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Crop productivities and radiation use efficiencies for bioregenerative life support

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Abstract

NASA's Biomass Production Chamber (BPC) at Kennedy Space Center was decommissioned in 1998, but several crop tests were conducted that have not been reported in the open literature. These include several monoculture studies with wheat, soybean, potato, lettuce, and tomato. For all of these studies, either 10 or 20 m^2 of plants were grown in an atmospherically closed chamber (113 m^3 vol.) using a hydroponic nutrient film technique along with elevated CO_2 (1000 or 1200 μmol mol^{-1}). Canopy light (PAR) levels ranged from 17 to 85 mol m^{-2} d^{-1} depending on the species and photoperiod. Total biomass (DM) productivities reached 39.6 g m^{-2} d^{-1} for wheat, 27.2 g m^{-2} d^{-1} for potato, 19.6 g m^{-2} d^{-1} for tomato, 15.7 g m^{-2} d^{-1} for soybean, and 7.7 g m^{-2} d^{-1} for lettuce. Edible biomass (DM) productivities reached 18.4 g m^{-2} d^{-1} for potato, 11.3 g m^{-2} d^{-1} for wheat, 9.8 g m^{-2} d^{-1} for tomato, 7.1 g m^{-2} d^{-1} for lettuce, and 6.0 g m^{-2} d^{-1} for soybean. The corresponding radiation (light) use efficiencies for total biomass were 0.64 g mol^{-1} PAR for potato, 0.59 g DM mol^{-1} for wheat, 0.51 g mol^{-1} for tomato, 0.46 g mol^{-1} for lettuce, and 0.43 g mol^{-1} for soybean. Radiation use efficiencies for edible biomass were 0.44 g mol^{-1} for potato, 0.42 g mol^{-1} for lettuce, 0.25 g mol^{-1} for tomato, 0.17 g DM mol^{-1} for wheat, and 0.16 g mol^{-1} for soybean. By initially growing seedlings at a dense spacing and then transplanting them to the final production area could have saved about 12 d in each production cycle, and hence improved edible biomass productivities and radiation use efficiencies by 66% for lettuce (to 11.8 g m^{-2} d^{-1} and 0.70 g mol^{-1}), 16% for tomato (to 11.4 g m^{-2} d^{-1} and 0.29 g mol^{-1}), 13% for soybean (to 6.9 g m^{-2} d^{-1} and 0.19 g mol^{-1}), and 13% for potato (to 20.8 g m^{-2} d^{-1} and 0.50 g mol^{-1}). Since wheat was grown at higher densities, transplanting seedlings would not have improved yields. Tests with wheat resulted in a relatively low harvest index of 29%, which may have been caused by ethylene or other organic volatile compounds (VOCs) accumulating in the chamber. Assuming a higher harvest index of 40% could be achieved by scrubbing VOCs, productivity of wheat seed could have been improved nearly 40% to 15.8 g m^{-2} d^{-1} and edible biomass radiation use efficiency to 0.30 g mol^{-1}.
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Keywords: CELSS; Controlled ecological life support systems; Bioregenerative; Crops; Space exploration

1. Introduction

NASA's Biomass Production Chamber at Kennedy Space Center, FL, USA began initial operation in 1987, with its first full stand production test in 1988 (Prince and Knott, 1989; Wheeler et al., 1996). The chamber provided 20 m^2 of growing area inside an atmospherically closed volume of 113 m^3, which allowed testing of candidate crops for space life support systems. The intent of the project was to provide a bioregenerative test bed to meet the life support needs of one person (Prince and Knott, 1989). The effort later evolved to provide a large scale test bed with a tightly closed atmosphere to complement fundamental testing at universities using atmospherically open chambers (e.g., Bubgee and Salisbury, 1988;

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Knight and Mitchell, 1988; Tibbitts and Wheeler, 1987; Tolley-Henry et al., 1988). The chamber was decommissioned in 1998 after nearly 10 years of continuous operation and many of the results from the crop tests have been reported, including biomass yields and gas exchange (CO_2 removal and O_2 production) rates (Stutte et al., 1999; Wheeler et al., 1993, 1996, 2003; Wheeler, 1992, 1996). But several studies and a full assessment of radiation (light) use efficiencies, namely, g biomass per unit photosynthetically active radiation (PAR), have not been reported in the open literature. These findings are presented here to provide data for systems analysis and trade studies for future life support options in space.

