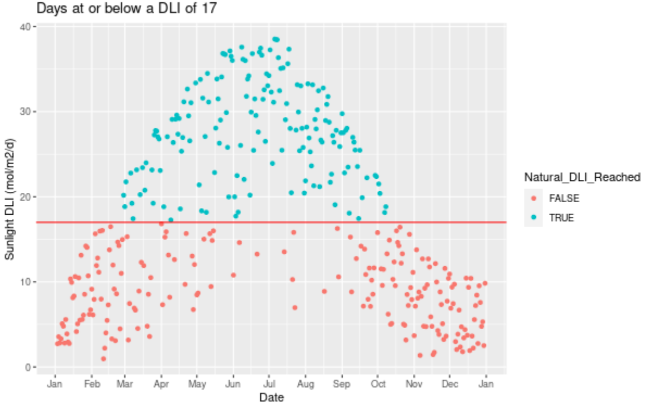
Grower Input

Greenhouse Transmission (%)	Target DLI (mol/m2/day)	Lighting Efficacy (umol/J)	Electricity Cost ($/kWh)	Hours On	Demand Charge ($/kW/month)	Percentile (%)	Area (ft2)
60.00	17.00	3.00	0.10	20.00	6.00	90.00	21600.00

Annual Demand Cost

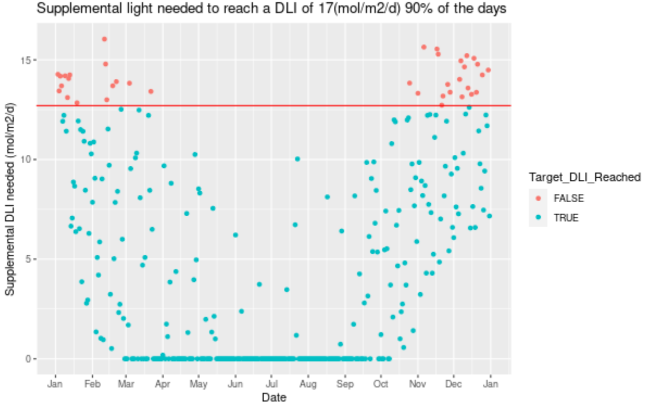
$ Per ft2	$ Per acre	$ Total Design
0.393	17,135	8,496

Sunlight (accounting for transmission)



Red line indicates the target DLI of 17(mol/m2/d)

Supplemental Light



led line indicates the maximum supplemental DLI needed, which is 12.7(mol/m2/d)

Weekly Lighting Cost

Week	$ Per ft2	$ Per acre	$ Total Design
1	0.079	3,448	1,710
2	0.065	2,837	1,407
3	0.056	2,422	1,201
4	0.048	2,110	1,046

