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Cowpeas and pinto beans: Performance and yields of candidate space crops in the laboratory biosphere closed ecological system

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Abstract

An experiment utilizing cowpeas (*Vigna unguiculata* L.), pinto beans (*Phaseolus vulgaris* L.) and Apogee ultra-dwarf wheat (*Triticum sativa* L.) was conducted in the soil-based closed ecological facility, Laboratory Biosphere, from February to May 2005. The lighting regime was 13 h light/11 h dark at a light intensity of 960 μmol m^{-2} s^{-1}, 45 mol m^{-2} day^{-1} supplied by high-pressure sodium lamps. The pinto beans and cowpeas were grown at two different planting densities. Pinto bean production was 341.5 g dry seed m^{-2} (5.42 g m^{-2} day^{-1}) and 579.5 dry seed m^{-2} (9.20 g m^{-2} day^{-1}) at planted densities of 32.5 plants m^{-2} and 37.5 plants m^{-2}, respectively. Cowpea yielded 187.9 g dry seed m^{-2} (2.21 g m^{-2} day^{-1}) and 348.8 dry seed m^{-2} (4.10 g m^{-2} day^{-1}) at planted densities of 20.8 plants m^{-2} and 27.7 plants m^{-2}, respectively. The crop was grown at elevated atmospheric carbon dioxide levels, with levels ranging from 300–3000 ppm daily during the majority of the crop cycle. During early stages (first 10 days) of the crop, CO_2 was allowed to rise to 7860 ppm while soil respiration dominated, and then was brought down by plant photosynthesis. CO_2 was injected 27 times during days 29–71 to replenish CO_2 used by the crop during photosynthesis. Temperature regime was 24–28 °C day/deg 20–24 °C night. Pinto bean matured and was harvested 20 days earlier than is typical for this variety, while the cowpea, which had trouble establishing, took 25 days more for harvest than typical for this variety. Productivity and atmospheric dynamic results of these studies contribute toward the design of an envisioned ground-based test bed prototype Mars base.

Keywords: Closed ecological system; Bioregenerative; Cowpea (*Vigna unguiculata* L.); Pinto bean (*Phaseolus vulgaris* L.); Space agriculture; Sweet potato; Light efficiency; Crop yields; Enhanced CO_2; Life support; Space candidate crops; Laboratory Biosphere

1. Introduction

An experiment which utilized a mixture of candidate space life support crops was conducted 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, pinto bean and cowpea from 4 February to 7 May 2005. Laboratory Biosphere is tightly sealed closed ecological system in the shape of a horizontal steel cylinder 3.68 m long × 3.65 m diameter. Two soil beds on the east and west side of a central walkway are each 2.13 m long × 1.26 m wide × 30 cm deep providing a total growing area of 5.37 m^2. Twelve 1000 watt high pressure sodium lamps provide plant growth lighting. An internal air handling system through which cold refrigerant is delivered from outside is provided for temperature control. A complete technical description of Laboratory Biosphere is found in Dempster et al. (2004).

The cowpea variety used was Texas Pink-eye (TXPE) (*Vigna unguiculata*), supplied by plant breed researchers at Texas A&M University (with the cooperation of Prof. Creighton Miller and Research Associate Douglas Scheuring). The variety originated from a cross of TX63-7, a

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breeding line from the Texas program, and US-432 of the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) (Fery and Dukes, 1990). The specific cultivar used was TX123 BE, a type of Texas Pink-eye. Texas Pink-eye is a bush-type of southern pea. The variety was developed for the following improvements: the erect bush-habit, without runners facilitates narrow-row spacing; low amount of lodging, seed-shattering and loss in the field; tends to ripen most of its seeds at one time and above foliage height which permits easier harvesting; matures at nominally 60 days, ten days earlier than most other southern peas; resistant to chlorosis in calcareous or alkaline soils (which has been a problem in the Laboratory Biosphere soils originally collected in New Mexico) and to root knot and mosaic virus (Miller and Scheuring, 1994, 1993).

The pinto bean (*Phaseolus vulgaris* L.) variety used was Grand Mesa, developed and supplied by Prof. Mark Brick of Colorado State University. Grand Mesa is a medium maturity variety, typically harvested 94 days after planting (Brick et al., 2005). It was released in 2001 and has been developed with resistance to rust, common mosaic virus and white mold. It has an upright growth habit and is day-neutral.