2. Methods and materials

2.1. Biomass Production Chamber

NASA's Biomass Production Chamber (BPC) provided 20 m^2 of crop growing area separated on four vertically stacked shelves (5 m^2 each) (Wheeler et al., 1996, 2003) (Fig. 1). Each shelf supported 16 plastic trays (0.3125 m^2 per tray), for a total of 64 trays for the entire chamber (Prince and Knott, 1989). 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, providing a situation reasonably similar to what might be encountered in space. When doors were opened, daily leakage rates could approach 20–30% of the volume per day depending on the duration of the opening event. Carbon dioxide (CO_2) uptake by the plants was offset by controlled injections of pure CO_2 to hold a set point of 1000 or 1200 μmol mol^{-1} (0.10 or 0.12 kPa) during the light cycles, while CO_2 was allowed to accumulate from plant respiration during the dark cycles (Wheeler, 1992). When the lamps came on in the morning, CO_2 concentrations quickly drew down to a set point, where controlled injections began (Wheeler, 1992). These drawdowns lasted approximately 60–90 min depending on how much CO_2 accumulated during the dark cycle, which in turn depended on the length of the dark period and the respiration rate of the crop. Oxygen (O_2) concentrations were allowed to vary slightly (from 21% to 23%) but typically remained near 21% (21.0 kPa) as a result of routine door openings for plant maintenance activities (Wheeler, 1996). 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; Stutte and Wheeler, 1997), including the gaseous plant hormone ethylene (Wheeler et al., 2004).

All plants were grown hydroponically using a recirculating nutrient film technique (Mackowiak et al., 1997; Wheeler et al., 2003). 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 (Prince and Knott, 1989). 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, but not in μ-g settings, where containment of nutrient solutions would be required (Wright et al., 1988; Dreschel and Sager, 1989; Morrow et al., 1995). Starting nutrient con-

Fig. 1. NASA's Biomass Production Chamber (BPC) located at Hangar L, Kennedy Space Center, FL, USA. The chamber provided a closed atmospheric volume of 113 m^3 and four vertically stack shelves providing 20 m^2 of plant growing area.

centrations were as follows: 7.5 mM N, 3.0 mM K, 0.5 mM P, 2.5 mM Ca, 1.0 mM Mg, 1.0 mM S, 60 μM Fe, 7.4 μM Mn, 0.96 μM Zn, 1.04 μM Cu, 7.13 μM B, and 0.01 μM Mo (Wheeler et al., 1999). Transpired water was condensed on the cooling coils of the heat-exchange system and either dumped in the early studies, or recycled back to the nutrient solution tanks for later studies (Wheeler et al., 2003). Nutrient solution volumes were maintained at a constant level either through daily additions of deionized water or continuous recycling of condensate water. Following volume adjustments to the tanks, nutrient stock solutions were added to maintain an electrical conductivity of 1.2 dS m^{-1}. Stock solution nutrient concentrations were as follows: 70 mM N, 56 mM K, 10 mM P, 12 mM Ca, 10 mM Mg, 10 mM S, 134 μM Fe, 96 μM Mn, 12.5 μM Zn, 13.5 μM Cu, 93 μM B, and 0.13 μM Mo (Wheeler et al., 1999). Nutrient solution pH was controlled to 5.8 using automatic additions of 0.4 M nitric acid (HNO_3). 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 species. 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 from resistance heating elements that provided up to 150 kW (Wheeler et al., 2003). Air was recirculated continuously with two 40-kW fans, providing about 400 m^3 min^{-1}, or about three volume exchanges per minute. This provided a thoroughly mixed atmosphere in the chamber.

