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Crop yield and light/energy efficiency in a closed ecological system: Laboratory Biosphere experiments with wheat and sweet potato

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Abstract

Two crop growth experiments in the soil-based closed ecological facility, Laboratory Biosphere, were conducted from 2003 to 2004 with candidate space life support crops. Apogee wheat (Utah State University variety) was grown, planted at two densities, 400 and 800 seeds m^{-2}. The lighting regime for the wheat crop was 16 h of light – 8 h dark at a total light intensity of around 840 μmol $m^{-2}s^{-1}$ and 48.4 mol $m^{-2}d^{-1}$ over 84 days. Average biomass was 1395 g m^{-2}, 16.0 g $m^{-2}d^{-1}$ and average seed production was 689 g m^{-2} and 7.9 g $m^{-2}d^{-1}$. The less densely planted side was more productive than the denser planting, with 1634 g m^{-2} and 18.8 g $m^{-2}d^{-1}$ of biomass vs. 1156 g m^{-2} and 13.3 g $m^{-2}d^{-1}$; and a seed harvest of 812.3 g m^{-2} and 9.3 g $m^{-2}d^{-1}$ vs. 566.5 g m^{-2} and 6.5 g $m^{-2}d^{-1}$. Harvest index was 0.49 for the wheat crop. The experiment with sweet potato used TU-82-155 a compact variety developed at Tuskegee University. Light during the sweet potato experiment, on a 18 h on/6 h dark cycle, totaled 5568 total moles of light per square meter in 126 days for the sweet potatoes, or an average of 44.2 mol $m^{-2}d^{-1}$. Temperature regime was 28 ± 3 °C day/ 22 ± 4 °C night. Sweet potato tuber yield was 39.7 kg wet weight, or an average of 7.4 kg m^{-2}, and 7.7 kg dry weight of tubers since dry weight was about 18.6% wet weight. Average per day production was 58.7 g $m^{-2}d^{-1}$ wet weight and 11.3 g $m^{-2}d^{-1}$. For the wheat, average light efficiency was 0.34 g biomass per mole, and 0.17 g seed per mole. The best area of wheat had an efficiency of light utilization of 0.51 g biomass per mole and 0.22 g seed per mole. For the sweet potato crop, light efficiency per tuber wet weight was 1.33 g mol^{-1} and 0.34 g dry weight of tuber per mole of light. The best area of tuber production had 1.77 g mol^{-1} wet weight and 0.34 g mol^{-1} of light dry weight. The Laboratory Biosphere experiment's light efficiency was somewhat higher than the USU field results but somewhat below greenhouse trials at comparable light levels, and the best portion of the crop at 0.22 g mol^{-1} was in-between those values. Sweet potato production was overall close to 50% higher than trials using hydroponic methods with TU-82-155 at NASA JSC. Compared to projected yields for the Mars on Earth life support system, these wheat yields were about 15% higher, and the sweet potato yields averaged over 80% higher.

Keywords: Closed ecological system; Bioregenerative; Dwarf wheat; Sweet potato; Light efficiency; Crop yields; Life support

1. Introduction

Results from two experiments in the Laboratory Biosphere (Dempster et al., 2004; Nelson et al., 2003), a soil-based closed ecological system in Santa Fe, New Mexico using wheat and sweet potato are reported.

The wheat variety used was Utah State University (USU) Apogee wheat (Bugbee and Koerner, 1997). Apogee is a dwarf wheat (around 50 cm tall), a cross between super dwarf wheat and Parula wheat about half the height of normal field wheat, developed for high yields in space, characterized by few tillers (side

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branches) and smaller, more efficient, leaves than normal wheat. It has been tested both at USU and at the Kennedy Space Center (Wheeler et al., 1996) and grown in an experiment on space station MIR. It has a very high harvest index and good response to high intensity lighting, both characteristics that make them ideal for bioregenerative life support systems (Bugbee and Salisbury, 1989).