Both legume species have been advocated as candidate crops for space agriculture. Leguminous crops are high protein sources and add nitrogen to soils. They require rhizobium innoculant in soils where they have not grown before. Both beans are self-pollinating and thus can provide seed for continuing sustainable production. Pinto beans have relatively good drought resistance, and are planted in both dryland and irrigated situations in the southwest of the U.S. They are susceptible to iron deficiency in strongly alkaline soil (higher than pH 8.0) or in heavy phosphorus soils, but this can be avoided with balanced fertilization and soil management. They require soil temperatures above 16 °C and germinate and grow best when temperatures range from 21 to 25 °C. Pinto beans will not set pods on blossoms with temperatures above 36 °C (Texas Guide, 2002). Cowpeas are also a versatile legume, grown in rainfall conditions from 275 to 400 mm, usually grown in field conditions without irrigation, and in a variety of soils with pH from 4.3 to 7.9. But, as with most crops, a well-drained soil with good water availability helps increase yields. Cowpea is moderately shade tolerant and is a summer annual with a crop cycle of 60–90 days for the earlier maturing varieties. Its young leaves are also edible, providing up to 25% protein; its green bean pods can be cooked and its dry seeds provide 24.8% protein (Davis et al., 1991). Pinto bean and cowpea varieties number in the thousands, and include both day-neutral and short-day varieties, which lend great flexibility to their use in the controlled environments of space agriculture. The varieties used in this experiment were both day-neutral.

The ultra-dwarf Apogee wheat (Bugbee and Koerner, 1997) was included to take advantage of the supply of a small amount of wheat dexcended from wheat which was grown to seed aboard the Mir space station. The seed was supplied by Dr. Galina Nechitailo with the intent to look at the growth characteristics and genetics of the space-descended wheat vs. normal Apogee ultra-dwarf wheat. The area planted to wheat included for comparison two rows of Apogee wheat collected from wheat previously grown in the Laboratory Biosphere (Nelson et al., 2005). The wheat results will be reported in a separate paper as the genetic studies are not yet complete.

2. Methodology

2.1. Planting densities/drying of crop

The cowpea was planted on the east side soil bed at two densities: 21 plants per square meter on the westside and 28 plants per square meter on the eastside of the soil bed. Over the 1.30 m^2 for each density, this amounted to 27 and 36 cowpea plants, respectively. The pinto bean was planted at 32.5 plants per m^2, and 37.5 plants per m^2. The pinto bean shared the west soil bed of the Laboratory Biosphere with the ultra dwarf wheat, so each planting covered 0.8 m^2, and the total number of plants was 26 for the less dense and 30 plants for the denser planting, on the north and south sides of the west soil bed, respectively.

Inedible crop residues (stems, leaves, pod husks) were first separated from the edible seeds and dried for about 4 days at 32 °C until loss of weight ceased. The seeds were first dried, whole, for 24 h at 32 °C to obtain partly dry, but viable seed for possible future use. Then subsamples were taken, dried for 46 h at 65 °C, finely ground, then dried for 8 more hours at 65 °C. No further weight loss occurred after being ground. The cowpea samples lost about 10% of their partly dry weight and the pinto bean samples lost about 14% of their partly dry weight during the 65 °C drying phase. The fully dry weights reported here are for all the harvested seeds assuming the same percentage weight losses as were observed in the samples.

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

Light was supplied by twelve overhead high pressure sodium lamps, each 1000 watts. Light regime was 13 hours light and 11 hours dark. Low-levels of light were maintained for the first week of the experiment, until plants germinated. Then light input at 960 $\mu mol\ m^{-2}\ s^{-1}$ averaged 44.9 $mol\ m^{-2}\ day^{-1}$.

Temperatures during light hours ranged from 21 to 29 °C and were kept somewhat cooler at night, 20–24 °C. The lower nighttime temperatures were probably not optimal for the pinto beans and cowpeas but were dictated by the production of wheat at the same time, which benefits from lower temperatures. These lower nighttime temperatures would be expected to slightly lower yield. Relative humidity in the Laboratory Biosphere mainly fluctuated between 42% and 55% during light hours during the bulk