2.2. Horticultural techniques

Wheat (*Tricitum aestivum* L.) cvs. Yecora Rojo, Veery 10, or Apogee seeds were sown at a rate of 400 seeds per tray (1600 per m^{-2}) and germinated with nylon wicks in hydroponic tray inserts described by Prince and Knott (1989). Seedlings were covered with white translucent tray covers for the first 4 d after planting to maintain high humidity and aid establishment. Tray covers likely caused some warming of the germination environment but these temperatures were not monitored. 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 dimming set points used for a given study, ranging from 509 to 930 μmol m^{-2} s^{-1} (Wheeler et al., 1996, 2003). 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 either at 24 °C in the light and 20 °C in the dark or 23 °C constant for the first 10–32 d, followed by 20 °C in the light 16 °C in the dark (Wheeler et al., 1996, 2003). Plants were harvested at physiological maturity when heads had lost their green color (77–86 d) (Fig. 2).

Soybeans (*Glycine max* L. [Merr.]) cvs. McCall or Hoyt were germinated in a manner similar to wheat and thinned to either four or six plants per tray (12.8 or 19.2 plants per m^2) at 10 d after planting. 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 (Fig. 3). Canopy level PAR ranged from 477 to 815 μmol m^{-2} s^{-1}, depending on the combination of HPS and MH 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.

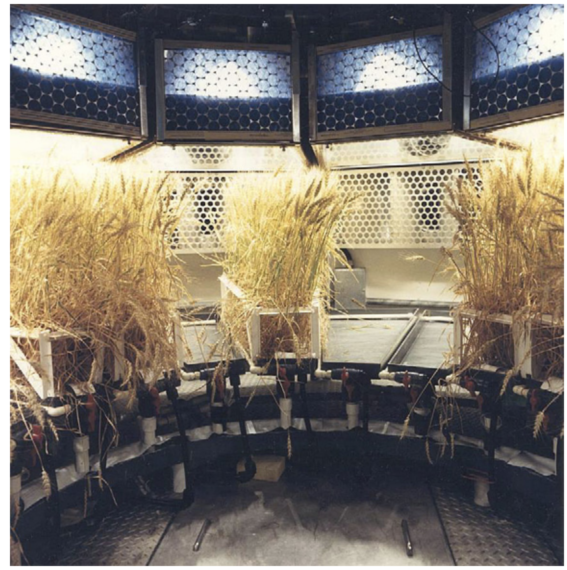

Fig. 2. Wheat plants ready for harvest inside NASA's Biomass Production Chamber. Plants were grown hydroponically using a nutrient film technique (NFT).

Potato (*Solanum tuberosum* L.) cv. Norland or Denali plantlets were grown *in vitro* (test tubes) 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 per m^2). Trays were initially covered with white translucent covers placed above the polyethylene sheet 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 (Wheeler et al., 1996). Canopy level PAR ranged from 655 to 917 μmol m^{-2} s^{-1} depending on the combination of HPS and MH lamps. Temperature regimes either used 20 °C in the light and 16 °C in the dark throughout growth, or started with 24 °C in the light and 20 °C in the dark, followed by 20 °C in the light and 16 °C in the dark after 2–4 weeks age. Plants were harvested at 91 or 105 d after planting (Fig. 4).

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^{-2}) at 9 d. All plants were grown under HPS lamps with a 12-h

Fig. 3. Soybean plants growing inside NASA's Biomass Production Chamber. Two of the four total shelves for growing plants are shown in the photo.

Fig. 4. Potato tubers ready for harvest inside NASA's Biomass Production Chamber. Plants were grown hydroponically using a nutrient film technique.

light/12-h dark photoperiod. Canopy level PAR ranged 549–893 μmol m^{-2} s^{-1} depending on the dimming set point, and temperatures were maintained at 26 °C in the light and 20 °C in the dark (Fig. 5). 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.

