Lighting Decisions for Greenhouse Production

Neil Mattson
nsm47@cornell.edu

Cornell College of Agriculture and Life Sciences
Cornell Controlled Environment Agriculture

Controlled Environment Agriculture or CEA facilities can range from the very low-tech such as row covers and high/low plastic covered tunnels, to fully automated glass greenhouses with computer controls. There have even been some CEA facilities on the international space station where astronauts have grown leafy greens both to eat and to advance scientific knowledge. The Cornell CEA program has worked with many different types of CEA facilities through the years. We developed a greenhouse hydroponic production method geared toward local food production. A prototype facility was built in Ithaca in the late 1990's and continues to function today producing more than 1000 heads of lettuce every day of the year. We continue to do research in the areas of supplemental lighting and commercial hydroponic vegetable production. Learn more about the CEA...

GLASE

The Greenhouse Lighting and Systems Engineering (GLASE) consortium is a public-private partnership led by Cornell University and Rensselaer Polytechnic Institute to integrate lighting systems into indoor CEA facilities.
Outline

• How much light do you have?
• How much light do you need?
• Cost to buy/operate lights
• Lighting control
Updated DLI maps
https://mapgallery.esri.com/map-detail/5b0f577674204e43b4a2329
Updated DLI maps
https://mapgallery.esri.com/map-detail/5b0f577674204e43b4a2329
What is your greenhouse’s light transmittance? Typically 50-70%
Outline

• How much light do you have?
• How much light do you need?
• Cost to buy/operate lights
• Lighting control
How much light do you need?

Flower Crops

• Propagation of plugs and cuttings
  – 8-12 mol m\(^{-2}\) d\(^{-1}\) (after callus)

• Bedding plants
  – 10-12 mol m\(^{-2}\) d\(^{-1}\) (species dependent)

• Flowering potted plants
  – 10-12 mol m\(^{-2}\) d\(^{-1}\) (species dependent)
  – Phalaenopsis orchids (6), potted miniature roses (14)

• Install lighting capacity of 50-100 µmol m\(^{-2}\) s\(^{-1}\)
## Table 2. DLI Requirements for Various Greenhouse Crops

<table>
<thead>
<tr>
<th>Species</th>
<th>Minimum acceptable quality</th>
<th>Good quality</th>
<th>High quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferns (Pteris Adiantum)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maranta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phalaenopsis (orchid)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saintpaulia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spathiphyllum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forced hyacinth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forced narcissus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forced tulip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aglaonema</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromeliads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caladium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dieffenbachia</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1=Requires ample water to perform well at high-light levels.  
2=Requires cool or moderate temperatures to perform well at high-light levels.  
3=Stock plants perform well under higher light levels than finished plants.

<table>
<thead>
<tr>
<th>Species</th>
<th>Average Daily Light Integral (Moles/Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Greenhouse</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Ferns (Pteris Adiantum)</td>
<td></td>
</tr>
<tr>
<td>Maranta</td>
<td></td>
</tr>
<tr>
<td>Phalaenopsis (orchid)</td>
<td></td>
</tr>
<tr>
<td>Saintpaulia</td>
<td></td>
</tr>
<tr>
<td>Spathiphyllum</td>
<td></td>
</tr>
<tr>
<td>Forced hyacinth</td>
<td></td>
</tr>
<tr>
<td>Forced narcissus</td>
<td></td>
</tr>
<tr>
<td>Forced tulip</td>
<td></td>
</tr>
<tr>
<td>Aglaonema</td>
<td></td>
</tr>
<tr>
<td>Bromeliads</td>
<td></td>
</tr>
<tr>
<td>Caladium</td>
<td></td>
</tr>
<tr>
<td>Dieffenbachia</td>
<td></td>
</tr>
</tbody>
</table>

Purdue Bulletin – Measuring daily light integral in the greenhouse  
https://www.extension.purdue.edu/extmedia/HO/HO-238-W.pdf
Light intensity effects time to flower

Pansy grown for 3 weeks under different lamps

Increasing light intensity

<table>
<thead>
<tr>
<th>DLI</th>
<th>8</th>
<th>10</th>
<th>12.5</th>
<th>16</th>
<th>19.5</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
How much light do you need?

