Growing Food for Space and Earth: NASA’s Contributions to Vertical Agriculture

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Plants for “Bioregenerative” Life Support

HUMANS

food (CH₂O) + O₂ → CO₂ + H₂O

Clean Water → Waste Water

Metabolic Energy

PLANTS

food (CH₂O) + O₂* + H₂O ← CO₂ + 2H₂O*

Clean Water ← Waste Water

Light
Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat)
- High harvest index (edible / total biomass)
- Horticultural considerations
  - planting, watering, harvesting, pollination, propagation
- Environmental considerations
  - lighting, temperature, mineral nutrition, CO₂
- Processing requirements
- Dwarf or low growing types
Recirculating Hydroponics with Crops

- Conserve Water & Nutrients
- Eliminate Water Stress
- Optimize Mineral Nutrition
- Facilitate Harvesting

Wheat / Utah State
Soybean KSC
Sweetpotato Tuskegee
Rice / Purdue

Root Zone Crops in Nutrient Film Technique (NFT)

Evapotranspiration from Plant Stand (potato)

Fig. 7

First Study
655 μmol m$^{-2}$ s$^{-1}$ PAR

Second Study
865 μmol m$^{-2}$ s$^{-1}$ PAR

Water, Nutrient, and pH Control

High Yields from High Light and CO$_2$ Enrichment

Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce - Exceeded Commercial Yield Models

Potential Energy Conversion to Biomass


Assuming a maximum 12% conversion efficiency from PAR to biomass:

\[ 1.6 \text{ g dry mass} / \text{ mol PAR} \]

### Some Upper Limits to Energy Conversion and Productivity

#### Field Crops Observations

<table>
<thead>
<tr>
<th>Crop</th>
<th>Productivity</th>
<th>Photosynthetic Energy Conversion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g DM m(^{-2}) d(^{-1}))</td>
<td>(%)</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td>43</td>
<td>7.0 (UK)</td>
</tr>
<tr>
<td>Maize</td>
<td>40</td>
<td>6.8 (US)</td>
</tr>
<tr>
<td>Sudan Grass</td>
<td>52</td>
<td>6.0 (US)</td>
</tr>
</tbody>
</table>

#### CEA NASA Studies

<table>
<thead>
<tr>
<th>Crop</th>
<th>Productivity</th>
<th>Radiation Use Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g DM m(^{-2}) d(^{-1}))</td>
<td>(g DM mol(^{-1}) PAR)</td>
</tr>
<tr>
<td>Wheat</td>
<td>61</td>
<td>1.44 Utah State(^{3})</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>0.67 Utah State(^{4})</td>
</tr>
<tr>
<td>Potato (12(\Rightarrow)24 h photoper.)</td>
<td>45</td>
<td>0.97 Univ. Wisc.(^{5})</td>
</tr>
<tr>
<td>(12 h photoper. only)</td>
<td>38</td>
<td>1.15 Univ. Wisc.(^{5})</td>
</tr>
</tbody>
</table>

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2. Original data based on total solar irradiance; table data reflect efficiency based on PAR (400-700 nm)
Closed Systems Issues
Canopy CO$_2$ Uptake / O$_2$ Production (20 m$^2$ Soybean Stand)

CO$_2$ Exchange Rates of Soybean Stands

- Photosynthesis
- Night Respiration
- Canopy Lodged
- Harvest
- High Temp Event

Wheeler et al., 2004. EcoEngineering.
Effect of CO$_2$ Concentration on Photosynthesis (potato)

**Fig. 6**

Similar results for wheat and soybean

**CO$_2$ Compensation Point**

\[ y = 0.15x - 14.6 \]

\[ R^2 = 0.99 \]

(97)

Canopy / Stand Ethylene Production

A

Wheat
Soybean
Lettuce
Potato

Ethylene Concentration (ppb)

Days After Planting

B

Wheat
Soybean
Lettuce
Potato

Biomass (kg)

Days After Planting

C

Wheat
Soybean
Lettuce
Potato

Ethylene / Biomass (ppb / kg)

Days After Planting

Ethylene Production - Tomato cv. Reimann Philipp

Ethylene in Closed Systems

Epinastic Wheat Leaves at ~120 ppb

Epinastic Potato Leaves at ~40 ppb
NASA’s Biomass Production Chamber (BPC)
An Attempt at Vertical Agriculture!