Fig. 5. Tomato plants growing inside NASA's Biomass Production Chamber. Two of the four total shelves for growing plants are shown in the photo. Fruits were harvested at regular intervals as they ripened.

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^{-2}) 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 336 μmol m^{-2} d^{-1}, and temperatures were maintained at a constant 23 °C. Lower PAR levels were used to reduce the incidence of leaf tipburn, which commonly occurs when lettuce plants grow in controlled environments (Barta and Tibbitts, 1991). Plants were harvested at 28 or 30 d after planting (Fig. 6).

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. Harvest index for each species was calculated by dividing edible DM by the total DM. Productivities (g m^{-2} d^{-1}) were calculated by taking total dry mass yields and dividing by the available 20 m^2 area and the total days of growth starting from seeds or *ex vitro* plantlets (for potato). Radiation use efficiencies or RUEs,

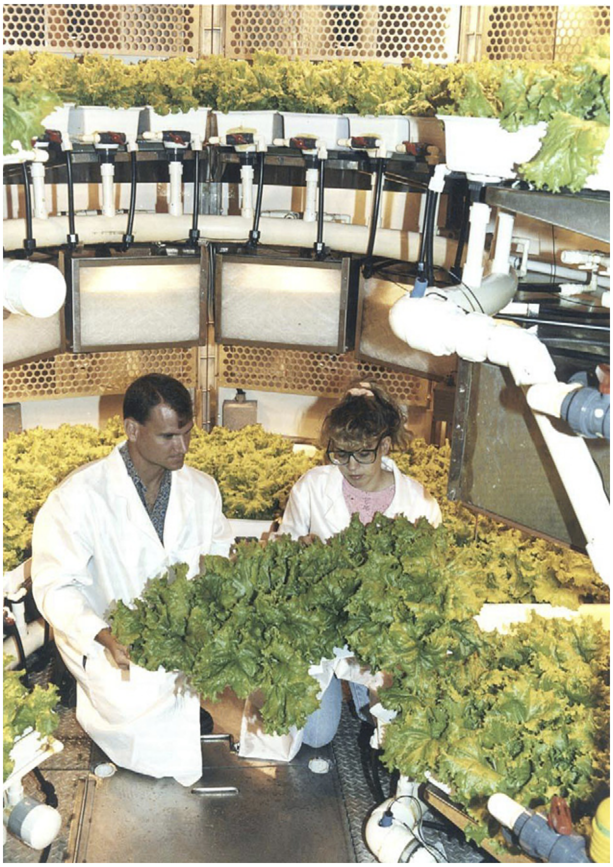

Fig. 6. Lettuce plants ready for harvest inside NASA's Biomass Production Chamber. Two of the four total shelves for growing plants are shown in the photo.

expressed as g DM mol^{-1} PAR, were calculated by dividing DM productivities by the average daily integrated PAR measured at the canopy level. Additional estimates of productivity and radiation use efficiency were calculated by subtracting 12 d from the crop production cycle for soybean, potato, and tomato, assuming that seedlings could be grown during this time in a densely spaced "nursery", which would be separate from the final production area.

Carbon dioxide removal rates were calculated from carbon content of harvested biomass analysis. This carbon content calculation has been shown previously to correlate closely with direct canopy gas exchange measurements in the BPC (Wheeler et al., 1996, 2003). Direct canopy gas exchange measurements were taken only during periods of chamber closure. Oxygen production was estimated from CO_2 uptake and assuming a 1:1 molar ratio CO_2 removed to O_2 produced, i.e., an assimilation quotient of 1.0. This is reasonably accurate for carbohydrate producing crops, but may have underestimated the O_2 produced by soybeans, which have a higher fat content (Wheeler, 1996; Tako et al., 2001). Water production rates from evapotranspiration were measured from condensate collected from the cooling coils of the heat-exchange system, and corroborated by summing the daily inputs of water, stock solution, and acid for pH control in the hydroponic systems (Wheeler et al., 1999).

