WHEAT PRODUCTION IN CONTROLLED ENVIRONMENTS

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ABSTRACT

Our goal is to optimize conditions for maximum yield and quality of wheat to be used in a controlled-environment, life-support system (CELSS) in a Lunar or Martian base or perhaps in a space craft. With yields of 23 to 57 g m^{-2} d^{-1} of edible biomass, a minimum size for a CELSS would be between 12 and 30 m^2 per person, utilizing about 600 W m^{-2} of electrical energy for artificial light. Temperature, irradiance, photoperiod, carbon-dioxide levels, humidity, and wind velocity are controlled in state-of-the-art growth chambers. Nutrient solutions (adjusted for wheat) are supplied to the roots via a recirculating system that controls pH by adding HNO^3 and controlling the NO_3/NH_4 ratio in solution. A rock-wool plant support allows direct seeding and densities up to 10,000 plants per $meter^2$. Densities up to 2000 plants m^{-2} appear to increase seed yield. Biomass production increases almost linearily with increasing irradiance from 400 to 1700 µmol m^{-2} s^{-1} of photosynthetic photon flux (PPF), but the efficiency of light utilization decreases over this range. Photoperiod and temperature both have a profound influence on floral initiation, spikelet formation, stem elongation, and fertilization. High temperatures (25 to 27°C) and long days shorten the life cycle and promote rapid growth, but cooler temperatures (20°C) and shorter days greatly increase seed number per head and thus yield (g m^{-2}). The life cycle is lengthened in these conditions but yield per day (g m^{-2} d^{-1}) is still increased. We have evaluated about 600 cultivars from around the world and have developed several breeding lines for our controlled conditions. Some of our ultra-dwarf lines (30 to 50 cm tall) look especially promising with high yields and high harvest indices (percent edible biomass).

INTRODUCTION

What are the size and energy constraints on a bioregenerative system that utilizes photosynthesis of higher plants to capture light energy and convert it to the chemical bond energy of food needed to support a human being? Imagine that the human being, thanks to advanced gene-transfer techniques, could personally manage the photosynthetic conversion, absorbing and converting 100% of visible light energy into a form that could be utilized by the body. Assume that the human energy requirement is 11,700 kJ d^{-1} (2800 kcal d^{-1}). The solar constant above the earth's atmosphere is 1.36 kW m^{-2}. About half of that is photosynthetically active radiation (PAR): 0.68 kW m^{-2} or 0.68 kJ m^{-2} s^{-1}. The 11,700 kJ d^{-1} required by our hypothetical astronaut is equal to 0.135 kJ s^{-1} (kW), which divided by the 0.68 kJ m^{-2} s^{-1} PAR gives about 0.2 m^2 $person^{-1}$.

A human being intercepts an area of about 0.5 to 0.9 m^2 of sunlight, if the rays are from the front or back and normal to the long axis of the body. Thus, our hypothetical space traveler could do fairly well if he or she wore few clothes and stayed in the sun all the time in a position that would intercept about half the incoming radiation.

Not even the most efficient plant can convert 100% of absorbed PAR into the chemical-bond energy of food, however. Indeed, the theoretical maximum efficiency for photosynthesis is about 25% (based on 8 photons per molecule of fixed CO_2), and 13.5% (15 photons per molecule CO_2) is a more realistic figure. Thus, our photosynthesizing astronaut--or the best imaginable canopy of photosynthesizing plants under the best of conditions--would require about 0.8 m^2 (25% efficiency) or 1.5 m^2 (13.5% efficiency) to produce the 11,700 kJ d^{-1} that

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are required. So the photosynthesizing space dweller is already in trouble. Animals lack sufficient surface to be directly supported by photosynthesis.

Under full sunlight, few plants photosynthesize at anything approaching 13.5% efficiency. If we reduce the irradiance to half of full sunlight, we will need at least 3.0 m^2, and if our plants are in the light only about half the time (12 h d^{-1}), the value becomes 6.0 m^2. And if only about half of the biomass produced by the plant can be eaten as food (50% harvest index), the value goes up again to about 12 m^2.