Vegetables

• Within bounds: 1% more light $\rightarrow$ 1% more yield

• Lettuce and Herbs
  – 12-17 mol m$^{-2}$ d$^{-1}$
  – For head lettuce
  – greater light $\rightarrow$ tipburn
  – Vertical airflow fans important

• Microgreens
  – 12 mol m$^{-2}$ d$^{-1}$

• Install lighting capacity of 100-200+ µmol m$^{-2}$ s$^{-1}$
Lettuce and Light

• 17 mol m\(^{-2}\) d\(^{-1}\) target
  – Assumes good air flow (paddle fans)
• If > 17 mol m\(^{-2}\) d\(^{-1}\) for 3 days in a row → leaf tip burn
• If poor air flow or concerned about tip burn, set a lower target
• Days to harvest at:
  – 17 mol       35 days
  – 10 mol       60 days
  – 5 mol        119 days!
Low light →
Excessive stem elongation
Leaf Tip Burn (Calcium deficiency at high light)
Microgreens DLI and CO$_2$

Mustard

Mustard ‘Garnet Giant’

Jonathan Allred, Cornell University

*Significance of linear (L) or quadratic (Q) regression: NS, *, **, *** denotes nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.
Microgreens DLI and CO$_2$

*Significance of linear (L) or quadratic (Q) regression: NS, *, **, *** denotes nonsignificant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.

Jonathan Allred, Cornell University
How much light do you need?

Fruiting Crops

• Cucumber
  – 15 mol m\(^{-2}\) d\(^{-1}\) minimum, >30 mol m\(^{-2}\) d\(^{-1}\) optimum

• Tomato
  – 20 mol m\(^{-2}\) d\(^{-1}\) minimum, >30 mol m\(^{-2}\) d\(^{-1}\) optimum

• Sweet Pepper
  – 20 mol m\(^{-2}\) d\(^{-1}\) minimum, >30 mol m\(^{-2}\) d\(^{-1}\) optimum

• Strawberries
  – 17 mol m\(^{-2}\) d\(^{-1}\) minimum, >20 mol m\(^{-2}\) d\(^{-1}\) optimum

• Install lighting capacity of 100-200+ \(\mu\)mol m\(^{-2}\) s\(^{-1}\)
How much light do you need?

Fruiting Crops

• Require daily dark period of 4-6 hours
• Continuous light causes physiological disorders
  – Leaf chlorosis
  – Reduced plant size
  – Reduced yield
• Install lighting capacity of 100-200+ μmol m\(^{-2}\) s\(^{-1}\)
Strategies for determining target light intensity

(Target DLI - *Minimum ambient DLI) / Photoperiod
= Hourly LI mol/m²/hr

Hourly LI X 1,000,000 µmol/mol / 3,600 s/hr
= Target PPFD µmol/m²/s

*Minimum ambient DLI

• This could be the actual lowest DLI based on weather station data
• Lowest DLI except in the 10% most extreme cases
• Or based on monthly average calendar
Strategies for determining target light intensity

Example: **Tomato**, 18 hour photoperiod
Target DLI 20 mol/m²/d, min. amb. DLI 5 mol/m²/d

\[
\text{(Target DLI - Minimum ambient DLI) / Photoperiod}
\]

\[
= \text{Hourly LI mol/m²/hr}
\]

\[
(20 \text{ mol/m²/d } - 5 \text{ mol/m²/d } / 18) = 0.83 \text{ mol/m²/hr}
\]

\[
(0.83 \text{ mol/m²/hr}) \times (1,000,000 \text{ µmol/mol}) / (3,600 \text{ s/hr}) = 231 \text{ µmol/m²/s}
\]
Outline

• How much light do you have?
• How much light do you need?
• **Cost to buy/operate lights**
• Lighting control
Considerations when choosing new lights

• Wall-plug efficacy
• Initial cost ($/fixture x # of fixtures)
• Lifespan (often reported to 70% output)
• Bulb replacement cost
• Installation cost
• Shading of fixture
• Uniformity of light plan
• Wavelength/Light quality?
### Lamp Life L70 (to 70% output)

<table>
<thead>
<tr>
<th>Bulb Type</th>
<th>Life (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent</td>
<td>10,000</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>20,000</td>
</tr>
<tr>
<td>High Pressure Sodium</td>
<td>30,000</td>
</tr>
<tr>
<td>LED</td>
<td>50,000</td>
</tr>
</tbody>
</table>

- Bulbs can be replaced for fluorescent/HID but not for LED.
- May make economical sense to replace bulbs/lights before L70 is reached.
## Highest measured efficacies (so far)

