

# NASA's Controlled Environment Agriculture Testing for Space Habitats

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**Abstract:** NASA and other space agencies have an interest in using plants for human life support in space. The plants could provide food and O<sub>2</sub> for the humans, while removing CO<sub>2</sub> and helping purify wastewater. Studies to date have shown that a wide range of crops can be grown in controlled environment conditions envisioned for space. Light is a critical factor both for crop productivity and system power costs, and recent improvements in LEDs make them a preferred lighting option for space. Because space systems would be tightly closed, issues such as ethylene build-up and management must be considered. Ultimately, the costs and reliability of biological life support options must be compared with more conventional life support approaches. Findings to date suggest that about 20-25 m<sup>2</sup> of crops could supply the O<sub>2</sub> for one human, while about 50 m<sup>2</sup> would be required for food (dietary calories).

*Keywords:* bioregenerative, CEA, hydroponics, LED, lighting, photosynthesis

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## 1. INTRODUCTION

Human space travel requires a reliable supply of O<sub>2</sub>, food, water, and methods for managing waste products, such as CO<sub>2</sub>, wastewater, and solid wastes. For short duration missions, this can be accomplished largely with stowage and resupply, but for longer missions, stowage and resupply become increasingly costly. In this case, regenerative technologies for air and water become essential. One approach for this is to grow plants. Through photosynthesis, the plants could remove and chemically reduce CO<sub>2</sub>, while generating O<sub>2</sub> (Galston, 1992). In addition, if you choose edible crops, you could simultaneously produce food. This concept is not new and has been studied since the 1950s, with many of the earlier studies focusing on algae instead of higher plants (Myers, 1954; Nitta and Yamashita, 1985).

Because of the harsh external environment of space, any crop production systems for life support would have to be carried out inside protected, controlled environments, similar to what might be used for growth chambers or plant factories on Earth. Large scale (>20 m<sup>2</sup>) crop production tests for life support systems have been conducted by different space agencies, including the Russian Bios-3 project in Krasnoyarsk (Gitelson et al., 1989), NASA's

Biomass Production Chamber (Wheeler et al., 1996, 2003), the Japanese Controlled Ecological Experiment Facility (CEEF) (Tako et al., 2009), and most recently the Chinese Lunar Palace 1 test (Chen et al., 2014). In addition, smaller scale (< 2 m<sup>2</sup>) plant systems have been tested inside human habitats to simulate what might occur on early missions, where the plants might first be used to provide only supplemental fresh food (MacElroy et al., 1992; Massa et al., 2011).

Some findings from NASA studies to demonstrate crop production in controlled environments for human life support are reviewed here.

## 2. MATERIALS AND METHODS

NASA's Biomass Production Chamber (BPC) provided 20 m<sup>2</sup> of crop growing area separated on four vertically stacked shelves (5 m<sup>2</sup> each) (Fig. 1). Each shelf supported 16 plastic trays (0.31 m<sup>2</sup> per tray), for a total of 64 trays. The atmosphere inside the chamber was closed with the chamber doors typically opened once daily to accommodate environmental and plant measurements. While the doors were closed, atmospheric leakage was approximately 5–10% of the volume per day.

Carbon dioxide (CO<sub>2</sub>) was controlled at 1000 or

1200 ppm (0.10 or 0.12 kPa) during the light cycles, while CO<sub>2</sub> was allowed to accumulate from plant respiration during the dark cycles. When the lamps came on in the morning, CO<sub>2</sub> concentrations quickly drew down to a set point, where controlled injections began (Wheeler et al., 2003). Oxygen (O<sub>2</sub>) concentrations were allowed to vary slightly (from 21% to 23%) but typically remained near 21% (21.0 kPa) due to door openings for maintenance activities. Relative humidity levels were kept near 65%–75% for all studies. The atmospheric closure allowed both biogenic and non-biogenic volatile organic compounds (VOCs) to accumulate over time (Batten et al., 1995), including the gaseous plant hormone ethylene (Wheeler et al., 2004).

All plants were grown hydroponically using a recirculating nutrient film technique (Wheeler et al., 1999). Each of the four growing shelves with 16 trays had one nutrient solution tank and one circulating pump located outside of the chamber, with the headspace of each tank vented back to the chamber. Nutrient solutions returned to the circulation tanks by gravity dependent flow, which should work in fractional g environments such as on the Moon or Mars.