External View - Back

20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers

Control Room

Hydroponic System
NASA’s Biomass Production Chamber (BPC)
Wheat

(*Triticum aestivum*)

planting

harvest
Soybean
(Glycine max)
Lettuce

(Lactuca sativa)
Potato
(Solanum tuberosum)
Automation Technologies for CEA

ALSARM Robot in NASA Biomass Production Chamber
Effect of Light on Crop Yield

Studies Include:
- Wheat (4)
- Soybean (4)
- Potato (4)
- Lettuce (3)
- Tomato (2)

Photosynthetically Active Radiation (mol m\(^{-2}\) d\(^{-1}\))

Crop Yield (g m\(^{-2}\) d\(^{-1}\))

Electrical Power for BPC

- 96 400-W HPS lamps with dimming ballasts
- Two 30 kW blowers (400 m$^3$ min$^{-1}$)
- Two 15-ton (52 kW) chillers for cooling
- 100 kW water heater for air re-heat

→ Not designed for energy efficiency!!
# The Importance of Lighting

---Electric Lamp Options---

<table>
<thead>
<tr>
<th>Lamp Type</th>
<th>Conversion Efficiency</th>
<th>Lamp Life* (hrs)</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent/Tungsten**</td>
<td>5-10%</td>
<td>2000</td>
<td>Intermd.</td>
</tr>
<tr>
<td>Xenon</td>
<td>5-10%</td>
<td>2000</td>
<td>Broad</td>
</tr>
<tr>
<td>Fluorescent***</td>
<td>20%</td>
<td>5,000-20,000</td>
<td>Broad</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>25%</td>
<td>20,000</td>
<td>Broad</td>
</tr>
<tr>
<td>High Pressure Sodium</td>
<td>30%</td>
<td>25,000</td>
<td>Intermd.</td>
</tr>
<tr>
<td>Low Pressure Sodium</td>
<td>35%</td>
<td>25,000</td>
<td>Narrow</td>
</tr>
<tr>
<td>Microwave Sulfur</td>
<td>35-40%+</td>
<td>?</td>
<td>Broad</td>
</tr>
<tr>
<td>LEDs (red and blue)****</td>
<td>&gt;40%</td>
<td>100,000</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

* Approximate values.

** Tungsten halogen lamps have broader spectrum.

*** For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.

**** State-of-Art Blue and Red LEDs most efficient.
**LED Studies**

Red...photosynthesis  
Blue...photomorphogenesis  
Green...human vision

**Some NASA Related References:**


Solar Collector / Fiber Optics For Plant Lighting

Up to 400 W light delivered to chamber (40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.

2 m² of collectors on solar tracking drive (SLSL Bldg, NASA KSC)

Nakamura et al. 2010. Habitation
Human Habitats and Crops for Supplemental Food

Habitat Demonstration Unit (HDU) Test 2011

NASA's HDU at Desert Test Site

HGU Test 2012

Plant Atrium or Growing Shelf
Plant Growth on the International Space Station—VEGGIE Plant Chamber.
Some Lessons Learned from NASA CEA / Vertical Ag work

• Over half of maintenance / upkeep time dedicated to nutrient system management
  – If condensate water is retrieved, pay attention to elemental content
• Extensive work for optimizing hydroponic solution replenishment recipes
  – We made no attempts to reduce nitrate in tissue
• Consider ability to reach all sections of the growing area; it was not easy for use to inspect the back of our trays; consider shelf-to-shelf height
• Initially we sanitized hydroponic hardware following crops, but later abandoned in favor of thorough cleaning
• Consider innovative means for improving energy efficiency, e.g., if possible use heat from lamps and power supplies for air “re-heat”
• Worker safety—consider sunglasses for working around bright red and blue LEDs
Agriculture in Space

As we explore sustainable living for space, we will learn more about sustainable living on Earth.