If the light for photosynthesis must be generated electrically, this would require about 600 W m^{-2} if high pressure sodium (HPS) lamps are used (37.6% efficient) in the most efficient reflectors (90% efficient). This would produce a photosynthetic photon flux (PPF) of 1000 micromoles of photons per square meter per second (µmol m^{-2} s^{-1}; 200 W m^{-2} PAR), which is about half of full sunlight at the earth's surface. To irradiate 12 m^2 would require 7.2 kW. In a functioning controlled, ecological, life-support system (CELSS), additional electric power would be required to operate the environmental control system, various aspects of food processing, repair and maintenance of the equipment, waste disposal, and mineral-nutrient regeneration for the plants. In calculating the total energy requirement, energy expended by the space farmers would also have to be considered. So far, our NASA-funded CELSS project has been concerned only with the food production part of a CELSS.

Consider another approach to the calculation: One-hundred grams of typical, whole-grain, hard-red spring wheat contain about 13 g of water, 14 g of protein, 2.2 g of fat, and 69.1 g of total carbohydrate (including 2.3 g of fiber). Bomb calorimeter studies indicate that the 100 g of wheat would provide 1647 kJ (394 kcal) of food energy, and if we assume that 94% of this energy is digestible, this would provide 1500 kJ (370 kcal). To provide the 11,700 kJ d^{-1} required by a human being, about 680 g d^{-1} of oven-dry wheat (780 g d^{-1} of typical wheat) or its equivalent in other food would be required. If this were to be produced in 12 m^2, yields would have to reach 57 g m^{-2} d^{-1}. If the production area was 30 m^2, then average daily production would need to be 23 g m^{-2} d^{-1}. Even if the 30 m^2 is doubled for safety, a moon farm about the size of an American football field (about 6000 m^2 including end zones) would support 100 inhabitants of Lunar City. Our objective has been to see what yields (g m^{-2} d^{-1}) can be achieved in a totally controlled environment and thus to test the reality of these figures.

In our studies /3/, we have taken a dual approach: agronomy/physiology and plant breeding. Which environmental and cultural factors are important to achieve high yields per unit of input energy and in the least possible area? How do these factors interact with each other and exactly how do they influence ultimate yield? Is it necessary to develop new cultivars for the special environments that can be produced in a CELSS? Can we breed cultivars for these new environments? The rest of this paper reports our efforts to answer these questions.

THE DEVELOPMENT OF HARDWARE

Much of our project has been concerned with the development of equipment and systems to achieve the necessary environmental control. These efforts fall logically into three categories: control of the foliar environment, control of the root environment, and the mechanics of supporting the plants.

The Foliar Environment

We began our studies with the purchase of three high-quality, controlled-environment growth chambers. These provide control of temperature, humidity, irradiance (PAR), photoperiod, and air flow. Control of air flow is achieved with variable speed fans and in all studies is regulated between 0.5 and 2 m s^{-1}. To increase irradiance levels so that they approach those of full sunlight, high pressure sodium lamps were added to all chambers. In one chamber, 5.2 kW of metal halide and HPS lamps were added to provide 2000 µmol m^{-2} s^{-1} PPF (full sunlight). In this chamber, a water filter below the lamps is used to reduce non-photosynthetic radiation. This water filter reduces total radiation by 37% without reducing PPF.

In addition to the three relatively small chambers (1 m^2 of growing space in each), we have built a six-subcompartment chamber specifically for photoperiod studies. The air conditioning and air delivery system is common to all six compartments, but they are separated from each other by barriers so that each compartment can experience its own photoperiod and irradiance level. The six lighting systems are exclusively HPS lamps, with the light filtered through 5 cm of chilled water. Temperatures in the 6 compartments remain within 0.2°C of each other.

We enrich carbon dioxide (CO_2) concentrations in all locations to 1000 µmol mol^{-1} of air. Our CO_2 enrichment system uses carbon dioxide from compressed gas cylinders and mixes it with air from above the building. This CO_2-enriched air is then piped to the chambers. An

infrared gas analyzer continuously monitors CO_2 levels in all chambers and greenhouse bays that are also part of this project (and which have been outfitted with CO_2 enrichment, HPS lamps to raise irradiance especially during winter, and a layer of flowing water over the top of the greenhouse glass). We do not use a feedback system to automatically control CO_2 levels, because we have found that CO_2 levels can easily be maintained at 1000 plus or minus 50 $\mu mol\ mol^{-1}$ with manual control.

One chamber has been sealed and outfitted with large cooling coils that circulate water below the air temperature in the chamber but above the dew point so that no liquid water condenses on the air conditioning system. In this chamber the root-zone environment is sealed to isolate it from the foliar environment. This means that photosynthetic rates of entire canopies of plants in the chamber can be measured (by monitoring input gas volumes and input and output CO_2 levels).