The sweet potato variety was TU-82-155 sweet potato developed by the George Washington Carver Agricultural Experiment Station at Tuskegee University. This cultivar exhibits a compact growth habit, early bulking, medium dry matter, resistance to disease, and is tolerant of reduced light and carbon dioxide enrichment. The variety was developed from open pollination of maternal parent "Carver" and selection was made for desirable characteristics including earliness, high dry matter, resistance to diseases and compact growth. From a large population of breeding lines, this cultivar was selected based on its high and stable storage root yield, earliness and dry matter content. It is resistant to Fusarium wilt and has some resistance to sclerotial blight (Tuskegee University, 1999). It has undergone testing in the Variable Pressure Growth Chamber Controlled Environment Facility at Johnson Space (Barta et al., 2000).

2. Planting densities

Wheat: the west bed was planted with 400 seeds m^{-2} (5 cm × 5 cm) and the east bed with 800 seeds m^{-2} a spacing of 3.5 cm × 3.5 cm. Since previous USU and Kennedy Space Center work with wheat has been in hydroponic culture with a medium for holding the seeds, we wanted to evaluate in a soil-based system the impact of crop density on crop development and yield. The wheat was covered with plastic sheeting and kept without light for three days after planting to retain moisture and hasten germination. Surviving plant density was 225–355 m^{-2} (average 283 over six subsections) on the west bed, and 341–707 m^{-2} (average 503 over six subsections) on the east bed (Table 1).

Sweet potato: sweet potato cuttings were planted 25 cm (10 inches) apart, measured from the center of the cuttings. Thirty six cuttings were planted on each of the east and west beds.

By planting in a hexagonal pattern it is possible in principle to realize 15.5% higher density than using a square pattern while maintaining any given minimum spacing between plants. Constraints of edge effects will interfere with the ideal as the plant spacing dimensions begin to approach the dimensions of the bed. The hexagonal pattern maximized planting density for wheat which was closely spaced, and allowed 36 sweet potato on each side as compared to 32 which would have resulted from a square pattern at 25 cm.

3. Light, temperature and other environmental conditions for the crops

Wheat: considerable experience with wheat in small controlled chamber work has demonstrated the advantages of phasic control of day length and temperature to maximize harvest index and crop yield. For example, while long day lengths shorten time for maturity in wheat crops, some delay increases overall and per-day

Table 1
Above-ground biomass and seed yield, Apogee wheat in Laboratory Biosphere, February–May 2003

Sections	Length of crop (days)	No. of plants	No. of heads	Average no. heads per plant	Above ground Biomass incl. seed (g)	Biomass ($g\ m^{-2}$)	Seed yield (g)	Seed yield ($g\ m^{-2}$)
West soil bed								
NW path	85	114	324	2.8	735.4	1643.4	360.8	806.3
NW window	85	101	289	2.9	589.4	1317.1	305.8	683.4
Middle path	87	159	410	2.6	749.3	1674.4	378.5	845.8
Middle window	87	141	329	2.3	650.4	1452.5	339.7	759.1
SW path	89	113	391	3.5	934.3	2087.8	410.1	916.4
SW window	89	132	385	2.9	728.4	1626.8	386.0	862.6
Total west bed (2.69 m^2)		760	2128	2.8	4387.2	1634.0	2180.9	812.3
East soil bed								
NE path	85	153	343	2.2	393.7	879.8	188.2	420.6
NE window	85	196	385	2.0	317.9	710.4	202.7	453.0
Middle path	87	194	281	1.4	430.3	961.6	209.1	467.3
Middle window	87	317	362	1.1	518.1	1157.8	260.1	581.2
SE path	89	252	312	1.2	635.1	1419.2	301.4	673.5
SE window	89	242	319	1.3	807.8	1805.1	359.1	802.5
Total east bed (2.69 m^2)		1354	2002	1.5	3102.9	1155.3	1520.6	566.3
Total Laboratory Biosphere		2114	4130	2.0	7490.1	1394.8	3701.5	689.3

Yields were higher on the west side where seeds were planted half as densely as on the east side.

yields. Thus, although Apogee wheat with continuous light (24 h) might have a crop length as short as 62 days, it has been shown that optimal yields are obtained when crop maturation is slowed down by having some dark period each day and by lower temperatures during the flowering and seed-filling portions of the crop cycle. Previous research has also shown that higher temperatures during initial vegetative growth are beneficial to the dwarf wheat varieties (Bugbee and Salisbury, 1989; Salisbury et al., 1987).