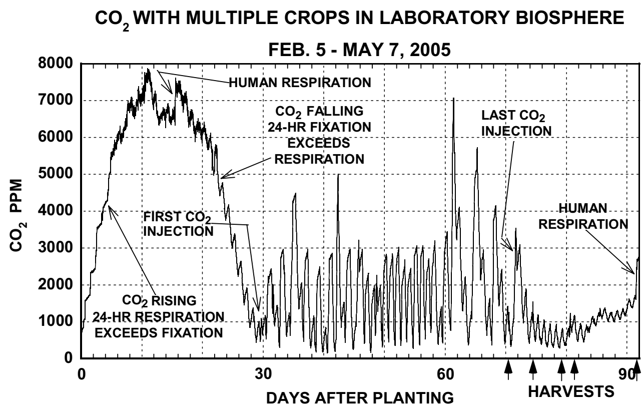

Fig. 1. Atmospheric carbon dioxide concentrations in the Laboratory Biosphere during the experiment. Pinto bean (which occupied 32% of the cropping area) was harvested at day 70 and 74, wheat (18% of area) at days 79 and 81, and cowpea (50% of area) at day 91 when the experiment was terminated. Early rise of carbon dioxide concentrations was due to dominance of soil respiration and human respiration from entries to the facility during planting while plants were germinating and young. There were 27 injections of carbon dioxide during days 27–71. Drawdown was by photosynthesis.

of the growth period of the crops, and 35–45% during early and later stages when plant transpiration was decreased. Humidity increased to the 75–85% range at night.

Carbon dioxide in the atmosphere was supplied by soil respiration during early germination periods and after senescence, and by 27 injections during days 29–71 from a gas cylinder, was mostly maintained in the 300–3000 ppm range with a few excursions. The sharp rise in carbon dioxide at the beginning stages of the experiment was also due to human presence (respiration) in the facility for crop-tending activities. There was strong photosynthetic draw down of CO_2 during light hours by the crop. During the first 11 days of the crop, with soil respiration dominating, atmospheric CO_2 levels rose to around 7500 ppm. During days 12–28, photosynthesis drew CO_2 down to 444 ppm and then injections of CO_2 commenced (see Fig. 1). The wide range of CO_2 concentrations enabled observation of widely varying CO_2 fixation rates at the many different concentrations (see Dempster et al., in press, for discussion of atmospheric dynamics during the experiment).

4. Results

4.1. Phenology

Compared to normal field-grown Grand Mesa pinto beans (Brick et al., 2005), flowering was seen at day 30 rather than 51 days and they appeared ready to harvest after 63 days rather than 94 (Table 1). In Texas, harvest is normally 65–80 days after planting for Texas Pink-eye, but since that harvest is done mechanically, it is usually done when an optimum crop of the seed pods is ready for harvest. In the Laboratory Biosphere we waited until the crop was fully mature since harvesting was by hand, and fallen pods could be easily collected. The cowpeas were slow to establish and appeared ready for harvest at 85 days and were harvested on day 91, somewhat longer than the 65–80-day norm for this variety. Part of this may have been caused by poor germination and the need to fill gaps with greenhouse grown plants in peat pots at day 10.

4.2. Crop data

Table 2 summarizes environmental conditions, the harvest data and efficiency indices for the cowpea and pinto bean crops. We note substantial differences between the denser and less dense plantings, although we also know there are microclimatic differences due to directionality and non-uniformity of air circulation within the system. Consequently the air may be warmer or cooler, dryer or moister at one exact location than another due to the com-

Table 1
Phenology of the cowpea and pinto bean crops in the Laboratory Biosphere

Day after planting	Pinto beans	Cowpea
7	Half the plants emergent	1/4 to 1/2 the plants are emergent
10		Non-emergent plants replaced with seeds started in pots in a greenhouse on day 0
12	Some putting out second pair of leaves	
14	Some plants have three pairs of leaves	Some putting out second pair of leaves
21	The best plants are 12–20 cm tall	The tallest are 10–15 cm tall
30	2/3 of plants have vining tendrils up to 60 cm, flower buds on lower leaf axils	
35	Stakes placed to support height of stems	3–6 leaves per plant, several with vines
43	First fruiting observed	8–10 leaves, most with vines 7.5–30 cm
45		First flowers
63	Leaves yellowing, dying back. Pods with pink stripes appear harvest ready; plants appear senescent aside from some top green viny end	Some mature pods are deep purple, plants are up to 120 cm tall
70	North area harvested, 26 plants	
74	South area harvested, 30 plants	
85		Plants appear senescent and ready to harvest
91		Harvested all plants

Table 2
Summary of environmental parameters, planting and yields of the cowpea and pinto bean crops in the Laboratory Biosphere