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>Power consumption (W)</th>
<th>PAR flux (μmol/s)</th>
<th>PAR efficacy (μmol/J)</th>
<th>PAR efficacy (mol/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INC</td>
<td>102.4</td>
<td>32.8</td>
<td>0.32</td>
<td>1.15</td>
</tr>
<tr>
<td>CFL</td>
<td>61.4</td>
<td>54.6</td>
<td>0.89</td>
<td>3.20</td>
</tr>
<tr>
<td>LED (INC replacement)</td>
<td>17.2</td>
<td>23.9</td>
<td>1.39</td>
<td>5.00</td>
</tr>
<tr>
<td>HPS (single ended)</td>
<td>700</td>
<td>1,092</td>
<td>1.56</td>
<td>5.62</td>
</tr>
<tr>
<td>HPS (double ended)</td>
<td>1,234</td>
<td>1,962</td>
<td>1.59</td>
<td>5.72</td>
</tr>
<tr>
<td>LED (bar)</td>
<td>214</td>
<td>511</td>
<td>2.39</td>
<td>8.60</td>
</tr>
</tbody>
</table>

A.J. Both Rutgers University
Comparing Efficacy of Greenhouse Lighting Fixtures

• Neil Mattson, David de Villiers, Lou Albright, Cornell University
• A.J. Both, Rutgers University
<table>
<thead>
<tr>
<th>Fixture</th>
<th>Power (Watts)</th>
<th>Par Flux / Light Output (µmol/s)</th>
<th>Wall-plug Efficacy (mol/kWh)</th>
<th>Cost ($ / fixture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR Source 1000W DE HPS</td>
<td>1077</td>
<td>1712</td>
<td>5.72</td>
<td>$407</td>
</tr>
<tr>
<td>Gavita Pro 600W SE HPS</td>
<td>700</td>
<td>1092</td>
<td>5.62</td>
<td>$294</td>
</tr>
<tr>
<td>Heliospectra LX602-G LED (100% on R/W/B)</td>
<td>649</td>
<td>772</td>
<td>4.27</td>
<td>$1,849</td>
</tr>
<tr>
<td>Illumitex PowerHarvest W 10 Series LED</td>
<td>510</td>
<td>872</td>
<td>6.16</td>
<td>$1,299</td>
</tr>
<tr>
<td>LumiGrow Pro 650™ LED (100% on R/W/B)</td>
<td>566</td>
<td>764</td>
<td>4.86</td>
<td>$1,369</td>
</tr>
<tr>
<td>Philips GreenPower LED Toplighting DR/B – Med. B</td>
<td>216</td>
<td>516</td>
<td>8.60</td>
<td>$500</td>
</tr>
</tbody>
</table>

Fixtures from 2016
Cost data, from online July 2016.
Always check with supplier for current cost and bulk pricing.
How much area can one fixture light?

Calculating by dividing light output (µmol/s) by target instantaneous light (µmol m\(^{-2}\) s\(^{-1}\))

Example: PAR Source/Agrosun DE 1000 W
- Light output: \(1712\ \mu\text{mol/s}\)
- Target: \(200\ \mu\text{mol m}^{-2}\ \text{s}^{-1}\)

\[
1712 / 200 = 8.56 \text{ m}^2
\]

\(\Rightarrow\) \(92\ \text{ ft}^2\)

Also consider mounting height and light pattern.
<table>
<thead>
<tr>
<th>Fixture</th>
<th>Par Flux / Light Output (µmol/s)</th>
<th>Square feet coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR Source 1000W DE HPS</td>
<td>1712</td>
<td>92</td>
</tr>
<tr>
<td>Gavita Pro 600W SE HPS</td>
<td>1092</td>
<td>59</td>
</tr>
<tr>
<td>Heliospectra LX602-G LED (100% on R/W/B)</td>
<td>772</td>
<td>42</td>
</tr>
<tr>
<td>Illumitex PowerHarvest W 10 Series LED</td>
<td>872</td>
<td>47</td>
</tr>
<tr>
<td>LumiGrow Pro 650™ LED (100% on R/W/B)</td>
<td>764</td>
<td>41</td>
</tr>
<tr>
<td>Philips GreenPower LED Toplighting DR/B – Med. B</td>
<td>516</td>
<td>28</td>
</tr>
</tbody>
</table>
Electricity cost for 1 fixture per year

\[
\frac{\text{Power (Watts) x hours on per year}}{1000} = \text{kWh / year}
\]

Example: \(\frac{(1077 \text{ W} \times 2592 \text{ hrs})}{1000} = 2,791 \text{ kWh / year}\)

\[2,791 \text{ kWh/yr} \times \$0.105 \ (\text{cost of kWh}) = \$293 / \text{yr electricity}\]
Electricity cost per square foot