Required Lighting System Capacity

176 umol/m2/s

Max Supplemental DLI Capacity

12.7 mol/m2/d

Comparing 100% vs. 90% of days with target met

90% of days target met

Annual Lighting Cost

$ Per ft2	$ Per acre	$ Total Design
1.435	62,519	31,001

Annual Demand Cost

$ Per ft2	$ Per acre	$ Total Design
0.393	17,135	8,496

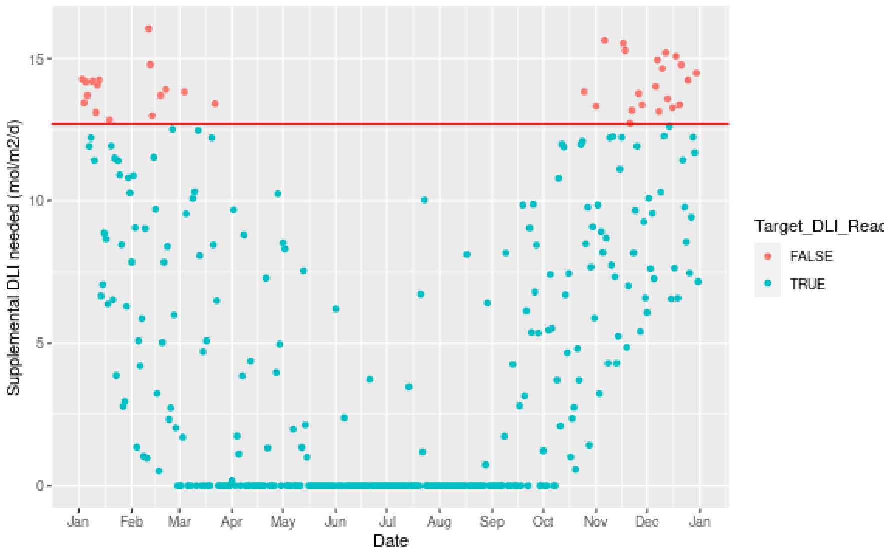
100% of days target met

Annual Lighting Cost

$ Per ft2	$ Per acre	$ Total Design
1.481	64,492	31,979

Annual Demand Cost

$ Per ft2	$ Per acre	$ Total Design
0.497	21,637	10,729



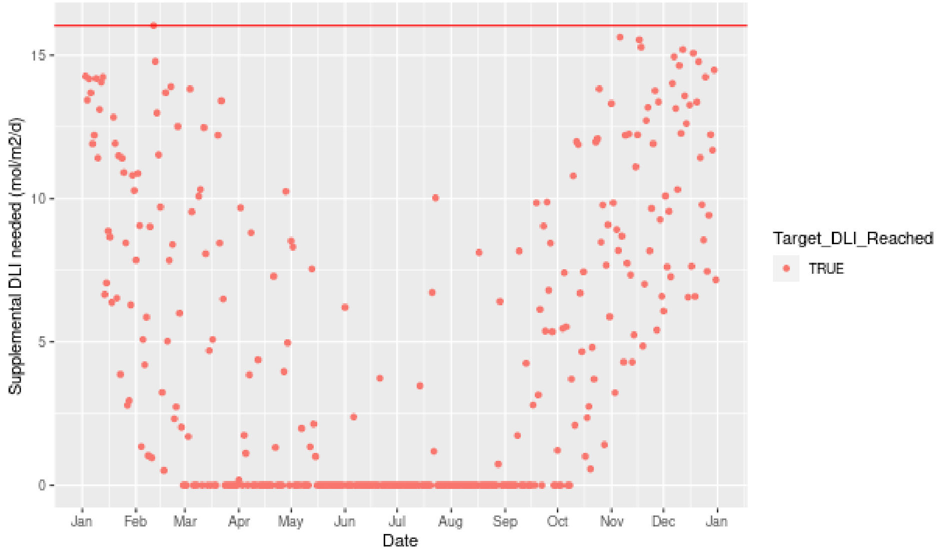
Red line indicates the maximum supplemental DLI needed, which is 12.7(mol/m2/d)

Required Lighting System Capacity

176 umol/m2/s

Max Supplemental DLI Capacity

12.7 mol/m2/d



Red line indicates the maximum supplemental DLI needed, which is 16.04(mol/m2/d)

