Greenhouse CO$_2$ concentrations – are we limiting growth?

Jennifer Boldt and James Altland
USDA-ARS
Current USDA research

• Energy efficiency
• Lighting and nutrition
• CO₂
• Non-chemical weed control
• Rice hull biochar
• Silicon
Photosynthesis

- Light Energy
- Oxygen
- Carbon dioxide
- Water
Sensing the greenhouse environment

- We “feel” temperature
- We “see” light
- We “see”/“feel” water (...and fertilizers)
- But we can’t see, smell, touch, taste, or hear CO$_2$
- Out of sight, out of mind?
August 1958 - August 2016

Atmospheric CO2

August CO2 | Year Over Year | Mauna Loa Observatory

- August 2016: 402.24 ppm
- August 2015: 399.00 ppm
- August 2014: 397.21 ppm

CO2-earth Featuring Scripps data of September 5, 2016
Potential benefits of CO$_2$ enrichment

- Earlier flowering
- Larger flowers
- Better branching
- Thicker stems
- Greater plant mass

![Comparison of plant weights](image)

J. Frantz
How similar are CO$_2$ levels inside vs. outside the greenhouse?

- CO$_2$ moves from high to low concentration
- When plants photosynthesize, they take up CO$_2$
- As a result, a layer of low [CO$_2$] air forms around plants
- This is especially common during periods of high light and moderate temperature
  - Sunny days in winter when the greenhouse is sealed tightly to increase heating efficiency
  - Even in a well-ventilated greenhouse, [CO$_2$] will decline in/around the plant canopy
CO$_2$ decline in a greenhouse: an example

GH volume: 43,750 ft$^3$
GH footprint: 2500 ft$^2$

Assumptions:
• 400 ppm starting CO$_2$
• No air exchange
• Average light use efficiency
• Only one layer of plants receiving direct sunlight (no baskets)

Ending CO$_2$ concentration after 1 h, at the following PAR concentrations:

Even so, it shows that CO$_2$ levels can decline dramatically in a tightly sealed greenhouse on a sunny day!

<table>
<thead>
<tr>
<th>PAR (µmol·m$^{-2}·s^{-1})$</th>
<th>CO$_2$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 (winter)</td>
<td>392</td>
</tr>
<tr>
<td>200 (cloudy)</td>
<td>384</td>
</tr>
<tr>
<td>300 (cloudy + SL)</td>
<td>376</td>
</tr>
<tr>
<td>500 (part sun)</td>
<td>360</td>
</tr>
<tr>
<td>1000 (sunny)</td>
<td>320</td>
</tr>
</tbody>
</table>
What impact can a decline in $[\text{CO}_2]$ have on photosynthesis?

Photosynthesis:
800 ppm: 77% $P_{\text{max}}$; 160% of $P_n$ at 400 ppm
400 ppm: 50% $P_{\text{max}}$
240 ppm: 28% $P_{\text{max}}$; 59% of $P_n$ at 400 ppm

Photosynthesis:
800 ppm: 71% $P_{\text{max}}$; 161% of $P_n$ at 400 ppm
400 ppm: 45% $P_{\text{max}}$
240 ppm: 26% $P_{\text{max}}$; 58% of $P_n$ at 400 ppm
What impact can a decline in [CO₂] have on photosynthesis?

• We often think in terms of adding CO₂ to attain above-ambient levels
• However, we may be limiting plant growth without even realizing it
• Increasing CO₂ levels can allow us to further reap the benefits of supplemental lighting
• It can also allow us to grow plants cooler or warmer than optimal without negatively impacting plant growth
**PhotoSim: Leaf Photosynthesis Model for Floriculture Crops**

Jennifer Boldt, USDA-ARS; Paul Fisher, University of Florida; John Erwin, University of Minnesota

Thanks to American Floral Endowment for providing research funding

### Enter your climate conditions

<table>
<thead>
<tr>
<th>Current conditions</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crop Species</strong></td>
<td>Impatiens</td>
</tr>
<tr>
<td><strong>Current light level at canopy</strong></td>
<td>300 µmol m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td><strong>Current carbon dioxide (CO(_2)) level in ppm</strong></td>
<td>400 ppm</td>
</tr>
<tr>
<td><strong>Current leaf temperature</strong></td>
<td>70 F</td>
</tr>
</tbody>
</table>

### Changed conditions

| Which climate factor would you like to change? | CO\(_2\) (no change in other factors) |
| New level for CO\(_2\)? | 240 ppm |

### Photosynthetic Efficiency

**Graph 1:**
- Relative Growth Rate vs. Light Level (µmol m\(^{-2}\) s\(^{-1}\))
- Graphs showing growth rates under varying light levels.

**Graph 2:**
- Relative Growth Rate vs. CO\(_2\) (ppm)
- Graphs showing growth rates under varying CO\(_2\) levels.

**Graph 3:**
- Relative Growth Rate vs. Temperature (F)
- Graphs showing growth rates under varying temperature conditions.