3. Results and discussion

Total biomass yields, CO_2 removal, O_2 production, and water production values are shown in Table 1. Results showed that using a range of species and fixed plant spacing from seed to harvest produced an average of 11.3 g m^{-2} d^{-1} of edible biomass, removed an average of 36.0 g m^{-2} d^{-1} of CO_2, and produced 3965 g m^{-2} d^{-1} (3.96 L m^{-2} d^{-1}) of condensed water.

The best productivities for each species along with their radiation use efficiencies (RUE) are shown in Table 2. Productivities for total biomass ranged from 7.7 g m^{-2} d^{-1} for lettuce to 39.6 g m^{-2} d^{-1} for wheat, while productivities for edible biomass ranged from 6.0 g m^{-2} d^{-1} for soybean to 18.4 g m^{-2} d^{-1} for potato. The RUE values for total biomass ranged from 0.43 g mol^{-1} for soybean to 0.64 g mol^{-1} for potato, while RUE values for edible biomass ranged from 0.16 g mol^{-1} for soybean to 0.44 g mol^{-1} for potato (Table 2).

In commercial controlled environment agriculture, seedlings are typically started in a nursery under lower light intensity and grown at a dense spacing. The seedlings are then transplanted to a wider spacing in a production

Table 1
Summary of outputs from NASA's Biomass Production Chamber

Crop	Operation time (days)	Total biomass (kg DM)[b]	Edible biomass (kg DM)[b]	CO_2 fixed (kg)	O_2 produced[a] (kg)	Water condensed (kg)
Wheat	417	235.9	70.7	363.2	265.3	33427
Soybean[c]	374	79.9	27.9	132.3	98.2	27013
Lettuce	114	13.9	12.9	20.5	15.0	4048
Potato	823	479.6	275.7	720.5	522.6	63085
Tomato[d]	171	44.9	22.2	67.5	49.1	16125
Totals	1899	854.2	409.4	1304.0	950.2	143698
Rate (g m^{-2} d^{-1})[e]		23.6	11.3	36.0	26.2	3965

[a] O_2 production estimated as a 1:1 molar ratio with CO_2 fixed.
[b] DM, dry mass.
[c] One of the four soybean studies only used only 10 m^2 instead of the total 20 m^2.
[d] One of the two tomato studies only used only 10 m^2 instead of the total 20 m^2.
[e] Rates (productivities) adjusted to account for soybean and tomato 10 m^2 studies.

Table 2
Highest productivities and radiation use efficiencies for crops grown in NASA's Biomass Production Chamber

Crop	Daily PAR[a] ($mol\ m^{-2}\ d^{-1}$)	Total DM[b] productivity ($g\ m^{-2}\ d^{-1}$)	Total DM RUE[c] ($g\ mol^{-1}$ PAR)	Edible DM productivity ($g\ m^{-2}\ d^{-1}$)	Edible DM RUE ($g\ mol^{-1}$ PAR)
Wheat	67.0	39.6	0.59	11.3	0.17
Soybean	36.5	15.7	0.43	6.0	0.16
Lettuce	16.8	7.7	0.46	7.1	0.42
Potato	42.2	27.2	0.64	18.4	0.44
Tomato	38.6	19.6	0.51	9.8	0.25

[a] PAR, photosynthetically active radiation.
[b] DM, dry mass.
[c] RUE, radiation use efficiency.