Root-zone Environment

A CELSS will ultimately need some kind of recirculating hydroponic system that maintains plant roots in an optimized environment. We have designed, built, and evaluated a hydroponic system that allows for nearly complete closure of the root-zone environment. The system contains four separate, root-zone compartments in each growth chamber, each with a surface area of 0.2 m^2 and a depth of 0.125 m. The volume of each compartment is therefore 0.025 m^3 (25 liters). The nutrient solution is pumped from a 0.1-m^3 reservoir. It flows through a distribution manifold in each of the root-zone compartments at a rate of 0.08 liter s^{-1}. The rapid flow rates help to provide both dissolved oxygen and good environmental uniformity between different root-zone compartments. The distribution manifold helps to ensure good uniformity within each compartment. The solution returns by gravity flow into a drain tube that is located in the center of the compartment, and then it drains back to the reservoir. Our measurements indicate that the solution is never less than 85% saturated with oxygen at all locations. The aeration is provided when the solution cascades back into the reservoir and causes considerable liquid/air contact by the bubbling action that occurs.

The total liquid volume of a system for a single growth chamber is 0.2 m^3. Each such system typically has a total dry biomass at harvest of ca. 3 kg. During the life cycle, each crop typically absorbs about 300 g of mineral elements from the solution and transpires 0.6 m^3 (600 liters) of water. The water and nutrients are replaced by adding a dilute refill solution that includes concentrations of the nutrients in proportion to their concentrations in the plant. All system components in contact with the solution are inert, including an epoxy-coated, magnetic-drive pump. The system is flushed between trials, cleaned with sodium hypochlorite, and then finally cleaned with acid.

We have now combined the three separate nutrient systems (one for each growth chamber) into a single system. Plants in all three chambers are thus supplied with the same nutrient solution. The liquid volume of the system could probably be reduced to minimize the mass, but our objective, thus far, has been to provide an optimum root-zone environment, rather than a small sized system.

The pH of the system is continuously monitored and controlled with an in-line pH electrode that opens a solenoid to introduce acid when the pH rises to 5.8 pH units. The pH change for young plants is very gradual, and nitric acid is added to maintain the pH between 5.5 and 5.8. As the ratio of plant mass to solution volume becomes larger, the pH changes more rapidly. After 25 days of growth we use a mixture of ammonium nitrate and nitric acid in the pH adjustment solution. The ammonium ion gradually decreases the pH as it is absorbed. As the ammonium is depleted from solution, the pH gradually rises again until it reaches pH 5.8, and the solenoid admits more control solution.

Plant Support

Much work on plant response to environment has involved individual plants, but virtually all crops used in a cells will be grown in dense canopies of plants to absorb as much light as possible. Plant response to environment is strongly influenced by the close presence of other plants, so it is imperative that CELSS research be conducted with canopies of plants. But how dense should the canopy be?

In several studies, we have found that increasing densities well beyond the optimum for field production (about 200 to 300 plants m^{-2}) has resulted not only in better light interception and increased biomass production but also in increased final yields of grain. We have therefore been concerned with methods of supporting the plants at high densities. We have now completed tests of a third-generation, germination and support system. Our first system was capable of supporting 550 plants per $meter^2$. We germinated the plants in vermiculite and transplanted them into foam plugs that were placed in a rigid styrofoam lid. This process required an hour to transplant 0.2 m^2 of plants. The second system held plants between bars and strips of foam. This allowed us to use plant densities of up to 1500

TABLE 1 The Effect of Photosynthetic Photon Flux (PPF) on Early Growth of Wheat

PPF $\mu mol\ m^{-2}\ s^{-1}$	PPF $mol\ m^{-2}\ d^{-1}$	Crop Growth Rate $g\ m^{-2}\ d^{-1}$	PPF Utilization Efficiency $g\ m^{-2}\ d^{-1}\ mol^{-1}$	Leaf Area Index	Shoot Percent Dry Mass
400	23.0	30.3	1.32	13.4	10.9
600	34.6	44.2	1.28	13.5	10.7
800	46.1	46.1	0.98	14.2	11.2
1000	57.6	43.9	0.76	15.7	11.2
1400	80.6	53.9	0.67	15.4	11.7
1700	103.7	65.5	0.63	18.9	11.8

* Plants harvested at canopy closure, 24 days after planting
Plant density: 2,000 plants per m^2
Cultivar: Yecora Rojo

plants per m^2, but it still required the labor-intensive step of transplanting. We are now using an inert rockwool material (Grodan; used in commercial hydroponics) that allows us to plant seeds directly at densities of up to 10,000 plants m^{-2} or higher. The rockwool material is kept wet during germination and until roots are well established in the nutrient solution below. Optimum density in one preliminary experiment was about 2000 plants m^{-2}.