Transpired water was condensed on the cooling coils of the heat-exchange system and passed through ion exchange columns, and then recycled back to the nutrient solution tanks. Nutrient solution volumes were maintained at a constant level either through daily additions of deionized or condensate water. Nutrient solution electrical conductivity was controlled 1.2 dS m<sup>-1</sup> with additions of concentrated stock solutions. Solution pH was controlled to 5.8 using automatic additions of 0.4 M nitric acid. Lighting was provided by 96 400-W lamps using either high pressure sodium (HPS) or metal halide (MH) lamps, or mixtures of the two depending on the crop. Cooling and dehumidification were provided by two copper heat-exchange coils using cold water from two 52-kW chillers. Following each cold coil was a reheat coil supplied with hot water. Air was recirculated continuously with two 40-kW fans, providing about 400 m<sup>3</sup> min<sup>-1</sup>, or about three to four volume exchanges per minute.

### Horticultural techniques

Wheat (*Triticum aestivum* L.) seeds of cvs. Yecora Rojo, Veery 10, or Apogee were sown at a rate of 400 seeds per tray (1600 per m<sup>2</sup>) and germinated with nylon wicks in hydroponic trays. Seedlings were covered with white translucent tray covers for the first 4 d after planting to maintain high humidity and aid establishment. Light was provided with HPS lamps as either constant light (24 h) or a 20-h light /

4-h dark photoperiod. Photosynthetically active radiation (PAR) at the plant canopy level varied depending on the set points for a given study, ranging from 510 to 930 μmol m<sup>-2</sup> s<sup>-1</sup>. In studies using constant light, temperature was maintained at 23°C. For studies using a 20-h light/4-h dark photoperiod, temperatures were maintained at 24°C in the light and 20°C in the dark. Plants were harvested at physiological maturity when heads had lost their green color (77–86 d).

Soybeans (*Glycine max* L. [Merr.] cvs. McCall or Hoyt were germinated in a manner similar to wheat and thinned to four or six plants per tray (12.8 or 19.2 plants m<sup>-2</sup>) (Fig. 1). Light was provided with HPS, MH, or a combination of HPS and MH lamps as a 12-h light/12-h dark or a 10-h light/14-h dark photoperiod. Canopy level PAR ranged from 475 to 815 μmol m<sup>-2</sup> s<sup>-1</sup>, depending on the combination of lamps, and temperatures were controlled to 26°C in the light and 20°C in the dark. Plants were harvested at 90 or 97 d after planting, when nearly all the seeds pods had turned a brown color.



Fig. 1. NASA's Biomass Production Chamber at Kennedy Space Center with soybean crop. Two of the four shelves are shown; the chamber provided 20 m<sup>2</sup> of growing area in a closed atmosphere

Potato (*Solanum tuberosum* L.) cvs. Norland or Denali plantlets were grown in vitro for ca. 28 d and transplanted to flexible, white polyethylene sheets

covering the trays (three plants per tray) and then thinned at 10 d to two plants per tray (6.4 plants m<sup>-2</sup>). Trays were initially covered with white translucent covers for 4 d to promote plantlet establishment. Lighting was provided as a 12-h light / 12-h dark photoperiod, but for one study, the photoperiod was extended to 16-h light/8-h dark at 65 d after planting. Canopy level PAR ranged from 655 to 915 μmol m<sup>-2</sup> s<sup>-1</sup> depending on the combination of HPS and MH lamps. Temperature regimes either used 20°C (light) 16°C (dark) throughout growth, or started with 24°C (light) and 20°C (dark), followed by 20°C (light) and 16°C (dark) after 2–4 weeks age. Plants were harvested at 91 or 105 d after planting (Fig. 2).



Fig. 2. Potato tubers ready for harvest in NASA's Biomass Production Chambers. Plants were grown using nutrient film technique (Wheeler, 2006).