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Environmental Conditions

**Graph:**
- Comparison between current and changed environmental conditions.
[CO$_2$] concentration in growth chamber

Fluorescent/incandescent lamps (DLI = 35 mol·m$^{-2}·d^{-1}$)
72 °F ADT
### [CO$_2$] in a greenhouse

**Graph:**
- X-axis: Date range from April 14, 2016, to June 13, 2016.
- Y-axis: CO$_2$ concentration in ppm.

#### CO$_2$ Concentration Summary

<table>
<thead>
<tr>
<th></th>
<th>Day</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>227 ± 32</td>
<td>292 ± 27</td>
</tr>
<tr>
<td>May</td>
<td>261 ± 35</td>
<td>296 ± 19</td>
</tr>
<tr>
<td>June</td>
<td>288 ± 16</td>
<td>304 ± 16</td>
</tr>
</tbody>
</table>

#### Table of CO$_2$ Concentration and Temperature

<table>
<thead>
<tr>
<th></th>
<th>Day</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Avg.</td>
</tr>
<tr>
<td>April</td>
<td>260</td>
<td>297</td>
</tr>
<tr>
<td>May</td>
<td>260</td>
<td>297</td>
</tr>
<tr>
<td>June</td>
<td>260</td>
<td>297</td>
</tr>
</tbody>
</table>
125 $\mu$mol m$^{-2}$ s$^{-1}$ PAR
(5.4 mol m$^{-2}$ d$^{-1}$)

250 $\mu$mol m$^{-2}$ s$^{-1}$ PAR
(10.8 mol m$^{-2}$ d$^{-1}$)

uncontrolled CO$_2$
366 ± 24

400 ppm CO$_2$
403 ± 3

800 ppm CO$_2$
800 ± 3
LOW = 125 µmol m\(^{-2}\) s\(^{-1}\) PAR; HIGH = 250 µmol m\(^{-2}\) s\(^{-1}\) PAR
LOW = 125 $\mu$mol m$^{-2}$ s$^{-1}$ PAR; HIGH = 250 $\mu$mol m$^{-2}$ s$^{-1}$ PAR
LOW = 125 µmol m\(^{-2}\) s\(^{-1}\) PAR; HIGH = 250 µmol m\(^{-2}\) s\(^{-1}\) PAR
LOW = 125 µmol m⁻² s⁻¹ PAR; HIGH = 250 µmol m⁻² s⁻¹ PAR
When would be the best time to add CO$_2$?

Factors to consider:

- Type of plant (based on photosynthesis type)
- Ventilation schedule
- Use of supplemental lighting
- Greenhouse temperature
Photosynthetic pathways

- **C3 plants (most greenhouse crops)**
  - CO₂ uptake/fixation occurs during day
  - CO₂ supplementation ideal in early morning and throughout day
  - Typically see a 15-30% increase in growth with elevated CO₂

- **C4 (adapted to hot, dry environments)**
  - Stomates partially closed during day
  - Utilize a CO₂-concentrating mechanism in leaves
  - Less responsive to CO₂ supplementation (0-10%)
  - Indirect effects – increased WUE

- **CAM (orchids, cacti, succulents, bromeliads)**
  - Stomates closed during day, open at night
  - Therefore, they will respond best to CO₂ supplementation at night
Controlled:
63 °F (17.2 °C)
500 ppm CO₂

Uncontrolled:
65 °F (18.3 °C)
CO₂ allowed to drift

<table>
<thead>
<tr>
<th></th>
<th>Greenhouse 1</th>
<th>Greenhouse 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂:</td>
<td>500 ppm</td>
<td>“Ambient” (&lt; 400 ppm)</td>
</tr>
<tr>
<td>Temperature:</td>
<td>63 °F (17.2 °C)</td>
<td>65 °F (18.3 °C)</td>
</tr>
<tr>
<td>Cost:</td>
<td>$110/month</td>
<td>$231/month</td>
</tr>
<tr>
<td>(lots of assumptions)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon used:</td>
<td>408 lb/month</td>
<td>1,210 lb/month</td>
</tr>
<tr>
<td>(CO₂ + propane)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fresh weight (grams per plant)**

- Not controlled: [Graph showing low fresh weight]
- Controlled: [Graph showing high fresh weight]

**Leaves per plant**

- Not controlled: [Graph showing low leaf count]
- Controlled: [Graph showing high leaf count]
How can we alleviate CO$_2$ depletion?

• If not adding supplemental CO$_2$
  • Increase air exchange rate (this is a balance with heating costs)
  • Provide fans to mix the air and reduce the formation of a low-CO$_2$ zone around plants

• Supplemental CO$_2$
  • 600-1000 ppm is a good range
  • Above 1000 ppm, additional returns in growth will be small
  • Remember, too much of a good thing can be bad!
  • High CO$_2$ can cause plant injury
  • Ideal range for plants is below that which begins to impact human health (> 3000 ppm)
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