Therefore, the experimental parameters called for temperature to be maintained for the first 20–25 days (until anthesis) at 23–25 °C (73–77 °F) and after flowering until the end: 20 °C max in light (68 °F) – and 17 °C (62 °F) in dark periods. Lighting regime was 16 h of light – 8 h dark at a total light intensity of around 840 mol $m^{-2} s^{-1}$ and 48.4 mol $m^{-2} d^{-1}$ over 84 days on average to harvest (the three initial days were without light) or an average total light input of 4064 mol m^{-2}.

Sweet potatoes: the lighting cycle was approximately 18 h of light/6 h dark since this variety of sweet potato does not do well with continuous light, and yields decline at more than 18 h of light per day (Mortley, pers. comm.). The experimental protocol for light intensity called for 600–700 μmol PPF $m^{-2} s^{-1}$, or 38.9–45.4 mol $m^{-2} d^{-1}$. Actual light during the sweet potato experiment totaled 5568 total moles of light in 126 days for the sweet potatoes, or an average of 44.2 mol $m^{-2} d^{-1}$. Temperature regime was 28 ± 3 °C day/22 ± 4 °C night. Control of relative humidity (RH) was considered more important than during the wheat experiment since previous work in RH studies comparing 50% and 85%, a 29% greater root yield was obtained at the higher RH, but lower foliage yield (Mortley, pers. comm.). It is believed that high RH benefit plant growth through either increased stomatal conductance and by extension increased CO_2 uptake for photosynthesis or from increased cell expansion and thus increased leaf area again for photosynthesis or a combination of both. RH parameters goals for the experiment were to maintain RH between 70% and 80% during the light, and provide for adequate air circulation and allow night time RH to climb to 85–90%.

4. Results

4.1. Crop yield – total aboveground biomass, seed yield, harvest index

Wheat: Table 1 gives the harvest data for the Apogee wheat crop. Total aboveground biomass was 7490.1 g, with 3701.5 g of seed from 5.37 m^2 of soil for a crop harvested after 85–89 days (harvest was done in stages over five days).

Average biomass was 1395 g m^{-2}, 16.0 g $m^{-2} d^{-1}$ and average seed production was 689 g m^{-2} and 7.9 g $m^{-2} d^{-1}$. The less densely planted side was more productive than the denser planting, with 1634 g m^{-2} and 18.8 g $m^{-2} d^{-1}$ of biomass vs. 1156 g m^{-2} and 13.3 g $m^{-2} d^{-1}$; and a seed harvest of 812.3 g m^{-2} and 9.3 g $m^{-2} d^{-1}$ vs. 566.5 g m^{-2} and 6.5 g $m^{-2} d^{-1}$. The best area of the less dense planting produced 2090 g m^{-2} of biomass, 24.0 g $m^{-2} d^{-1}$; and 917 g m^{-2} of seed, 10.5 g $m^{-2} d^{-1}$. The overall harvest index was 0.49 for the entire crop, and virtually the same for the two planting beds.

The sweet potato crop experiment ran for 126 days. Aboveground biomass is summarized in Table 2. The data show that aboveground biomass (wet weight) was almost 50% higher on the east side of the Laboratory Biosphere (6.7 kg vs. 4.5 kg), and dry weight was some 40% higher. There was considerable variance, with the best side on the west side exceeding aboveground biomass production of the poorest section of the east.