Tomato (*Lycopersicon esculentum* L.) seeds of cv. Reimann Philipp 75/59, a "cherry" type tomato, were germinated using nylon wicks similar to soybean and wheat. Trays were covered with white translucent covers for 5 d after planting to promote seedling establishment, and plants were thinned to two per tray (6.4 plants m<sup>-2</sup>) at 9 d. All plants were grown under HPS lamps with a 12-h light / 12-h dark photoperiod. Canopy level PAR ranged 550–890 μmol m<sup>-2</sup> s<sup>-1</sup> depending on the dimming set-point, and temperatures were maintained at 26°C (light) and 20°C (dark). Fruits were harvested periodically as they ripened to a full red color beginning at 65 d after planting, with the final harvest occurring at 84 or 91 d after planting.

Lettuce (*Lactuca sativa* L.) cv. Waldmann's Green seeds were germinated using nylon wicks similar to soybean, wheat, and tomato. Trays were covered with white translucent covers for 3 d to promote seedling establishment. Plants were thinned to six per tray (19.2 plants m<sup>-2</sup>) at 9 d after planting. Plants

were grown under either HPS or MH lamps with a 16-h light / 8-h dark photoperiod. Canopy level PAR ranged from 280 to 335 μmol m<sup>-2</sup> d<sup>-1</sup>, and temperatures were maintained at a constant 23°C. Plants were harvested at 28 or 30 d after planting.

At harvest, all plant biomass was placed in a ventilated oven and dried at 70°C for at least 72 h until completely dry. For tomato fruit and potato tubers, 100-g subsamples were taken from each tray and oven dried at 70°C. The percent dry mass (DM) from the subsamples was then multiplied by the total fresh mass in each tray to estimate the total fruit or tuber DM.

### 3. RESULTS AND DISCUSSION

Total dry biomass, edible biomass, and water used by the wheat (six crops), soybean (four crops), lettuce (five crops), potato (eight crops), and tomato (two crops) are shown in Table 1.

**Table 1. Yields and water use of multiple crops grown in NASA's Biomass Production Chamber**

Crops	Days	Total Biomass (kg)	Edible Biomass (kg)	Water Used (L)
Wheat	417	236	71	33427
Soybean <sup>1</sup>	374	80	28	27013
Lettuce	114	14	13	4048
Potato	823	480	276	63085
Tomato <sup>1</sup>	171	45	22	16125

<sup>1</sup> One study used on 10 m<sup>2</sup> instead of the normal 20 m<sup>2</sup>.

Yields were highly dependent on photosynthetically active radiation (PAR) provided to the plants (Fig. 3). For example, lettuce was typically grown with a 16 / 8 (light / dark) photoperiod and 300 μmol m<sup>-2</sup> s<sup>-1</sup>, or

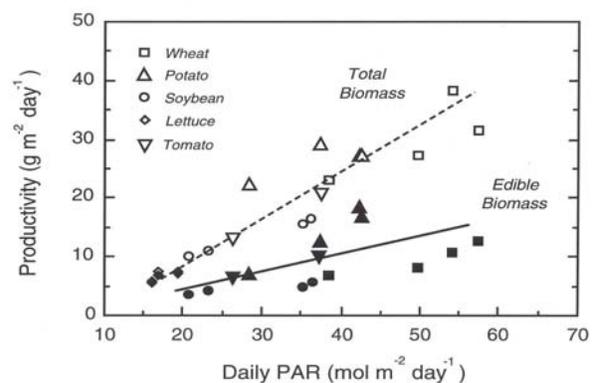


Fig. 3. Dry mass productivity of different crops grown in NASA's Biomass Production Chamber as a function of photosynthetically active radiation—PAR (Wheeler et al., 1996).

about  $17.3 \text{ mol m}^{-2} \text{ d}^{-1}$ , and hence biomass yields were lower than other crops. Total biomass ranged from 23 to  $40 \text{ g m}^{-2} \text{ d}^{-1}$  for wheat, 10 to  $16 \text{ g m}^{-2} \text{ d}^{-1}$  for soybean, 6 to  $8 \text{ g m}^{-2} \text{ d}^{-1}$  for lettuce, 22 to  $33 \text{ g m}^{-2} \text{ d}^{-1}$  for potato, and 13-20  $\text{g m}^{-2} \text{ d}^{-1}$  for tomato (Fig. 3) (Wheeler et al., 2003).