Required Lighting System Capacity

223 umol/m2/s

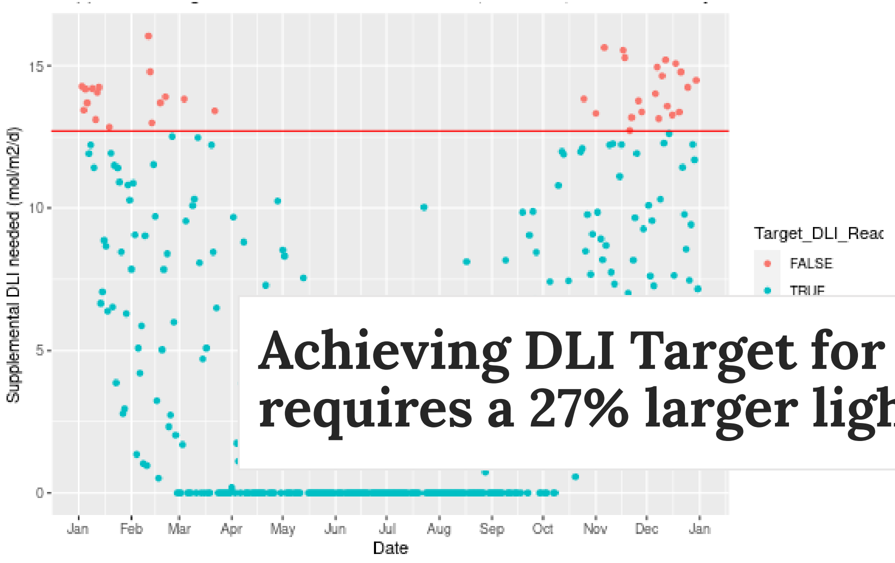
Max Supplemental DLI Capacity

16.04 mol/m2/d

90% of days **target met** 100% of days

Lighting Approaches to Maximize Profits

Achieving DLI Target for 100% of days vs. 90% requires a 27% larger lighting installation



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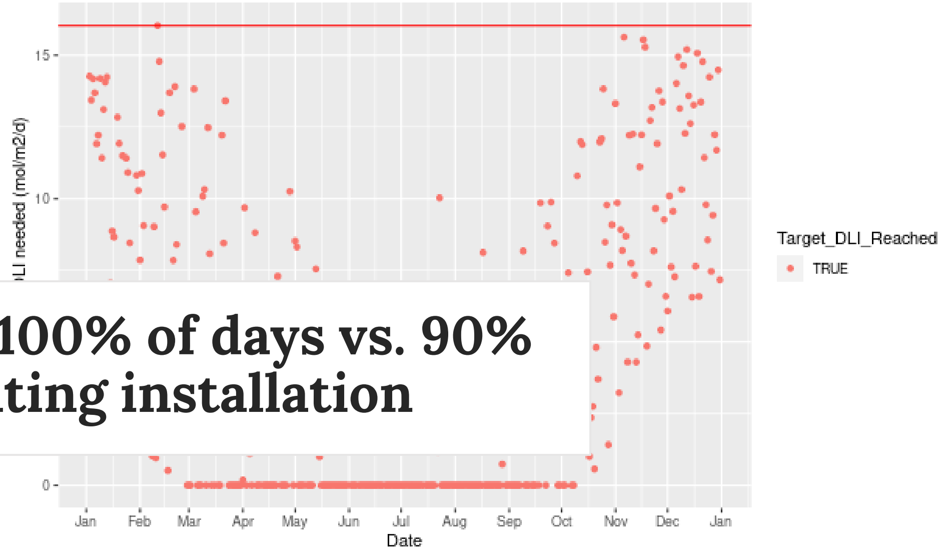

Red line indicates the maximum supplemental DLI needed, which is 16.04(mol/m2/d)

90% of days		100% of days
Required Lighting System Capacity 176 umol/m2/s	→	Required Lighting System Capacity 223 umol/m2/s
Max Supplemental DLI Capacity 12.7 mol/m2/d		Max Supplemental DLI Capacity 16.04 mol/m2/d

90% of days **target met** 100% of days

Lighting Approaches to Maximize Profits

www.hortlamp.org → Outreach

LAMP Lighting Calculators

- 'Unlimited lighting' calculator
- 'Unlimited lighting' calculator in EXCEL
- 'How large should my lighting system be' calculator
- 'How often will I reach my target DLI' calculator
- 'How many fixtures do I need?' calculator
- DLI Interactive Maps - United States

Fixtures needed and electricity cost - Inputs

	A	B	C	D	E
1	**LAMPS NEEDED CALCULATOR**				
2	estimating lamp needs for greenhouse space				
3	© Neil Mattson, Cornell University 4/23/15				
4	Updated May 2021, note that PPE in µmol/J is now used				
5	Use the tabs Lamp 1 and Lamp 2 to input the data for tv				
6					
7	Fill in yellow highlighted boxes				
8	200	Target instantaneous light intensity (µmol/			
9	1090	Lamp power consumption (W)			
10	43560	Area to light (square feet), note that there			
11	1.80	Photosynthetic photon efficacy (PPE, µmol/			
12	10%	percent light lost from edge effects			
13	2000	total hours lights are on per year			
14	$0.160	cost of electricity ($/kWh)			
15	$350	cost of individual light fixture ($/fixture)			