Sweet potato tuber harvest data is presented in Table 3. To estimate dry weight, three average sized potatoes from each section were selected. A half inch section was cut from each potato and weighed in sections wet and then dried for 15 days at 46 °C. Dry weight percentage varied from 18.7% to 21.2% of wet weight, and the average percentage for each section was used in comput-

Table 2
Aboveground biomass for sweet potato crop in Laboratory Biosphere experiment, September 2003–January 2004

Section	Wet weight (kg)	Dry weight (kg)	Dry weight (g m^{-2})	Dry weight (g m^{-2})
East side bed				
SE	1.85	0.6	670.4	5.3
ME	2.2	0.8	893.9	7.1
NE	2.65	0.95	1.06	8.4
Total (average) east side	6.7	2.35	875	6.9
West side bed				
SW	1.3	0.5	558.7	4.4
MW	1.45	0.55	614.5	4.9
NW	2.1	0.63	704	5.6
Total (average) west side	4.85	168	625.7	5.0

Density of planting of sweet potato was equal on west and east side.

Table 3
Tuber harvest data for sweet potato crop experiment in Laboratory Biosphere, September 2003–January 2004

	Weight of wet tubers	No. of tubers	Average weight per tuber	Dry weight (kg)	Dry weight ($g\ m^{-2}$)	Wet weight ($g\ m^{-2}$)	Wet weight ($g\ m^{-2} d^{-1}$)	Dry weight ($g\ m^{-2} d^{-1}$)
East bed								
SE	8.8	72	0.12	1.68	1880	9830	78.0	14.9
ME	6.1	75	0.08	1.21	1350	6820	54.1	10.7
NE	8.3	49	0.17	1.56	1740	9270	73.6	13.8
Total (average) east bed	23.2	196	0.12	4.45	1660	8640	68.6	13.2
West bed								
SW	5.2	71	0.07	1.10	1220	5810	46.1	9.7
MW	5.1	82	0.06	0.95	1060	5700	45.2	8.4
NW	6.2	82	0.08	1.17	1310	6920	54.9	10.3
Total (average) west bed	16.5	235	0.07	3.22	1190	6150	48.8	9.4
Total	39.7	431	0.09	7.68	1430	7390	58.7	11.3

The reason for yield differences is at present unknown, although micro-variability of environmental parameters such as humidity and temperatures at crop level may exist.

ing dry weight yields. The data show that as with above-ground biomass, the east soil bed produced significantly higher yield of tuber than the west (in wet weight, 23.2 kg vs. 16.7 kg, a difference of 39% and in dry weight 4.45 kg vs. 3.32 kg, a difference of 34%). The best section of the west bed had a comparable tuber harvest to the poorest section on the east. Tuber size showed significant differences as well, with the average tuber on the east weighing 120 g and the average tuber on the west 70 g. There were no obvious differences to account for these results although, it is possible that differences in micro-environmental conditions, such as temperature and RH at the level of the crop, might be responsible. The best side during wheat production was different than the best side during the sweet potato experiment.

4.2. Light efficiency of the crops

For the wheat, average light efficiency was 0.34 g biomass per mole, and 0.17 g seed per mole. The best area of wheat had an efficiency of light utilization of 0.51 g biomass per mole and 0.22 g seed per mole.

For the sweet potato crop, light efficiency per tuber wet weight was 1.33 g mol^{-1} and 0.26 g dry weight of tuber per mole of light. The best area of tuber production had 1.77 g mol^{-1} wet weight and 0.34 g mol^{-1} of light dry weight.

5. Discussion

Harvest indices of 0.56 and 0.60 were reported for Apogee in greenhouse studies and light efficiency for Apogee has ranged from 0.3 g seed/mol of light in greenhouse trials to 0.15 g seed/mol in field studies (Bugbee and Koerner, 1997). The Laboratory Biosphere experiment's light efficiency was somewhat higher than the field results and the best portion of the crop at 0.22 g mol^{-1} was in-between those values. Using Yecoro Rojo, a predecessor dwarf wheat variety to Apogee, studies in the Kennedy Space Center (KSC) Breadboard facility reported average light efficiency of 0.18 g seed/mol (Wheeler et al., 1996).

