Development of Bioregenerative Life Support for Longer Missions:

When Can Plants Begin to Contribute to Atmospheric Management?

Raymond M. Wheeler
Surface Systems Office
NASA Kennedy Space Center
Florida, USA
raymond.m.wheeler@nasa.gov
Plant Photosynthesis

\[ \text{CO}_2 + 2\text{H}_2\text{O}^* \xrightarrow{\text{light}} (\text{CH}_2\text{O}) + \text{H}_2\text{O} + \text{O}_2^* \]

Edible (food)

Inedible (waste)

For carbohydrate (CH\textsubscript{2}O) type crops, Assimilation Quotients (AQs) are \(~1.0\) (mol CO\textsubscript{2} / mol O\textsubscript{2})
For fat producing crops, AQ’s are lower, e.g., 0.8-0.9 (Tako et al., 2010)
Nitrogen, NH\textsubscript{4} vs. NO\textsubscript{3}, can also affect AQ, with NO\textsubscript{3}, resulting in lower AQs (Bloom et al., 1989)
Factors Affecting Plant Photosynthesis and Growth

• Water and Nutrients—Assume these will be optimized but there are challenges for micro and reduced gravity settings.

• Temperature—Assume this will be optimized for the given crop species.

• Carbon Dioxide—Optimal range for C$_3$ crops probably 1000 to 2000 ppm (0.1 – 0.2 kPa); chambers open to cabin air might be exposed to “super-elevated CO$_2$”, which can cause some problems.

• Light
  1) Light must be intercepted by the leaves or photosynthetic organs. Light on the floors or walls does no good!
  2) Most crops show a linear response of photosynthesis to light across the lower light range.
Effect of Light on Crop Yield
(Data from NASA Biomass Production Chamber)

Studies Include:
- Wheat
- Soybean
- Potato
- Lettuce
- Tomato

Canopy CO\textsubscript{2} Uptake / O\textsubscript{2} Production
(20 m\textsuperscript{2} Soybean Stand)

CO₂ Exchange Rates of Soybean Stands

Wheeler et al. 2006. EcoEngineering.
Fig. 6: CO₂ Exchange Rate vs. CO₂ Concentration

- CO₂ Compensation Point
- Optimal Concentration

Mathematical equation: $y = 0.15x - 14.6$

- $R^2 = 0.99$

Effect of Light on Photosynthesis

### Area for CO₂ Removal / O₂ Production for One Person

<table>
<thead>
<tr>
<th>Radiation Use Efficiency</th>
<th>PPF (µmol m⁻² s⁻¹)</th>
<th>250</th>
<th>500</th>
<th>750</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g mol⁻¹ PAR)</td>
<td>Daily Light Integral (mol m⁻² d⁻¹)</td>
<td>14.4</td>
<td>28.8</td>
<td>43.2</td>
<td>57.6</td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td>94.4</td>
<td>47.2</td>
<td>31.5</td>
<td>23.6</td>
</tr>
<tr>
<td>0.75</td>
<td></td>
<td>63.0</td>
<td>31.5</td>
<td>21.0</td>
<td>15.7</td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td>47.2</td>
<td>23.6</td>
<td>15.7</td>
<td>11.8</td>
</tr>
</tbody>
</table>

* Biomass production data assuming Assimilation Quotient or AQ = 1.0 (i.e., biomass all CH₂O)
** Assumes daily O₂ requirement of 830 g / person-day (NASA SPP 30262)
*** Assumes a 16 h light / 8 h dark photoperiod
Area Per Person for $\text{O}_2$

Number of Plant Chambers for One Person’s Oxygen

(with 500 \mu mol m^{-2} s^{-1} PAR and 0.75 RUE)

- VEGGIE (0.15 m$^2$) → 210
- Salad Machine (2.0 m$^2$) → 16
- Plant Module (10 m$^2$) → 3
A “Salad Machine” for Space Station and Transit Missions

One Human’s Oxygen from 11 m² of Wheat!

Edeen and Barta. 1995. JSC No. 33636
Harvest Index (%) Ranges for Some Crops*

If inedible biomass recycled aerobically, this will consume some $O_2$. Hence high harvest index plants benefit gas exchange for life support.

* Data gathered from controlled environment tests at KSC Breadboard Project and CELSS literature.

Role of Bioregenerative Components for Future Missions

Short Durations (early missions)  Longer Durations  Autonomous Colonies

Stowage and Physico-Chemical

Bioregenerative

Plant Growing Area

~1-5 m² total  ~10-25 m² / person  ~50 m² / person

Conclusions

- Bioregenerative life support components will likely expand as mission distances and durations increase.
- Near-term missions can benefit from the production of fresh foods to supplement the crews’ diet.
- Contributions of plants to O$_2$ production and CO$_2$ removal will be minimal with small, food production systems.
- A plant production module in the range of 10 m$^2$ could begin to contribute to O$_2$ production.
- The O$_2$ production and CO$_2$ removal by plants is strongly affected by light.
- Radiation (light) use efficiency (RUE) is an important aspect to plant performance in future life support systems. Levels up to 1.0 g biomass / mol of photons have been documented and should be achievable.
Thank you!

Astronaut Steve Swanson
Harvesting Lettuce on the ISS
Light, Productivity, and Crop Area Requirements

- **Area Required (m² / person)**
- **Productivity (g m⁻² day⁻¹)**

**Graph Details**:
- **Light (mol m⁻² day⁻¹)**
- **Area**: Bright Sunny Day on Mars
- **Productivity**: Bright Sunny Day on Earth

- **Axes**:
  - Vertical: Area Required (m² / person)
  - Horizontal: Light (mol m⁻² day⁻¹)
  - Productivity (g m⁻² day⁻¹)