Hypothetical Fixture 1

HPS DE

- 200 µmol m^{-2} s^{-1}
- 2,000 hours annually

Fixtures needed and electricity cost - Results

	A	B	C	D	E	F	G	H
17	**Calculations** (don't modify these boxes)							
18	4,047	Square meters to light (note 1 square meter = 10.7639 square feet)						
19	1,962	Lamp output µmol/s						
20	413	Light fixtures needed without edge effects						
21	459	Light fixtures needed with edge effects						
22	$160,650	Total cost of light fixtures (assuming edge effects)						
23	1,000,620	kWh of electricity to light this many lamps for the given number of hours						
24	$160,099	electricty cost ($/area in cell A8/yr)						
25	$3.68	electricity cost ($/square foot/yr)						
26	$39.56	electricity cost ($/m^2/yr)						
27								
28	*Note* placement of lamps should be determined by a lighting professional to optimize t							
29		Lamps needed may be somewhat more if want uniform lighting at the edges						

Comparing 2 Fixtures

	A	B	C	D	E
7	Fill in yellow highlighted boxes				
8	200	Target instantaneous light intensity (µmol/r			
9	1090	Lamp power consumption (W)			
10	43560	Area to light (square feet), note that there a			
11	1.80	Photosynthetic photon efficacy (PPE, µmol/.			
12	10%	percent light lost from edge effects			
13	2000	total hours lights are on per year			
14	$0.160	cost of electricity ($/kWh)			
15	$350	cost of individual light fixture ($/fixture)			
16					
17	**Calculations** (don't modify these boxes)				
18	**4,047**	Square meters to light (note 1 square meter			
19	**1,962**	Lamp output µmol/s			
20	**413**	Light fixtures needed without edge effects			
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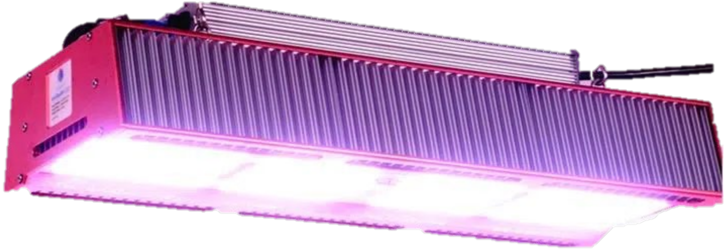
25	**$3.68**	electricity cost ($/square foot/yr)			
26	**$39.56**	electricity cost ($/$m^2$/yr)			
27					

Calculations | **Lamp 1** | Lamp 2

Comparing 2 Fixtures



Lamp 1

- DE HPS
- PPE: 1.8 µmol/J
- Cost: $350

Lamp 2

- LED
- PPE: 3.1 µmol/J
- Cost: $950

200 µmol m^{-2} s^{-1} target, 2,000 hours annually
Lighting 1 acre, 10% light loss to edges
Electricity at **$0.08 vs. $0.16** / kWh

Comparing 2 Fixtures

Electricity at **$0.08** / kWh

	A	B	C	D	E	F	G
28	**Summary statistics comparing Lamp 1 vs. Lamp 2** (don't modify these boxes						
29	**$3.69**	Cost to purchase Lamp 1 ($/sf)					
30	**$10.90**	Cost to purchase Lamp 2 ($/sf)					
31	**$1.84**	Electricity cost Lamp 1 ($/sf/yr)					
32	**$1.07**	Electricity cost Lamp 2 ($/sf/yr)					
33	**9.36**	Simple payback in years for Lamp 2 vs. Lamp 1 (difference in upfr					
34							
35	*Note* placement of lamps should be determined by a lighting professional						
36		Lamps needed may be somewhat more if want uniform lighting a					

$$\text{Simple payback} = \frac{\text{upfront price difference}}{\text{annual electricity price difference}}$$

