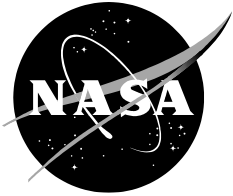


NASA/TM-20205008832



# **NASA's Contributions to Vertical Farming**

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**October 2020**

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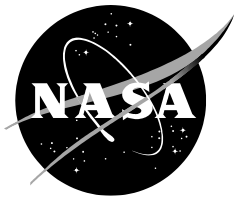
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# NASA's Contributions to Vertical Farming

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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. These systems will be volume and power constrained and will require recycling of water and nutrients. 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. NASA funded research patented the use of LEDs for plant lighting in 1990 and supported their continued development for the next 15 years. To explore volume efficiency, concepts such as vertically stacked hydroponic systems and light banks were tested in NASA's Biomass Production Chamber at Kennedy Space Center US from 1988 through 2000. This was perhaps one of the first examples of an operational vertical farms. Findings from these and related tests around the world suggest that with ~40 mol m<sup>-2</sup> day<sup>-1</sup> of PAR, 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).

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

## 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> (Myers, 1954; Gitelson et al., 1989; Galston, 1992; Yamashita and Wheeler, 2014). 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; Gitelson et al., 1992).

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 (>5 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), the European Space Agency's MELISSA Pilot Plant (Lasseur et al., 2010), and most recently the Chinese Lunar Palace 1 tests (Fu et al, 2016). In addition, smaller scale (< 5 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). For all space settings, power, mass, and volume will be constrained, and optimal use and recycling of available water and nutrients will be a necessity (Salisbury, 1992; Wheeler, 2017).

To address some of these challenges, NASA developed and operated its "Biomass Production Chamber" (BPC) at Kennedy Space Center, Florida, US from 1988 through 2000 (Prince and Knott, 1989). The chamber was used a test platform for validating fundamental findings from crop tests at universities (Wheeler, 2017). The university research was typically carried out in more conventional growth chambers (~1 m<sup>2</sup> scale) and with an open atmosphere (Wheeler, 2017). The BPC provided 20 m<sup>2</sup> of growing area with a tightly closed atmosphere, to simulate conditions that might be encountered in space. A review of the of the design and capabilities of this chamber, and its contribution to current vertical farming are presented here

## MATERIALS AND METHODS

NASA's Biomass Production Chamber (BPC) was a retired hypobaric test chamber used in the Mercury and program (Prince and Knott, 1989; Dreschel et al., 2019). The cylindrical chamber was 3.7 m diameter and 4.3 m high. The decision was made to maintain the chamber in an upright position (Fig. 1), just as it operated for hypobaric testing, rather than laying the chamber horizontally, which might be a more likely situation for space setting (e.g., on Mars). Internally, the chamber provided 20 m<sup>2</sup> of crop growing area separated on four vertically stacked shelves (5 m<sup>2</sup> each) (Fig. 2). Each shelf supported 16 trapezoidal shaped 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). Unlike commercial vertical farms, this allowed continuous tracking of crop photosynthesis and respiration using closed or semi-close gas exchange techniques (Wheeler, 1992). Oxygen (O<sub>2</sub>) concentrations were allowed to vary slightly from 21% to 23% (21–23 kPa) 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 (NFT) with a modified ½ strength Hoagland / Arnon solution (Wheeler et al., 1999). This minimized the amount of standing water volume and mass in the growing trays. Each of the four growing shelves with 16 trays had one nutrient solution reservoir 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 reservoirs by gravity dependent flow, which should work in fractional g environments such as on the Moon or Mars. Nutrient solution volumes were maintained at a constant level either through daily additions of deionized or recycled 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.

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 for temperature control. Transpired water (humidity) condensed by cooling coils was passed through ion exchange columns, and then recycled back to the nutrient solution reservoirs. Lighting was provided by 96 400-W dimmable lamps using either high pressure sodium (HPS) or metal halide (MH) lamps, or mixtures of the two depending on the crop. 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. Air velocities at the plant canopy level ranged from 0.2 to 1.5 m s<sup>-1</sup>.