Annual electricity cost for 1 fixture divided by number of square feet lit

Example: PAR Source/Agrosun DE 1000 W

- Electricity cost $293 / yr
- Square feet lit 92 ft$^2$

$293 / 92 = \$3.18 / \text{ft}^2 / \text{yr}$
Lamps on for 2592 hrs/yr  
10% loss from edge effects  
Target light: 200 µmol m\(^{-2}\) s\(^{-1}\)  
Illumitex PowerHarvest 10 Series W fixture
**Neil’s calculator: fixtures needed and electricity costs**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td><strong>Calculations</strong> (don’t modify these boxes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>4,047</td>
<td>Square meters to light (note 1 square meter = 10.7639 square feet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>510</td>
<td>Lamp power consumption (W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>929</td>
<td>Lamps needed without edge effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1,033</td>
<td>Lamps needed with edge effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>5</td>
<td>Daily light integral (mol/m²/day PAR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1,364,237</td>
<td>kWh of electricity to light this many lamps for the given number of hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>$143,245</td>
<td>electricity cost ($/area in cell A8/yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>$3.29</td>
<td>electricity cost ($/sf/yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td><em>Note</em> placement of lamps should be determined by a lighting professional to optimize</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Available at: http://cea.cals.cornell.edu/
## Lighting 1 acre greenhouse

<table>
<thead>
<tr>
<th>Fixture</th>
<th>Fixtures to light 1 acre</th>
<th>Cost of fixtures ($)</th>
<th>Fixture cost ($/sf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR Source 1000W DE HPS</td>
<td>473</td>
<td>$192,511</td>
<td>$4.42</td>
</tr>
<tr>
<td>Gavita Pro 600W SE HPS</td>
<td>742</td>
<td>$218,148</td>
<td>$5.01</td>
</tr>
<tr>
<td>Heliospectra LX602-G LED (100% on R/W/B)</td>
<td>1,049</td>
<td>$1,939,601</td>
<td>$44.53</td>
</tr>
<tr>
<td>Illumitex PowerHarvest W 10 Series LED</td>
<td>929</td>
<td>$1,206,771</td>
<td>$27.70</td>
</tr>
<tr>
<td>LumiGrow Pro 650™ LED (100% on R/W/B)</td>
<td>1,060</td>
<td>$1,451,140</td>
<td>$33.31</td>
</tr>
<tr>
<td>Philips GreenPower LED Toplighting DR/B –</td>
<td>1,569</td>
<td>$784,500</td>
<td>$18.01</td>
</tr>
<tr>
<td>Medium B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fixtures from 2016

Lamps on for 2592 hrs/yr

Target light: 200 µmol m\(^{-2}\) s\(^{-1}\)
# Lighting 1 acre greenhouse

<table>
<thead>
<tr>
<th>Fixture</th>
<th>kWh electricity (1 yr.)</th>
<th>Electricity cost (1 yr.)</th>
<th>Electricity cost ($/sf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR Source 1000W DE HPS</td>
<td>1,320,965</td>
<td>$138,701</td>
<td>$3.18</td>
</tr>
<tr>
<td>Gavita Pro 600W SE HPS</td>
<td>1,345,067</td>
<td>$141,232</td>
<td>$3.24</td>
</tr>
<tr>
<td>Heliospectra LX602-G LED (100% on R/W/B)</td>
<td>1,769,370</td>
<td>$185,784</td>
<td>$4.27</td>
</tr>
<tr>
<td>Illumitex PowerHarvest W 10 Series LED</td>
<td>1,226,889</td>
<td>$128,823</td>
<td>$2.96</td>
</tr>
<tr>
<td>LumiGrow Pro 650™ LED (100% on R/W/B)</td>
<td>1,554,593</td>
<td>$163,232</td>
<td>$3.75</td>
</tr>
</tbody>
</table>

Fixtures from 2016
Lamps on for 2592 hrs/yr  Target light: 200 µmol m⁻² s⁻¹
How Many Light Fixtures Do I Need?

Thinking of adding or upgrading supplemental lights in your greenhouse? This alert will walk you through estimating how many light fixtures you need and their electricity cost.
Greenhouse lighting plan from lighting professionals

Example: www.pllight.com
Performance of baby leaf greens under HPS vs. LED during a 1-year period

- **LED**: Philips GreenPower LED toplighting model 9290-009-799, Deep Red/Blue
- **HPS**: Gavita Pro 6/750 FLEX
- Greenhouse with supplemental light to 17 mol·m⁻²·d⁻¹
- Arugula, kale, lettuce
  - Ca. 17 day crop cycle

Kale Harbick, David de Villiers, Jonathan Allred, Neil Mattson
Preliminary results

Arugula 'Astro'

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HPS</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>LED</td>
<td>0.9</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Relative Fresh weight (% HPS)
Preliminary results

Kale 'Red Russian'

Relative Fresh weight (% HPS)

- June
- July
- Aug.
- Sept.
- Oct.
- Nov.