Comparing 2 Fixtures

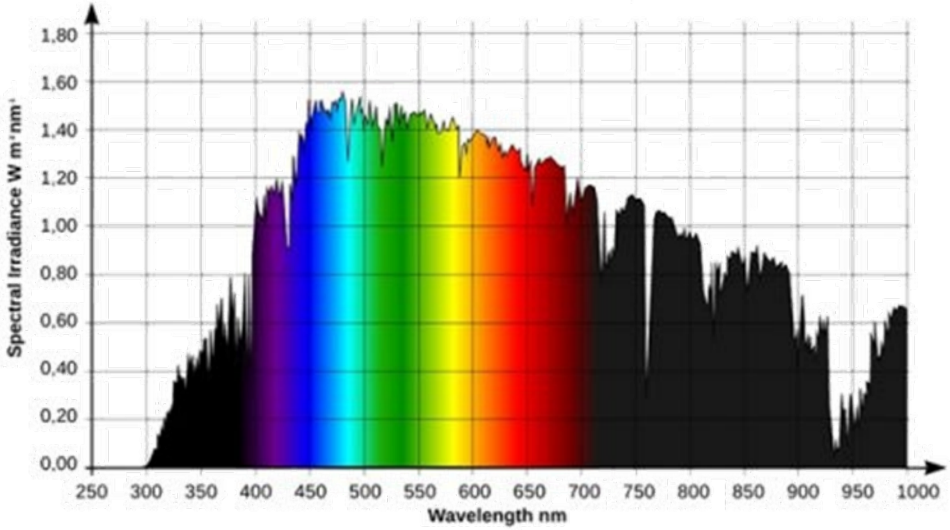
Electricity at **$0.16** / kWh

	A	B	C	D	E	F	G
28	**Summary statistics comparing Lamp 1 vs. Lamp 2** (don't modify these boxes)						
29	**$3.69**	Cost to purchase Lamp 1 ($/sf)					
30	**$10.90**	Cost to purchase Lamp 2 ($/sf)					
31	**$3.68**	Electricity cost Lamp 1 ($/sf/yr)					
32	**$2.13**	Electricity cost Lamp 2 ($/sf/yr)					
33	**4.68**	Simple payback in years for Lamp 2 vs. Lamp 1 (difference in upfr					
34							
35	*Note* placement of lamps should be determined by a lighting professional t						
36		Lamps needed may be somewhat more if want uniform lighting a					

$$\text{Simple payback} = \frac{\text{upfront price difference}}{\text{annual electricity price difference}}$$