### ***Crops Tested***

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 white nylon (Nitex) wicks in hydroponic trays. The idea of using the wicking was to minimize any consumables such as rockwool or peat cubes for space missions. 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 20°C in the light and 16°C in the dark. Plants were harvested at physiological maturity when heads had lost their green color (77–86 d).

Soybean (*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. 2). 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, with HPS lamps providing higher output of PAR than MH lamps. 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.

Potato (*Solanum tuberosum* L.) cvs. Norland or Denali plantlets were grown in vitro for 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 canopy



height and 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. 3).

Tomato (*Solanum esculentum* L.) seeds of cv. Reimann Philipp 75/59, a parthenocarpic type “cherry” 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, fresh mass was measured for all plant materials, and the biomass then placed in large ventilated ovens 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 from the subsamples was then multiplied by the total fresh mass in each tray to estimate the total fruit or tuber dry mass.

## 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. Yields were highly dependent on photosynthetically active radiation (PAR) provided to the plants (Fig. 4). 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 about 17.3 mol m<sup>-2</sup> d<sup>-1</sup>, and hence biomass yields were lower than other crops. Total biomass ranged from 23 to 40 g m<sup>-2</sup> d<sup>-1</sup> for wheat, 10 to 16 g m<sup>-2</sup> d<sup>-1</sup> for soybean, 6 to 8 g m<sup>-2</sup> d<sup>-1</sup> for lettuce, 22 to 33 g m<sup>-2</sup> d<sup>-1</sup> for potato, and 13-20 g m<sup>-2</sup> d<sup>-1</sup> for tomato (Fig. 4) (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 (Salisbury, 1991; Wheeler, 2004). But 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).

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). Electrical conductivity set points for nutrient solutions were maintained throughout growth even though it might have been more useful to reduce some nutrients (e.g., N) later in growth. The rationale for this was that crop production systems for life support would have to operate continuously and likely contain multiple species at different stages of development (Barta and Henderson, 1998). Related studies with different levels of nitrogen during different stages of growth of potato showed that maintaining consistent  $7.5 \text{ mM}$  nitrogen throughout growth resulted in greater biomass and tuber yields than lower concentrations or reduced N levels later in growth (Goins et al., 2004). Nonetheless, there were concerns that this could be wasteful of some nutrients, for example nitrate would build up in shoot tissues (McKeehen et al., 1996), or that high N throughout growth could reduce harvest index and generate more inedible biomass (Goins et al., 2004). But waste processing studies using stirred-tank bioreactors demonstrated that most of these nutrients, including nitrate could be leached from the inedible biomass and recycled to

grow more plants (Mackowiak et al., 1996; Strayer and Atkinson, 1997). For terrestrial vertical farms or plant factories, similar approaches might be considered, or the inedible biomass could be used as a feedstock for mammals, fish, insects, or edible fungi (Katayama et al., 2008; Li et al., 2013; Tako et al., 2010).

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 L m<sup>-2</sup> d<sup>-1</sup> (lettuce) to 5 L m<sup>-2</sup> d<sup>-1</sup> (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 mmol cations (K Ca, Mg) m<sup>-2</sup> d<sup>-1</sup> (lettuce) to nearly 60 mmol m<sup>-2</sup> d<sup>-1</sup> (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 (PAR) 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 and temperature, which determine vapor pressure deficits, photoperiod, and CO<sub>2</sub> concentration.

Because the atmosphere of the Biomass Production Chamber was relatively closed (~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 the 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). More recent studies with the Lunar Palace 1 facility showed that 69 m<sup>2</sup> of crops supported 100% of the air and water needs, and 55% of the food for a crew of 3 humans (Fu et al., 2016). To sustain higher crop productivity with high light would require denser 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 require more system mass and volume, which would be additional costs for space missions (Drysdale et al., 2003).