Comparison between HPS and LED treatments.
Outline

• How much light do you have?
• How much light do you need?
• Cost to buy/operate lights
• Lighting control
Consistent DLI = consistent growth

• Why is consistency important?
  – Growers
    • Predictable yields
    • Sales contracts
    • Predictable labor
  – Research
    • Reproducibility
Light Control Strategies for photosynthetic light

- Time clock
- Instantaneous thresholds light/shade
- Target daily light integral
Time clock

• Lights on for set time each day, often from:
  – October–March (North)
  – November-February (South)

• Manually turn off during “sunny” days?

Example

• Lights on 12 hours/day (6am-10am, 4pm-12am)
• 100 µmol m\(^{-2}\) s\(^{-1}\) x 12 hrs → 4.32 mol m\(^{-2}\) d\(^{-1}\)
Light data is from a typical meteorological year (TMY)
70% light transmission
Purple line: target DLI lettuce; Yellow line: target DLI many floriculture crops
Light data is from a typical meteorological year (TMY)
70% light transmission
Purple line: target DLI lettuce; Yellow line: target DLI many floriculture crops
Time clock

• Pros
  – No light sensors or computer control required

• Cons
  – No control over DLI
  – Over light (wasted energy)
  – Under light (reduced yield/quality)
  – Difficult for crop scheduling
Instantaneous thresholds for light and shade

- Computer control system
- Light sensor
  - Location?
    - Should be inside at plant canopy height

Example

- $< 200 \text{ \mu mol m}^{-2} \text{ s}^{-1}$ for 10 mins $\rightarrow$ Lights on
- $> 300 \text{ \mu mol m}^{-2} \text{ s}^{-1}$ for 10 mins $\rightarrow$ Lights off
- $> 600 \text{ \mu mol m}^{-2} \text{ s}^{-1}$ for 10 mins $\rightarrow$ Shade closed

Continue light in evening until DLI target met
Instantaneous thresholds for light and shade

- Pros
  - Target daily light integral can be met
  - Allows consistent crop scheduling
- Cons
  - May have excess light costs from times when over-lit or over-shaded
Target Daily Light Integral

- Light and Shade System Implementation (LASSI)
- Lou Albright, Cornell University

- Predicts natural light accumulation based on first few hours after sunrise
  - Lights on if predicted sunlight is insufficient
  - Deploys shades if predicted sunlight is too much

- Light/shade decisions made at ½ hour time steps
  - Delays shading when possible to avoid over shading
  - Lighting to take advantage of nighttime off-peak electricity rates when possible
Daily supplemental light
DLI without moveable shade
Supplemental light + moveable shade curtains
Electrical savings comparison of supplemental lighting control systems in greenhouse environments

K. Harbick, L.D. Albright, and N.S. Mattson
Cornell University

Written for presentation at the 2016 ASABE Annual International Meeting
Sponsored by ASABE
Orlando, Florida
July 17-20, 2016

Abstract. Greenhouse vegetable production can be optimized by properly controlling the conditions in the growing environment. Supplemental light and shade systems in a CEA greenhouse are typically controlled using manual control or time-clock control. Previous work describes a Light and Shade System Implementation (LASSI) that controls lighting to a consistent daily light integral (DLI) of
## Lighting Energy Savings

<table>
<thead>
<tr>
<th>City</th>
<th>Lettuce (17 mol/m²/d)</th>
<th>Tomato (25 mol/m²/d)</th>
<th>Floriculture (12 mol/m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elmira, NY</td>
<td>24%</td>
<td>20%</td>
<td>28%</td>
</tr>
<tr>
<td>Helena</td>
<td>28%</td>
<td>27%</td>
<td>39%</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>28%</td>
<td>27%</td>
<td>38%</td>
</tr>
<tr>
<td>Phoenix</td>
<td>56%</td>
<td>39%</td>
<td>69%</td>
</tr>
</tbody>
</table>

Data from Harbick et al., 2016
Why? Ex: controller performance MSP

• Threshold control has more aggressive shading and does not anticipate sunlight → ↑ use of supplemental lighting

• Threshold control → DLIs above/below target