When expressed as productivities, or yield rates, it is apparent that the amount of light directly affects the amount of planted area required to sustain humans for space life support systems. With higher light and higher productivities, less planted area would be required to support one human (Fig. 4; Salisbury, 1991; Wheeler, 2004). Of course this would depend on the species grown; for example grasses such as wheat and rice with vertically inclined leaves can tolerate high instantaneous PAR levels and wheat can even tolerate continuous light, while other crops might require dark periods (e.g., rice, soybean, and potato).

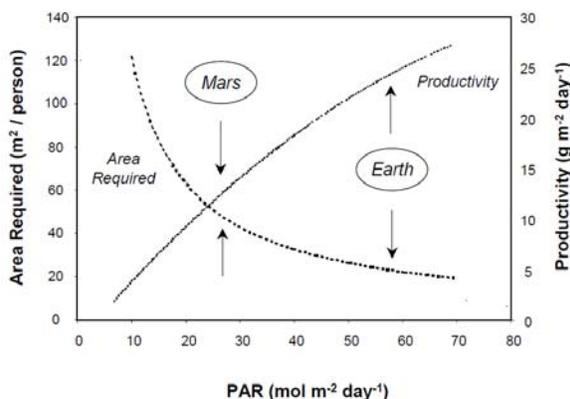


Fig. 4. Crop productivity and area required per person as a function of photosynthetically active radiation (PAR). Arrows indicate a bright sunny day on Earth and near equator on Mars (Wheeler, 2004).

By dividing the productivities by the total PAR provided to the plants, radiation use efficiency or RUE values can be calculated. The best RUE values for total dry mass (DM) were as follows: Wheat  $0.59 \text{ g mol}^{-1}$ ; soybean  $0.43 \text{ g mol}^{-1}$ ; lettuce  $0.46 \text{ g mol}^{-1}$ ; potato  $0.64 \text{ g mol}^{-1}$ ; and tomato  $0.51 \text{ g mol}^{-1}$  (Wheeler et al., 2008). These values were calculated assuming the plants required the same spacing from planting to harvest. But if seedlings had been started at closer spacing and then transplanted to the final spacing, productivities and RUE values for soybean, potato, tomato, and in particular, lettuce could have been improved. For example, if lettuce seedlings were grown for 12 days at closer spacing in a “nursery” and then transplanted to their final  $19.2 \text{ plants m}^{-2}$ , the RUE values would improve from  $0.46$  to  $0.80 \text{ g mol}^{-1} \text{ PAR}$ . Related NASA studies with

potatoes conducted at the University of Wisconsin reported RUE values as high as  $1.15 \text{ g mol}^{-1}$  for total DM and  $0.82 \text{ g mol}^{-1}$  edible DM with transplanting schemes (Wheeler, 2006).

The use of recirculating hydroponics (NFT) for these studies allowed the development of data sets on the use of water, nutrient stock solution, and acid for pH control for the different crops tested. All of the studies used nitrate as the sole source of nitrogen and hence the pH of the solution tended to rise over time, requiring additions of acid (Trelease and Trelease, 1935). EC set points were maintained throughout grow even though it might have been more useful to reduce some nutrients later (e.g., N) later in growth. The rationale for this was that ultimately such systems for life support would have to operate continuously and likely contain multiple species at different stages of development. There were concerns that this could be wasteful of some nutrients, for example nitrate would build up in shoot tissues (McKeehen et al., 1996), but subsequent studies with waste bioreactors demonstrated that many of these nutrients could be leached from the inedible biomass and recycled to grow more plants (Mackowiak et al., 1996).

**Table 2. Examples of water, nutrient (cation), and acid use for some crops grown in NFT in NASA’s Biomass Production Chamber.**

	Soybean	Wheat	Potato	Lettuce
Biomass ( $\text{g DM m}^{-2} \text{ d}^{-1}$ )	14.3	35.3	26.4	6.2
Water Use <sup>1</sup> ( $\text{L m}^{-2} \text{ d}^{-1}$ )	4.7	4.7	4.0	2.1
Nutrient Use <sup>2</sup> ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	29.2	58.3	44.7	16.3
Acid Use <sup>3</sup> ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	12.5	41.6	18.0	6.1
$\text{g DM / L water}$	3.1	7.7	6.7	2.9
$\text{g DM / mmol K, Ca, Mg}$	0.49	0.60	0.59	0.38
$\text{g DM / mmol acid}$	1.14	0.85	1.47	1.02

<sup>1</sup> Water use includes stock solution and acid volume.