	Cowpea West soil bed eastside	Cowpea West soil bed westside	Cowpea totals	Pinto bean East soil bed northside	Pinto bean East soil bed southside	Pinto bean totals
Planting						
Square meters	1.3	1.3	2.6	0.8	0.8	1.6
Total plants	27	36	63	26	30	56
Plants (m^{-2})	20.8	27.7	24.2	32.5	37.5	35
Production						
Dry non-edible (g)	389.0	874.6	1263.6	196.2	334.3	530.4
Seed yield partly dry (total grams)	270.3	501.8	772.1	315.4	537.4	852.8
Seed yield fully dry (total grams)	244.3	453.4	697.7	273.2	463.6	736.8
Seed yield fully dry ($g\,m^{-2}$)	187.9	348.8	268.3	341.5	579.5	460.5
Harvest index (%)	38.6	34.1	35.6	58.2	58.1	58.1
Harvest ready at day	85	85	85	63	63	63
Edible yield rate ($g\,m^{-2}\,day^{-1}$)	2.21	4.10	3.16	5.42	9.20	7.31
Light						
Integrated total ($mol\,m^{-2}$)	3651	3651	3651	2662	2662	2662
Avg. ($mol\,m^{-2}\,day^{-1}$)	42.9	42.9	42.9	42.3	42.3	42.3
Light efficiency						
Light efficiency (edible $g\,mol^{-1}$)	0.051	0.096	0.074	0.128	0.218	0.173
Light efficiency (total $g\,mol^{-1}$)	0.133	0.280	0.207	0.220	0.375	0.298
Light efficiency (total $mol\,mol^{-1}$, %)	0.445	0.933	0.689	0.735	1.249	0.992
Electrical energy, lighting						
Electrical energy for light ($kWh\,m^{-2}$)	2196	2196	2196	1601	1601	1601
Electrical efficiency ($g\,kWh^{-1}$ edible)	0.086	0.159	0.122	0.213	0.362	0.298
Electrical efficiency ($g\,kWh^{-1}$ total)	0.222	0.465	0.344	0.366	0.623	0.495
Electrical to chemical energy						
Edible (% conversion)	0.045	0.084	0.065	0.113	0.191	0.152
Total biomass (% conversion)	0.117	0.246	0.182	0.194	0.329	0.262
Average (ppm CO_2)						
First 10 days	4429	4429	4429	4429	4429	4429
Middle period	2820	2820	2820	3233	3233	3233
Last 10 days	763	763	763	2195	2195	2195
Planting to harvest	2798	2798	2798	3298	3298	3298

Partly dry was oven-dried seed at 32 °C, fully dry was after further drying at 65 °C (see text).

bined effects of evapotranspiration and heating of the airstream by light energy. Accurate data acquisition of temperature and humidity for these fine locational differences has not been done. Accordingly, we note the productivity differences, but do not necessarily attribute them entirely to planting densities.

For cowpea, the denser planting produced 125% more inedible biomass and 86% more seed than the less dense planting. For pinto bean, the denser planting produced 70% more inedible biomass and 70% more seed. These differences are reflected quantitatively throughout Table 2 in yields and efficiencies.

We observed that for both cowpea and pinto bean, they appeared harvest ready before the actual harvests were taken. The plants appeared senesced, were brown and dry. For pinto bean this was at day 63 (actually harvested on days 70 and 74) and for cowpea at day 85 (actually harvested on day 91). Table 2 shows production rates based on the evident harvest ready day.

5. Discussion

One of the most surprising results of this experiment was the rapid maturation of the Grand Mesa coupled with high productivity. Initiation of flowering occurred three weeks earlier (30 days vs. 51 days) than field practice and they appeared ready for harvest 31 days earlier (63 days vs. 94 days). At day 63, the plants were almost completely dried out and senesced apart from some green shoots at the tops of the bushes. Yield of seed was also high, and, with the short cropping time, the edible yield rate was considerably higher than the best field data we found (see Fig. 2). We note that the varying CO_2 concentration was nearly an order of magnitude greater than Earth's ambient concentration of around 375 ppm. If elevated CO_2 was the principal factor driving these results, it is interesting that the response in cowpea was not as marked: the Laboratory Biosphere crop time was long compared to field results with Texas Pink-eye (85 days vs. 65 days).