Table 3
Projected productivities and radiation use efficiencies using seedling transplants for soybean, lettuce, potato, and tomato, and improved harvest index for wheat[a,b]

Crop	Daily PAR[c] ($mol\ m^{-2}\ d^{-1}$)	Total DM[d] productivity ($g\ m^{-2}\ d^{-1}$)	Total DM RUE[e] ($g\ mol^{-1}$ PAR)	Edible DM productivity ($g\ m^{-2}\ d^{-1}$)	Edible DM RUE ($g\ mol^{-1}$ PAR)
Wheat	67.0	39.6	0.59	15.8	0.24
Soybean	36.5	18.1	0.50	6.9	0.19
Lettuce	16.8	13.5	0.80	12.4	0.74
Potato	42.2	30.7	0.73	20.8	0.49
Tomato	38.6	22.7	0.59	11.4	0.30

[a] Assumes 12 d eliminated from production cycles of soybean, lettuce, potato, and tomato by using seedling transplants.
[b] Assuming harvest index of wheat improved from 29% to 40% with removal of ethylene from the atmosphere.
[c] PAR, photosynthetically active radiation.
[d] DM, dry mass.
[e] RUE, radiation use efficiency.

environment just prior to when the shoots begin to grow rapidly. Assuming a single transplant step could save 12 d in each production cycle, edible biomass productivities and radiation use efficiencies would have improved by 13% for soybean (to $6.9\ g\ m^{-2}\ d^{-1}$ and $0.19\ g\ mol^{-1}$), by 13% for potato (to $20.8\ g\ m^{-2}\ d^{-1}$ and $0.50\ g\ mol^{-1}$), by 66% for lettuce (to $11.8\ g\ m^{-2}\ d^{-1}$ and $0.70\ g\ mol^{-1}$), and by 16% for tomato (to $11.4\ g\ m^{-2}\ d^{-1}$ and $0.29\ g\ mol^{-1}$) (Table 3).

Based on observations from at Utah State University (USA), seed set in some cultivars of wheat (such as Yecora Rojo) is decreased by ethylene gas (Klassen and Bugbee, 2004). Ethylene levels during some wheat tests in our chamber exceeded 100 ppb during rapid vegetative growth just prior to heading (Wheeler et al., 2004), which is high enough to adversely affect seed set (Klassen and Bugbee, 2004). If we assume that scrubbing ethylene and other VOCs with potassium permanganate or a catalytic oxidation system (Wheeler et al., 2003) would have allowed wheat plants to achieve a more typical harvest index of 40% instead of 29% observed, then the best edible biomass productivity for wheat could have increased by 40% from 11.3 to $15.8\ g\ m^{-2}\ d^{-1}$, while the RUE for edible biomass could have increased from 0.17 to $0.24\ g\ mol^{-1}$ (Table 3).

Applying these adjustments for reduced production cycles with soybean, lettuce, potato and tomato, and increased edible yield with wheat, a summary of more optimized outputs for NASA's Biomass Production Chamber can be calculated (Table 4). The calculations show that for a mixture of staple crops (wheat, potato, soybean) and supplemental "salad" type crops (lettuce, tomato), the outputs would be about $14\ g\ m^{-2}\ d^{-1}$ for edible dry biomass, $41\ g\ m^{-2}\ d^{-1}$ of CO_2 removal, $30\ g\ m^{-2}\ d^{-1}$ of O_2 production, and $4.5\ L\ m^{-2}\ d^{-1}$ of water transpired (Table 4).

These optimized outputs are based on the overall averages and not the best single yields obtained from the BPC, as shown in Table 2; hence further improvements are possible. For example, the best edible biomass yields for potato obtained from tests at the University of Wisconsin (USA) using similar light intensities but different cultivation techniques exceeded $30\ g\ m^{-2}\ d^{-1}$, while RUE exceeded $0.80\ mol^{-1}$ PAR (Wheeler, 2006). Moreover it is well established that biomass production and gas exchange outputs are closely tied to light intensity (Bubgee and Salisbury, 1988; Bugbee and Monje, 1992; Wheeler et al., 1993). Higher irradiance would likely increase the productivities for some of these species, particularly wheat, which has a vertical leaf architecture and can distribute incident light over a greater total leaf area (Bubgee and Salisbury, 1988). On the other hand, higher irradiance would likely decrease the RUE values.