<sup>2</sup> Nutrient use expressed as mmol of K, Ca, and Mg.

<sup>3</sup> Acid used expressed as mmol  $\text{H}^+$ .

Rates of acid, stock solution, and water use for typical wheat, soybean, potato, and lettuce crops are shown in Table 2. Average water use rates ranged from about  $2 \text{ L m}^{-2} \text{ d}^{-1}$  (lettuce) to  $5 \text{ L m}^{-2} \text{ d}^{-1}$  (wheat and soybean). The low rates for lettuce were a result of large portion of the growth cycle occurring before canopy cover was complete and maximum transpiration rates were reached. Nutrient use ranged from  $<20 \text{ mmol cations (K Ca, Mg) m}^{-2} \text{ d}^{-1}$  (lettuce) to nearly  $60 \text{ mmol m}^{-2} \text{ d}^{-1}$  (wheat), and acid

use ranged from 6 mmol H<sup>+</sup> m<sup>-2</sup> d<sup>-1</sup> (lettuce to over 40 mmol m<sup>-2</sup> d<sup>-1</sup> (wheat). When compared across several studies, requirements for acid and nutrients showed a near linear increase with light, and biomass production (Wheeler et al., 1999). The relationship between canopy water use and PAR was more complex and affected by additional factors, such as humidity, temperature, and photoperiod.

Because the atmosphere of the Biomass Production Chamber was relatively closed ( $\approx 10\%$  vol leaked / day when doors were kept closed), ethylene from plant metabolism would build-up in the atmosphere (Fig. 5). These plots show the accumulation of ethylene throughout the growth and development of wheat, soybean, lettuce and potato. For this particular study with potato, the photoperiod was temporarily switched from 12/12 (light/dark) to continuous light ca. 60 days, which caused a spike in ethylene production by the plants. This may have been a result of stress to the plants under continuous light. In most cases, ethylene production was highest during rapid vegetative growth. An exception to this was tests with tomatoes (not shown); as the tomato fruit began to ripen, there was a rapid climacteric rise of ethylene, which exceeded 500 ppb in the chamber (Wheeler et al., 2004).

#### Requirements for human life support

Based on the findings from the Russian Bios-3 project and NASA testing, about 20-25 m<sup>2</sup> of crops could supply the O<sub>2</sub> for one human, while about 50 m<sup>2</sup> would be required for dietary calories (2500 kcal person<sup>-1</sup> d<sup>-1</sup>). To provide all the spices, and flavors for a more complete diet would require more planted area (Masuda et al., 2005; Tako et al., 2010). To sustain higher crop productivity with high light would require more dense spacing of electric lamps, although overall power budgets might not differ much from using lower intensity lighting over larger areas. But the latter option would involve more system mass and volume, which would be additional costs for space missions (Drysedale et al., 2003).

For electric lighting options, light emitting diodes (LEDs) are rapidly emerging as the preferred choice for growing crops in space. Indeed, some of the first tests using LEDs to grow plants came from NASA sponsored research (Barta et al., 1992). The electrical conversion efficiencies for LEDs have improved significantly over the past 10 years, with state-of-the-art red and blue LEDs now exceeding 40% conversion efficiencies (Morrow, 2008). In addition, high quality LEDs can have an operating life of >50,000 h, which in turn would reduce resupply and replacement costs for space missions. These same economic advantages would also apply

for terrestrial plant factories (Massa et al., 2008). For space systems, perhaps a better approach for lighting might be to use solar light that could be collected and then delivered using fiber optics or light conduits to protected plant growth structures, (Drysedale et al., 2008; Nakamura et al., 2009).