RESULTS OF MANIPULATING ENVIRONMENTAL AND CULTURAL FACTORS

Optimizing Photosynthetic Photon Flux: Energy, Mass, and Volume Tradeoffs

Energy efficiency may become very important in a CELSS. Energy will be used in many ways in a regenerative system, but energy to power the lighting system for plant growth will be the single largest input if electric lamps are used to provide the photosynthetic photon flux (PPF) to drive photosynthesis. Changes in PPF utilization efficiency by plants could save more energy than all the other CELSS energy inputs combined. CELSS plant growth systems that utilize sunlight directly or that are powered by a nuclear reactor might not need to be concerned with PPF utilization efficiency. In these situations a large energy input could be used to reduce the mass and/or volume of the food production system. We have recently begun PPF input studies that are designed to determine the tradeoffs among energy, mass, and volume input parameters. Table 1 indicates that crop growth rates increase in direct proportion to increases in PPF ($r^2 = 0.85$). Although the growth increase is linear up to the highest PPF level tested, each additional unit of PPF input is used less efficiently by the plant canopy.

Optimizing Plant Nutrition in a Recirculating Hydroponic System

All plants can be grown hydroponically with a few basic nutrient solution recipes. There is a big difference, however, between slow growth and highly optimized, rapid growth. Achieving optimum growth and nutrition from seed imbibition to physiological maturity requires nutrient solutions that are individually tailored for each species being grown. The optimum composition of these solutions can change during the plant's life cycle and may need to be altered for different photosynthesis/transpiration ratios.

Very little research has been published on optimum concentrations of nutrients in solutions for wheat. When standard nutrient solutions are used for wheat, nutritional deficiencies or imbalances have appeared in our growth conditions. These imbalances are not always severe, but they can cause such foliar symptoms as necrotic leaf tips. We have observed that nutrient uptake in our circulating solution systems is not the same as in other, aerated but stationary containers. We have also observed that foliar symptoms vary with different transpiration rates, which are altered by leaf/air vapor-density gradients and by stomatal apertures, which are, in turn, altered by CO_2 levels. Table 2 shows the composition of nutrient solutions used during a life cycle of wheat in several of our successful yield trials. Note that ammonium ion is not added in the original solution but only in the

TABLE 2 Nutrient-Solution Compositions (mmoles per liter)

Mineral	Initial	Make-up
NH_4^+	0.0	0.01*
NO_3^-	15.0	3.75
P	0.2	0.5
K	3.2	1.00
Ca	12.0	1.50
Mg	4.0	0.50
S	2.0	0.50
Cl	16.0	0.04
Fe	0.124	0.0125
B	0.080	0.020
Mn	0.008	0.002
Zn	0.0008	0.0002
Cu	0.0003	0.000075
Mo	0.0001	0.000025
Si	0.300	0.075
Na	0.600	0.15

*NH_4^+ is added in pH control solution; 0.01 mM is an approximate average concentration.

in the make-up solution. Silicon may not be essential for wheat growth, but it is possible that lodging is less of a problem when plants have ample silicon.

Plants almost always respond to a nutrient deficiency by partitioning more photosynthate into the root system. This reduces the percent edible biomass. In short, optimum growth cannot be achieved by altering only the foliar environment. For this reason, we have built recirculating nutrient solution systems that can provide replicated data on root-zone effects in different foliar environments. We plan to use these, as well as our aerated, individual container systems, to further investigate and refine the root-zone ionic composition. Essential elements and deleterious levels of non-essential elements may both need to be investigated. We currently monitor, by ICP emission spectrophotometry, the concentrations of the essential elements in both foliar tissue and nutrient solutions.

Nitrate/ammonium nitrogen ratios.