Wheat yields in the Laboratory Biosphere can be compared with the NASA KSC Breadboard, seed production from Yecoro Rojo averaged 760 g m^{-2}, about 10% higher than the average seed production in the Laboratory Biosphere experiment. Best yields from Yecoro Rojo were 12.6 g seed $m^{-2} d^{-1}$ (at 24 h illumination with 57.5 mol $m^{-2} d^{-1}$) compared with the Laboratory Biosphere's average seed yield of 7.9 mol $m^{-2} d^{-1}$ and best area of 10.5 mol $m^{-2} d^{-1}$. However, when we compare a crop grown at comparable light input (49 mol $m^{-2} d^{-1}$) the yield for Yecoro was 8.1 mol $m^{-2} d^{-1}$ (Wheeler et al., 1996), not too different from the Laboratory Biosphere production. Earlier reports by (Salisbury et al., 1987) had reported yields of Yecoro Rojo in greenhouse studies as 504 g m^{-2} but in controlled chambers as high as 1224 g m^{-2} and 19 g $m^{-2} d^{-1}$.

At 45 mol $m^{-2} d^{-1}$ of light, Bugbee and Salisbury report that typical field agricultural wheat yields are 6 14 g $m^{-2} d^{-1}$, record field yields are 14 g $m^{-2} d^{-1}$ and Utah State University CELSS program controlled environmental chamber studies have produced 27 g $m^{-2} d^{-1}$. Yield increases with light input: at 150 mol $m^{-2} d^{-1}$, wheat production soars to 60 g $m^{-2} d^{-1}$, but efficiency of light utilization drops from 4.4% to 2.9% (Bugbee and Salisbury, 1989). Compared with Biosphere 2 production of wheat at relatively low light inputs (from 6.4 to 16.4 mol $m^{-2} d^{-1}$), with average wheat production of 120 g seed m^{-2}, the average production from this study is over five times higher, and the best area over seven times higher. At the highest light in Biosphere 2, 16.4 mol $m^{-2} d^{-1}$, yield was 240 g m^{-2}, about 1/3 that of the current study; total light was 2022 mol m^{-2} (about half of this study) and light efficiency was

0.12 g seed/mol, about 30% less efficient than the wheat crop in the Laboratory Biosphere (Silverstone and Nelson, 1996).

Projected yields for wheat for the planned Mars on Earth bioregenerative life support facility (Salisbury et al., 2002) were taken at three times average Biosphere 2 wheat yields to reflect using increased light levels ($50\ mol\ m^{-2}\ d^{-1}$) and were $7.3\ g\ m^{-2}\ d^{-1}$ (Silverstone et al., 2003). The current yields in the Laboratory Biosphere at $7.9\ g\ m^{-2}\ d^{-1}$ were thus 8% better than those projections, and the west side at $9.3\ g\ m^{-2}\ d^{-1}$ had a yield 27% better than Mars on Earth projections.

In three sweet potato crops in Biosphere 2, yields tracked increased light levels: at $7\ mol\ m^{-2}\ d^{-1}$, edible yield was $1.3\ kg\ m^{-2}$, at $14.6\ mol\ m^{-2}\ d^{-1}$, yield was $1.8\ kg\ m^{-2}$ and at $22.7\ mol\ m^{-2}$, yield was $2.9\ kg\ m^{-2}$ (all yields reported were fresh weight). Light efficiency for the three crops was $1.0\ g\ mol^{-1}$, $0.6\ g\ mol^{-1}$ and $0.8\ g\ mol^{-1}$, respectively (Silverstone and Nelson, 1996).

The anticipated yields of sweet potato for the Mars on Earth facility were extrapolated at twice Biosphere 2's best yields of $16\ g\ m^{-2}\ d^{-1}$ (at $25\ mol\ m^{-2}\ d^{-1}$) or $32\ g\ m^{-2}\ d^{-1}$ (Silverstone et al., 2003). The experiment in the Laboratory Biosphere at around $44\ mol\ m^{-2}\ d^{-1}$ averaged $58.7\ g\ m^{-2}\ d^{-1}$ were therefore 83% higher than the yield data projected for the Mars on Earth facility. The best side (the east) was over twice the projected yields, and the poorer side (the west) was still 50% higher.