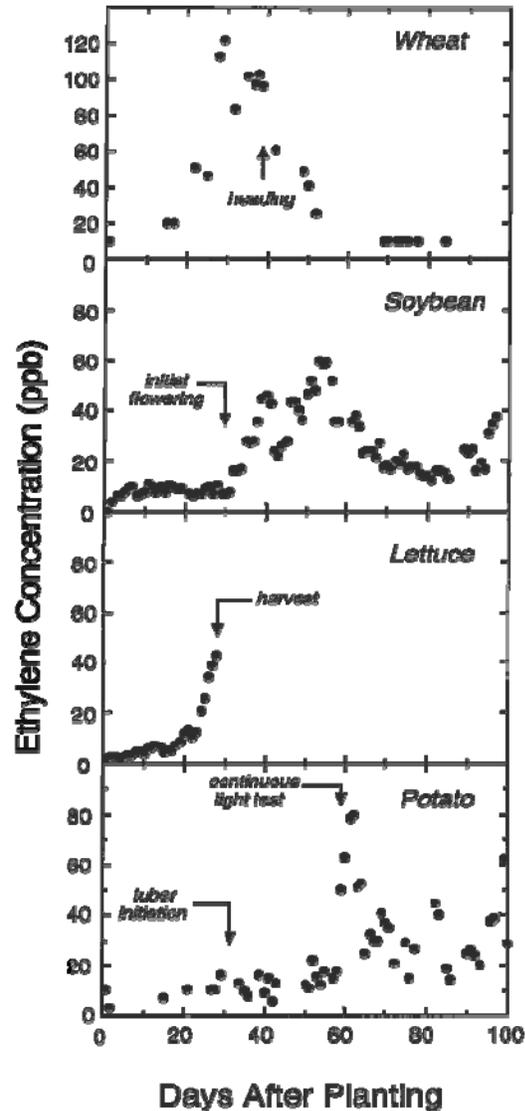


Fig. 5. Ethylene accumulation from 20 m<sup>2</sup> stands of wheat, soybean, lettuce and potato in a NASA closed Biomass Production Chamber (Wheeler et al., 2004).

An example of a solar concentrator based on parabolic mirrors and fiber optic delivery lines at NASA's Kennedy Space Center is shown in Fig. 6. When the system was installed, approximately 40% of the solar photosynthetically active radiation could be captured and delivered to a plant growth chamber inside of a building. One version of how this might be implemented in space is shown in Fig. 7, where solar collectors might deliver light to plants in a

protected chamber covered with regolith to provide radiation shielding (Sadler and Giacomelli, 2002).



Fig. 6. Top: Solar concentrators on the roof of the Space Life Science Laboratory at Kennedy Space Center, Florida; Bottom: Takashi Nakamura, Physical Sciences Inc., making measurements of light delivered from the concentrators (Nakamura et al., 2009).

#### 4. SUMMARY

Life support systems for space missions such as the current International Space Station are based largely on stowage and resupply, with so-called physico-chemical systems for controlling the environment and recycling some air and water. As mission distances and durations increase, so will the need for regenerative life support technologies. One approach would be to use plants and photosynthesis to generate food and oxygen, while scrubbing CO<sub>2</sub> from the cabin air. Plant systems along with bioreactors could also be used to purify and recycle wastewater. To achieve this will require carefully controlled environments to achieve high productivities, which in turn would minimize mission costs. In many ways, these efforts are analogous with plant factory systems that are in

current use on Earth. As we learn more about sustainable living approaches for space, we will learn more about sustainable living on Earth, and vice versa.

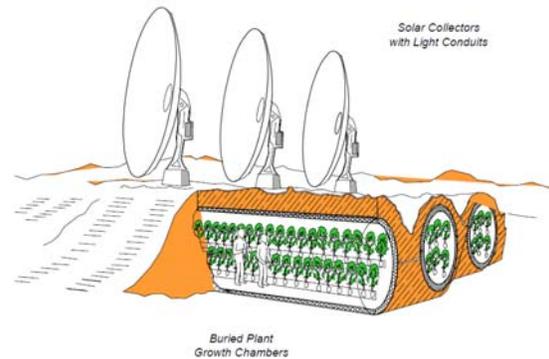


Fig. 7. Possible approach for space agriculture system. In this case, collectors would be used to track and capture sunlight, which is then delivered to radiation protected plant growth modules (Sadler and Giacomelli, 2002).

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