Wheat plants absorb ammonium from solution more rapidly than any other ion. Hydrogen ions are secreted to balance uptake of ammonium ions. We have found that this occurs throughout the life cycle. Providing ample ammonium along with nitrate nitrogen in nutrient solution has enhanced total nitrogen uptake in short-term studies of Cox and Reisenauer /1/ and of Huffaker, Reins, and Qualset /2/. An increased nitrogen content of foliar plant parts is associated with increased photosynthetic rates, prolonged leaf photosynthetic output, and increased grain protein. The nitrate/ammonium ratio can also alter the uptake of other ions. This ratio can be easily controlled in solutions, and its long-term effects on wheat growth need to be further studied. We plan to alter the concentrations of these ions in adjacent hydroponic systems, to monitor their uptake rates using our nitrate- and ammonium-specific ion electrodes, and to relate uptake rates to altered plant growth, specifically nitrogen and protein concentrations in foliar plant parts.

The Roles of Photoperiod and Temperature in Yield of Grain

The conditions that promote fastest total growth do not lead to the highest yields. This finding represents a major shift in our research approach. We have developed the term phasic environmental control to indicate that environmental conditions will need to be different for each phase of plant development. It now appears that maximum yields cannot be achieved without phasic environmental control. Five phases of development in the wheat life cycle are as outlined in Table 3.

Warm temperatures (25°C and above) promote rapid growth rates and a short life cycle, but they lead to small wheat spikes and very poor pollination. This is illustrated by Fig. 1 and Table 4. Cooler temperatures (20°C) cause slightly slower growth rates and lengthen the life cycle but greatly increase the spike size and seed set. At the cooler temperatures, a

TABLE 3 Five Stages of Wheat Development and associated length in a 60-day life cycle

Developmental Stage	Day Number	Associated Morphological Change
1. Vegetative	0-12	Germination and early leaf growth
2. Reproductive Initiation	13-18	Microscopic changes in apical meristem that determine ultimate spikelet number
3. Extension	19-30	Further development of floral parts and final determination of florets per spikelet
4. Anthesis	30-35	Pollination and fertilization
5. Grain Fill	36-60	Assimilate translocation into developing seed

TABLE 4 Photoperiod/Temperature Influence on Yield Components in Wheat

Plants per m^2	Spikes per m^2	Total Seeds per Spike	Mass per Seed (mg)	Total Yield g m^{-2}	Days to Harvest	Yield g m^{-2} d^{-1}	Harvest Index %	Yield g m^{-3} d^{-1}	g m^{-3} d^{-1} $mmol^{-1}$
Cool Temp. (20°C day, 15°C night), 14-h photoperiod									
1150	2007	21	29	1154	77	15.1	46	16.3	323
Cool Temp. (17°C), 24-h photoperiod									
1076	2387	16	30	1054	66	16.3	35	17.5	203
ns	ns	*	ns	ns	*	ns	*	ns	*
Warm Temp. (27°C), 14-h photoperiod									
1030	3234	5	27	279	66	4.3	11	4.3	85
Warm Temp. (27°C), 24-h photoperiod									
830	2128	10	29	872	61	14.2	29	14.4	167
*	*	*	ns	*	*	*	*	*	*

Statistics: Duncan's Least Significant Difference Test ($\alpha = 0.05$);
* = significantly different, ns = not significantly different.

shorter photoperiod also increased the number of seeds per spike and the yield per meter; but the days to harvest were also increased, so yield per day was decreased. In other experiments, however, we have also observed increased daily yields in response to relatively short photoperiods. These temperature and photoperiod effects are an example of the need for phasic environmental control to obtain the best of both worlds.

TESTING GERMPLASM AND BREEDING PLANTS FOR CONTROLLED ENVIRONMENTS

Results of Greenhouse Studies

We have tested about six hundred cultivars, made several hybrid crosses, and have begun large scale testing with our most promising breeding lines (Tables 5 and 6). These tests require considerable area, and it is not feasible to conduct them in our growth chambers. The tests, have, therefore, been conducted in a greenhouse section that provides environmental conditions similar to those that promote highest yields in the growth chambers.