For electric lighting options, light emitting diodes (LEDs) are rapidly emerging as the preferred choice for growing crops in space and for terrestrial vertical farms and plant factories (Morrow, 2008; Pattison et al., 2018; Kitaya, 2019). Some of the first tests using LEDs to grow plants came from NASA sponsored research at the University of Wisconsin and Quantum Devices Inc. (Bula et al., 1991; Barta et al., 1992), with continued development and testing of LEDs for plant lighting at Kennedy Space Center and the University of Wisconsin over the next 10-15 years (Tenessen et al., 1994; Goins et al., 1998; Yorio et al., 2001; Kim et al., 2004; 2005). 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 70-80% conversion efficiencies (Pattison et al., 2018). 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 and vertical farms (Massa et al., 2008; Morrow, 2008; Kitaya, 2019). For space systems, another 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 (Cuello et al. 2000; Nakamura et al., 2009), but these approaches would depend on the setting and the availability of sunlight.

## **SUMMARY**

Life support systems for space missions such as the current International Space Station are based largely on stowage and resupply, with 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 and vertical farming systems that are being used on Earth. As we learn more about sustainable living approaches for space, we will learn more about sustainable living on Earth, and vice versa.

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

Crops	Days of Testing	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>.



**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 (g DM m <sup>-2</sup> d <sup>-1</sup> )	14.3	35.3	26.4	6.2
Water Use <sup>1</sup> (L m <sup>-2</sup> d <sup>-1</sup> )	4.7	4.7	4.0	2.1
Nutrient Use <sup>2</sup> (mmol m <sup>-2</sup> d <sup>-1</sup> )	29.2	58.3	44.7	16.3
Acid Use <sup>3</sup> (mmol m <sup>-2</sup> d <sup>-1</sup> )	12.5	41.6	18.0	6.1
g DM / L water	3.1	7.7	6.7	2.9
g DM / mmol K, Ca, Mg	0.49	0.60	0.59	0.38
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 H<sup>+</sup>.



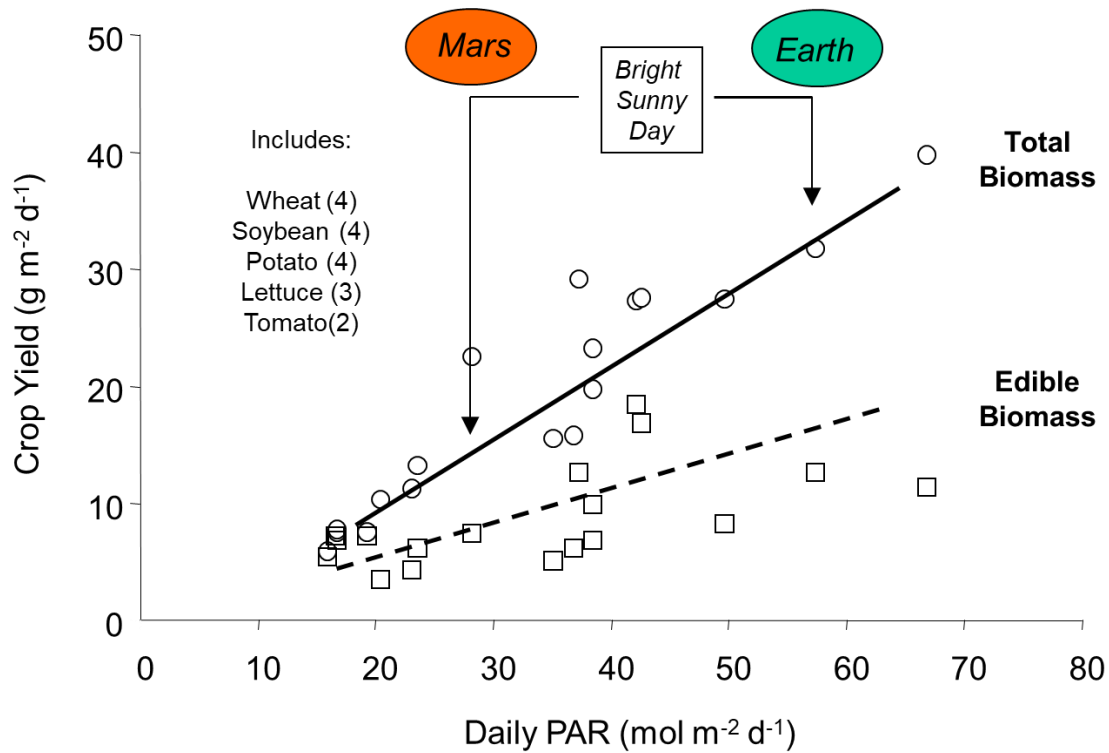
**Figure 1.** NASA's Biomass Production Chamber operated at Kennedy Space Center, Florida from 1988 to 2000.