Barta et al. (2000) grew TU-82-155 in hydroponic solution in a controlled environmental chamber at the Bioplex at Johnson Space Center, with a plant density of 17 plants m^{-2} and a photoperiod of 12 h light: 12 h dark. The photosynthetic photon flux was maintained at 500, 750 and $1000\ \mu mol\ m^{-2}\ s^{-1}$ during days 1–15, 16–28, 29-until harvest respectively at day 119. This is equivalent to 21.6, 32.4 and $43.2\ mol\ d^{-1}$ during these three periods of crop growth. 56.5 kg fresh mass of storage roots (84.1% moisture) were harvested from the $11.2\ m^2$ chamber, resulting in a yield $5.0\ kg\ m^{-2}$. Harvest index, based on fresh mass, was 38.6% or $42\ g\ m^{-2}\ d^{-1}$ (Barta et al., 2000). Total light during this experiment was $4676.4\ mol\ m^{-2}$. Dry weight harvest of sweet potato was $0.80\ kg\ m^{-2}$ ($5.045\ kg\ m^{-2}$ times 0.159 dry wet fraction). Light efficiency for the crop was $26.7\ mol\ m^{-2}$ carbohydrate and 0.57% mole efficiency. Harvest yield was therefore about $5\ kg\ m^{-2}$ or about 68% of the yield of the sweet potato tuber harvest in the Laboratory Biosphere experiment.

These results suggest that yields from candidate space crops grown in soil conditions can be competitive with those previously grown in hydroponic culture, and in some cases (e.g., the sweet potato root crop) may exceed them. Light efficiency is also comparable. The significance for space applications when soils may be created by amending in situ planetary resources will be the potential to reduce dependence on highly technical systems which rely on provision of consumables like hydroponic chemicals.

References

Barta, D.J., Henderson, K.E., Mortley, D.G., Henninger, D.L. Gas exchange, transpiration and yield of sweet potato grown in a controlled environment (Abstract). Life Support Biosphere Sci. 7 (1), 46, 2000.

Bugbee, B., Koerner, G. Yield comparisons and unique characteristics of the dwarf wheat cultivar "USU-Apogee". Adv. Space Res. 20 (10), 1891–1894, 1997.

Bugbee, B., Salisbury, F.B. Current and potential productivity of wheat for a controlled environment life support system. Adv. Space Res. 9 (8), 5–15, 1989.

Dempster, W.F., Alling, A., van Thillo, M., Allen, J.P., Silverstone, S., Nelson, M. Technical review of the Laboratory Biosphere closed ecological system facility. Adv. Space Res. 34, 1477–1482, 2004.

Nelson, M., Dempster, W.F., Alling, A., Allen, J.P., Rasmussen, R., Silverstone, S., Van Thillo, M. Initial experimental results from the Laboratory Biosphere closed ecological system facility. Adv. Space Res. 31 (7), 1721–1730, 2003.

Salisbury, F.B., Dempster, W.F., Allen, J.P., Alling, A., Bubenheim, D., Nelson, M., Silverstone, S. Light, plants and power for life support on mars. Life Support Biosphere Sci. 8, 161–172, 2002.

Salisbury, F.B., Bugbee, B., Bubenheim, D. Wheat production in controlled environments. Adv. Space Res. 7 (4), 123–132, 1987.

Silverstone, S., Nelson, M., Alling, A., Allen, J. Development and research program for a soil-based bioregenerative agriculture system to feed a four person crew at a Mars Base. Adv. Space Res. 31 (1), 69–75, 2003.

Silverstone, S.E., Nelson, M. Food production and nutrition in Biosphere 2: results from the first mission September 1991 to September 1993. Adv. Space Res. 18 (4/5), 49–61, 1996.

Tuskegee University, 1999. Announcement of release of sweet potato cultivar TU-82-155.

Wheeler, R.M., Mackowiak, C., Stutte, G., Sager, J., Yorio, N., Ruffe, L., Fortson, R., Dreschel, T., Knott, W., Corey, K.A. NASA's Biomass Production Chamber: a testbed for bioregenerative life support studies. Adv. Space Res. 18 (45), 215–224, 1996.