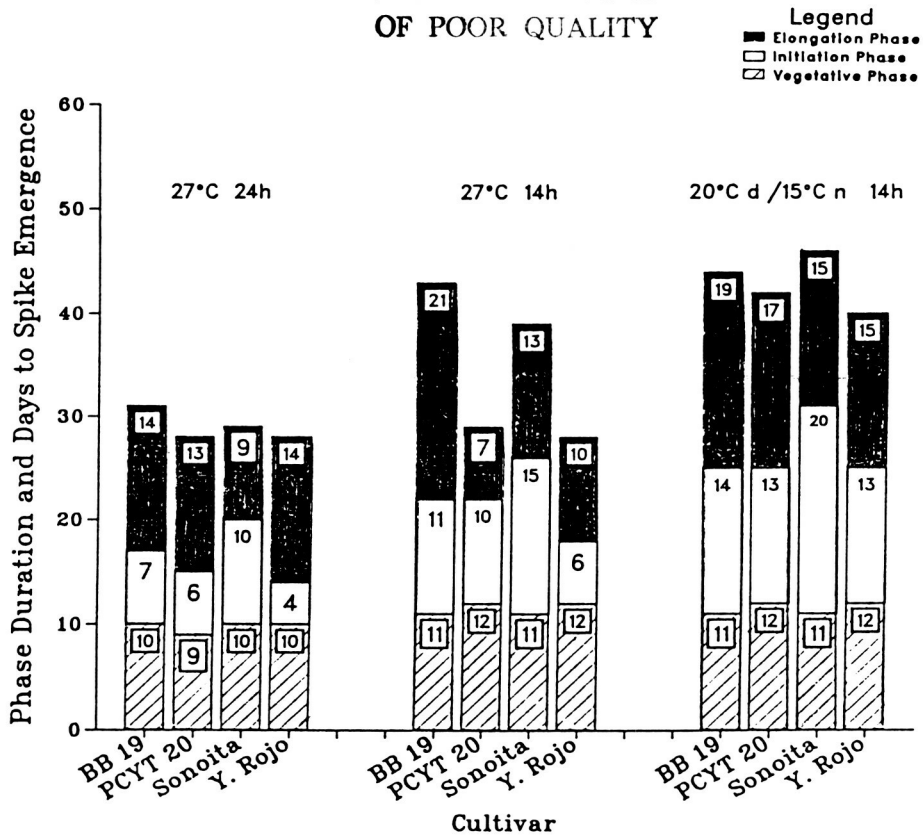

Fig. 1. Temperature/photoperiod influence on the phasic development of wheat.

TABLE 5 Results of a Replicated Cultivar Evaluation in the Greenhouse

Cultivar	Yield g m^{-2}	Ht cm	Yield g m^{-3}	Seeds per Head
BB-8	711	51	783	37
Veery 10	610	46	707	31
BB-16	548	38	692	40
PCYT 20	649	68	603	31
Fielder	664	88	519	33
Yecora Rojo	504	58	518	24
Sonoita	511	60	512	27
Anza	602	89	467	35
Fremont	541	86	428	35
BB-19	342	41	419	47
BB-11	375	53	406	35
Y.ROJO x O.Dwf.	328	47	376	15
Olesen's Dwarf	186	30	261	8
DLSD*	115.5	5.1	129	11

*Mean separation by Waller-Duncan test, K ratio = 100

We now have a group of 9 homozygous lines that are short (33 to 50 cm tall), have excellent head size and seed set, but may have below-average mass per seed at harvest. Good head size and seed set are much more difficult to achieve with environmental modifications than good

TABLE 6 Results of a Replicated Uniculm Trial in the Greenhouse

Line ID	Average Seed Mass per Primary Head (g)	Primary Head Seed Mass as Percent of Total Seed Mass
9	2.6	63
18	2.4	77
20	2.3	45
8	2.2	97
2	2.1	50
4	1.9	60
Fremont	1.9	26
12	1.8	63
10	1.8	76
5	1.8	92
1	1.7	97
19	1.5	75
6	1.5	100
Uniculm	1.4	95
DLSD	0.87	29

TABLE 7 Cultivar Evaluation: Replicated Study in Controlled Environments

	Spikes Per m^2	Seeds Per Spike	Mass Per Seed (mg)	Yield $g\ m^{-2}$	Days To Harvest	Yield $g\ m^{-2}\ d^{-1}$	Harvest Index %	Height cm	Yield $g\ m^{-3}\ d^{-1}$
Yecora Rojo	2130	18	34	1224	67	19	47	56	19.2
BB-19	1771	24	23	987	76	13	46	40	16.2
PCYT-20	2641	15	31	1127	71	16	33	65	15.3
Sonoita	1562	21	32	1067	76	14	50	56	14.6
DLSD (α = 0.05)	*	*	*	*	*	*	*	*	*

grain fill, so we are none-the-less very excited by this genetic contribution. We are also working with uniculm lines (Table 6) that could be density planted, leading to rapid canopy formation.