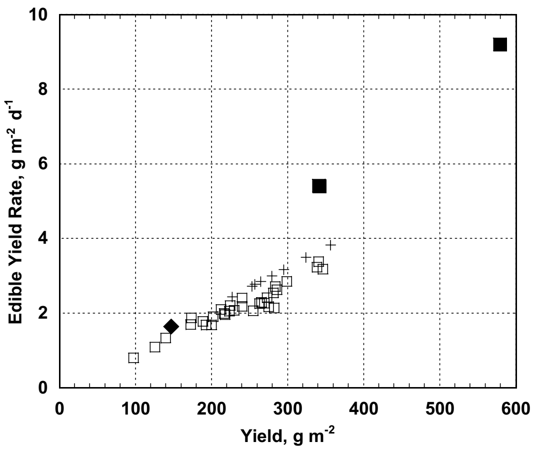

Fig. 2. Productivity of Grand Mesa pinto beans in Laboratory Biosphere compared to various field trials. All weights are for fully dry seeds, by direct measurement for Laboratory Biosphere, by subtracting the reported moisture content for the Colorado crops, and by subtracting the same average percentage moisture (12.96%) for the Arizona and Biosphere 2 crops. ■, Laboratory Biosphere 341.5 g m^{-2}, 5.42 g m^{-2} day^{-1} and 579.5 g m^{-2}, 9.20 g m^{-2} day^{-1} for north and south plots respectively. □, 32 field trials of Grand Mesa in Colorado, 1999–2005. +, eight different pinto bean varieties in Arizona, 2002 (Clark and Carpenter, 2002). ♦, one pinto bean crop in Biosphere 2, 1992 (Silverstone and Nelson, 1996).

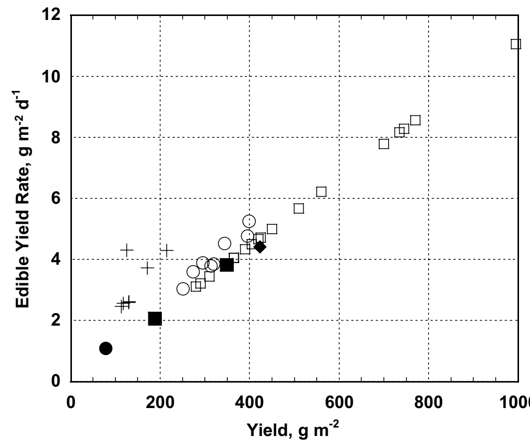

Fig. 3. Comparison of various cowpea productivities. ■, Laboratory Biosphere 187.9 g m^{-2}, 2.21 g m^{-2} day^{-1} and 348.8 g m^{-2}, 4.10 g m^{-2} day^{-1} for east and west plots, respectively, seeds only harvested. ○, purdue, artificially lit, leaves and seeds harvested (Bubenheim et al., 1990). +, purdue, artificially lit, leaves only harvested (Frantz et al., 2001). □, purdue, in a greenhouse with natural light plus various supplemental lightings (Ohler and Mitchell, 1996). ♦, blackeye pea outstanding field crops (Marsh et al., 1987). •, field grown cowpea reported by Texas A&M (Baker, 1998).

Purdue University scientists as part of their NASA-supported Bioregenerative Life Support NSCORT, tested cowpeas as a space crop. They looked at major factors including planting density, CO_2 levels and harvest strategies to increase productivity and yield of edible cowpea leaves and seeds (Ohler and Mitchell, 1996, 1995). They also examined strategies for increasing efficacy of delivery of light to crops, experimenting with "intracanopy lighting" to provide light under the canopy and reduce overall energy consumption (Frantz et al., 1998, 2001). Productivity data points from these Purdue studies are plotted in Fig. 3 with the cowpea productivities from Laboratory Biosphere in this experiment. We note that while Laboratory Biosphere pinto bean productivities exceeded field grown crops, the cowpea productivities are among the lower ranges of the Purdue studies. This suggests that substantial productivity advantages are available in controlled environments by comparison with field conditions.

Ogbuinya (1997), writing of African potentials for field agriculture, suggested that cowpea was capable of a maximum seed yield of 2500 kg hectare^{-1}, equivalent to 250 g m^{-2}. In controlled environmental conditions, yields can be greatly increased by improved environmental phasic control, CO_2 enhancement, improved lighting strategies etc.

Laboratory Biosphere studies contribute to the development plans for a prototype Mars Base bioregenerative life support facility. The design of such a facility must allow adequate cropping areas for a variety of staple and supplemental crops (Silverstone et al., 2003). The results reported here and earlier experiments with wheat and sweet potato (Nelson et al., 2005) lead to determination of required cropping areas. Understanding of the atmospheric dynamics and estimation of carbon dioxide/oxygen balances in such a bioregenerative life support facility are also furthered by these experiments in Laboratory Biosphere (Dempster et al., 2005; Dempster et al., in press).

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