The average irradiance for all of the BPC tests was approximately $750\ \mu mol\ m^{-2}\ s^{-1}$ (Wheeler et al., 2003), which would be roughly equivalent to $150\ W\ m^{-2}$ PAR. Assuming a power efficiency (W PAR/W electrical power

Table 4
Adjusted outputs from NASA's Biomass Production Chamber reflecting reduced production time using transplants for soybean, lettuce, potato, and tomato, and increased yields of wheat by implementing ethylene control[a]

Crop	Operation time (days)	Total biomass (kg DM)[b]	Edible biomass (kg DM)[b]	CO_2 fixed (kg)	O_2 produced[a] (kg)	Water condensed (kg)
Wheat[c]	417	235.9	94.4	383.2	265.3	33427
Soybean[d]	326	79.9	27.9	132.3	98.2	27013
Lettuce	66	13.9	12.9	20.5	15.0	4048
Potato	727	479.6	275.7	720.5	522.6	63085
Tomato[e]	147	44.9	22.2	67.5	49.1	16125
Totals	1683	854.2	433.1	1304.0	950.2	143698
Rate ($g\ m^{-2}\ d^{-1}$)[f]		26.8	13.6	40.9	29.8	4502

[a] Assumes 12 d eliminated from production cycles of soybean, lettuce, potato, and tomato by using seedling transplants.
[b] DM, dry mass.
[c] Wheat edible dry biomass increased to match a more typical harvest index of 40%.
[d] One of the four soybean studies only used only 10 m^2 instead of the total 20 m^2.
[e] One of the two tomato studies only used only 10 m^2 instead of the total 20 m^2.
[f] Values adjusted to account for soybean and tomato 10 m^2 studies.

to lamps) of 20% with the electric lighting system, this would indicate that achieving BPC yields would require $150\ W\ m^{-2}/0.20 = 0.75\ kW\ m^{-2}$ electrical power input for the lamps. This would not include power required for thermal control, water pumping, and environmental sensors, which would increase the total power requirement (Drysdale et al., 2000).

With recent interests in ISS operations and short duration Lunar missions, life support approaches have focused largely on stowage and resupply. When regenerative technologies are considered for such near-term missions, the focus has been on physico-chemical systems. Although bioregenerative systems with plants have high start up mass and power consumption rates, more efficient lighting systems and optimized horticultural techniques can reduce these costs substantially. Use of solar light in appropriate settings, such as the poles of the Moon, Mars transit, or less dust prone latitudes on Mars, can reduce these costs even further (Drysdale et al., 2000; Clawson and Hoehn, 2005). The experience from NASA's Biomass Production Chamber shows that a closed, plant production system can be operated on a near-continuous basis for 10 years. To our knowledge, this is the longest sustained demonstration of regenerative life support technologies undertaken to date. But more testing is needed. Other species need study to provide a more complete and acceptable diet for internationally diverse crews; the effects of modified water/nutrient delivery systems for operating in reduced gravity settings need more study; more accurate risk assessments and failure analyses should be conducted; and integrated operational tests with other life support subsystems are needed. Plant based bioregenerative life support systems can provide full atmospheric regeneration, and currently provide the only option for *in situ* food production. Consequently, plant based life support systems should provide the greatest level of autonomy for future space exploration.

Investments in bioregenerative research can also provide benefits for terrestrial applications. For example, the use of LED lighting for plant cultivation in space (Bula et al., 1991) has now expanded into commercial controlled environment agriculture; crop yields from life support studies demonstrate that yields in field agriculture might be pushed beyond current world records (Bubgee and Salisbury, 1988; Tibbitts et al., 1994; Wheeler, 2006); recirculating hydroponic techniques taken from life support testing are now being used to produce disease free seed potatoes (Wheeler, 2006); and quantification of canopy gas exchange, which is intrinsic to life support measurements, has proved to be a powerful diagnostic tool for assessing crop performance and stress (Bubgee and Salisbury, 1988; Bugbee and Monje, 1992; Wheeler et al., 1993).

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