The most significant message from our plant breeding efforts is that additional genetic selection is likely to have major effects on food production in a CELSS environment.

Results of Controlled-Environment Studies

Early breeding trials in the greenhouse indicated that line BB-19 was the most promising line, so it was selected for more detailed testing in controlled environment studies. Table 7 shows the mean values for yield components from three high yielding environments. Yecora Rojo, PCYT 20, and Sonoita are daylength-insensitive, full-dwarf cultivars (50 to 60 cm tall) that have consistently been high yielding in past studies.

The BB-19 line had significantly more seeds per spike than the other lines, but this did not result in a correspondingly higher yield, because the mean mass per seed was less than other lines. It is not yet clear why the mass per seed is below normal. It is

possible that our ultradwarf lines have such a large head in relation to their leaf area that they have become source limited even in our CO_2-enriched, optimizing environments.

A high yielding cultivar is not useful in a CELSS unless it can develop its high yield in a short period of time. Yecora Rojo was the earliest of the cultivars in this study, and it thus has an excellent yield per unit time. It's harvest index, as well as that of two other cultivars, is close to 50%, as good or better than normally occurs in the field (40 to 45%).

We have focused attention on ultra-dwarf cultivars for the following reasons:

1. Most importantly, they tend to have a higher harvest index than taller cultivars. In this study the tallest cultivar, PCYT 20, had the lowest harvest index. Harvest index is of particular concern in a regenerative system. It has been suggested that ultra-dwarf cultivars are not capable of achieving yields equal to taller cultivars, but this suggestion has been made on the basis of studies in non-optimizing field environments. In these environments the planting density is optimum for tall cultivars but suboptimum for their ultradwarf counterparts. Because of their small size, ultradwarf cultivars require higher planting densities to intercept all the available light.

2. Short cultivars are much easier to work with in the confined spaces of controlled environments.

3. Taller cultivars (50 to 100 cm) require support to prevent lodging. Short cultivars do not require this support.

4. Volume may become an important input parameter in a CELSS.

For these reasons, we are particularly interested in yield as g m^{-2} d^{-1}. The cubic meters of space are determined for the tables by measuring the final height of the cultivar and then adding 0.4 m to this value. The 0.4 m is added as space for the root zone and for the lighting system. A 60-cm cultivar would thus have the same yield per $meter^2$ as it does per $meter^2$. Using this ultimate expression of yield (g m^{-3} d^{-1}), Yecora Rojo was significantly higher than the other three cultivars. We are using it as a standard for our environmental studies.

We are also studying clonal propagation of wheat. The goal of this companion project, under the direction of Dr. John Carman, is to produce many (thousands) of somatic embryos from a single callus culture. Such an approach would allow the use of F_1 hybrids and would allow the astronauts to eat the seeds that would otherwise be needed for the next crop (up to ten percent of the harvest). It would have to be simple enough to be performed by astronaut farmers without too much expenditure of time. So far, the approach looks promising.

CONCLUSIONS

Our research has utilized small, replicated communities of wheat plants rather than individual, spaced plants. This approach requires more space for each treatment but allows us to directly measure treatment effects per unit area and thus to accurately predict the performance of the entire food production system of a CELSS.

The components of yield in wheat (spikes per $meter^2$, seeds per spike, and mass per seed) are directly affected by planting density; thus, optimal environmental conditions vary with density. We therefore feel that simultaneous optimization of both cultural and environmental factors is important to rapid progress in CELSS research.

It is possible to grow wheat through a 70-day life cycle and to obtain high yields in a completely recirculating nutrient solution. The ionic composition of the solution must be maintained, but the organic efflux from the plant roots appears to be rapidly oxidized by the microorganisms in solution. Total organic carbon has been about 10 mg per liter in our systems.

Obtaining rapid growth rates, a short life cycle, and high grain yields may require the use of phasic environmental control, which is the application of different environments at different stages of the wheat-plant life cycle. This type of control might require a CELSS design that had several relatively small compartments rather than one large compartment.

Developing new wheat cultivars for controlled environments may not only be useful but necessary to optimum efficiency in a CELSS.

The problems and potentials of this research are great. We anticipate using our customized controlled environment facilities to focus on obtaining data to determine the feasibility and future design of a CELSS. Although our yields are well above those obtainable in the field, they are still well below what they could be based on photosynthetic and cropping efficiencies. Much progress remains to be made.

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