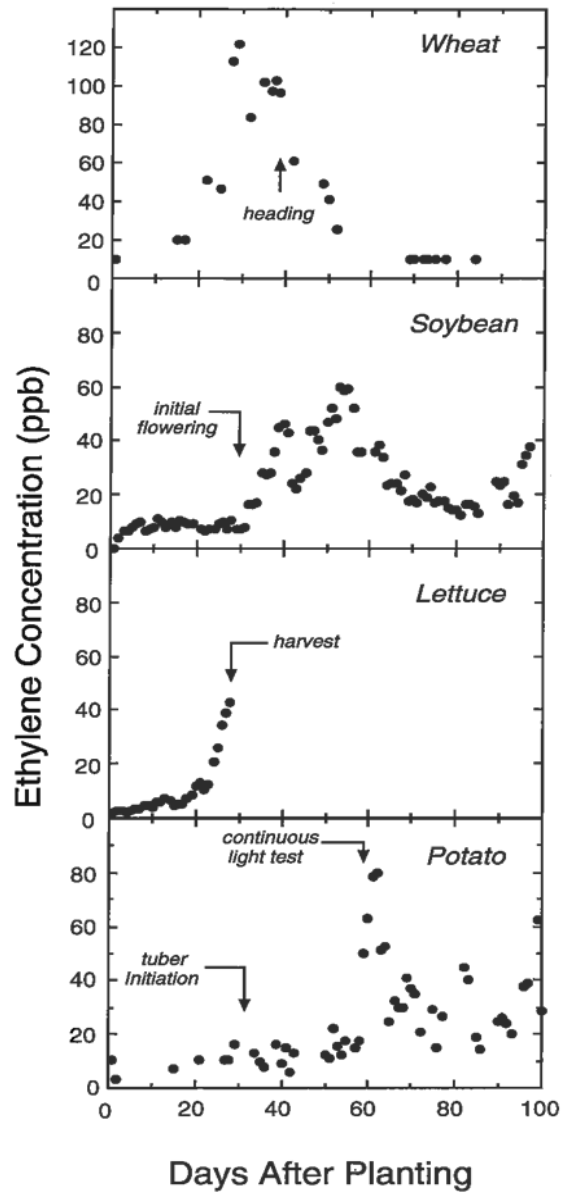
**Figure 2.** NASA's Biomass Production Chamber at Kennedy Space Center with a soybean crop. Two of the four shelves are shown; the chamber provided 20 m<sup>2</sup> of growing area in a closed atmosphere.



**Figure 3.** Potato tubers ready for harvest in NASA's Biomass Production Chambers. Plants were grown using nutrient film technique (Wheeler, 2006).



**Figure 4.** Dry mass productivity of different crops grown in NASA's Biomass Production Chamber as a function of daily photosynthetically active radiation. Arrows indicate a bright sunny day on Earth and near equator on Mars (Wheeler, 2004).



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