Importance of light spectrum
Greenhouse Supplemental Lighting

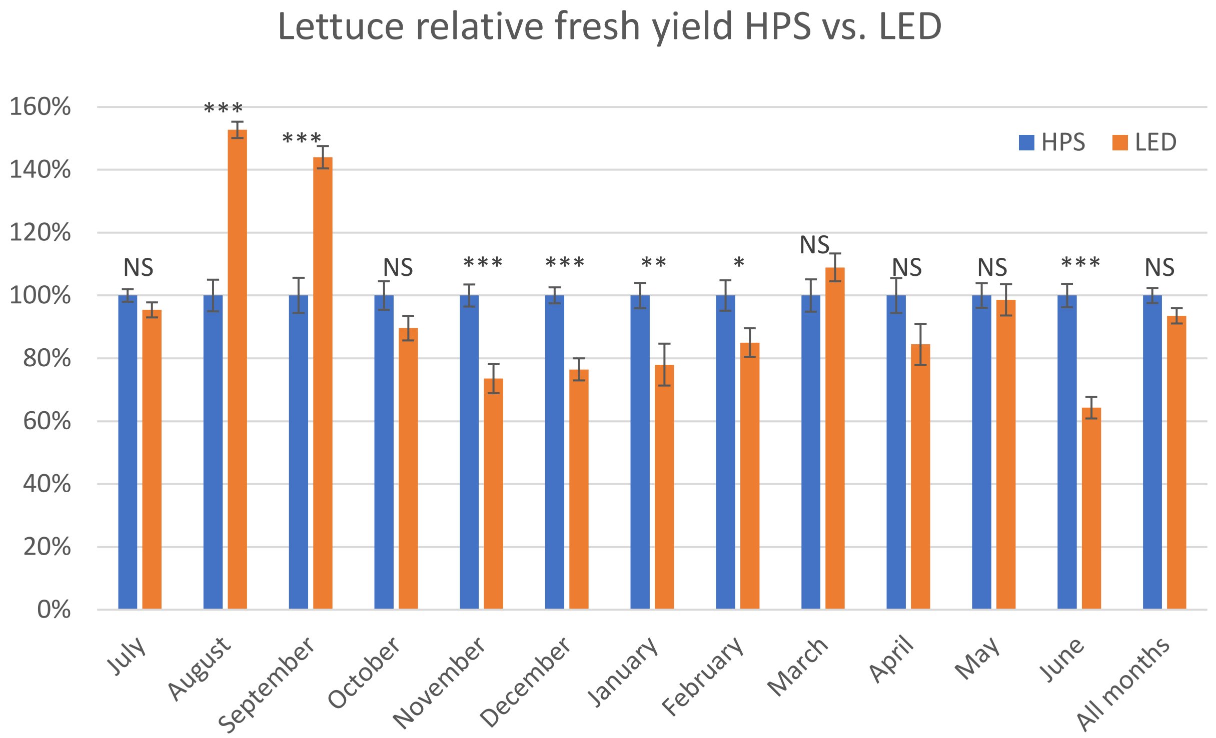
- Sunlight provides full spectrum
- Most spectral studies don't see significant differences in the greenhouse environment
- Favor high efficacy fixtures unless known crop responses to spectrum



Response of baby leaf greens to greenhouse lighting from LED or HPS

Lettuce results across 12-months

- DLI 17 mol·m^{-2}·d^{-1}
- HPS: Gavita Pro 6/750e Flex US DE
- LED: Philips GreenPower toplighting DR/B - Low Blue
- HPS yield favored in Nov. to Feb., plus June
- LED yield favored in Aug. and Sept.
- Averaged across year, yield not impacted by fixture



T-Test comparing HPS to LED light for a given month, NS, *, **, *** are non-significant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively

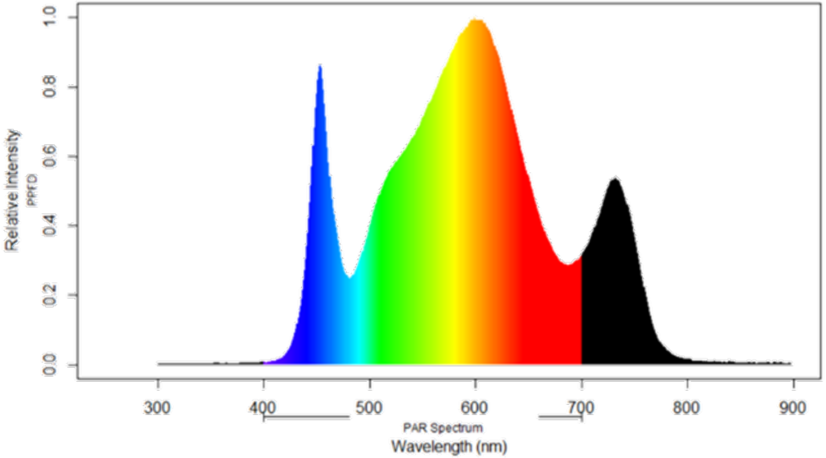
Cornell CALS
College of Agriculture and Life Sciences

Importance of light spectrum
Sole-Source Lighting

- Vertical Farm with leafy greens
  - Spectral distribution broad spectrum including far-red


Photo: Plenty

5700 K White with Far-Red LED



Questions?

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Lighting Approaches to Maximize Profits

USDA NIFA

United States Department of Agriculture

National Institute of Food and Agriculture

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