82

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PREPARATORY SPACE EXPERIMENTS FOR DEVELOPMENT OF A CELSS

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ABSTRACT

The purpose of a CELSS plant-production facility is to achieve maximum yield and quality in a minimum area (or volume) and with minimum inputs of mass and energy. Research with wheat and other crops has shown that maximum theoretical yields (determined by available light) can be approached if the best cultivars are grown at optimal day and night temperatures, humidity, wind velocity, photoperiod, CO_2, mineral nutrients, and plant density. Yield is nearly a straight-line function of irradiance at least up to sunlight-equivalent levels, but photosynthetic efficiency decreases with increasing irradiance. Will these generalizations hold in the worst-case situation of a microgravity CELSS? Or in the reduced lunar or Martian gravity?

Further space experimentation will be required to find out. So far, the few experiments with plants in space have not had environments truly suitable for CELSS studies. Nevertheless, results of this work suggest that plant growth could be adversely affected by microgravity. The goal of CELSS studies will be to examine effects of microgravity on yield and quality of plant products and on the interactions between irradiance and crop area. Measuring yield and quality of crops as a function of irradiance in microgravity is virtually unique to the CELSS program, as is an emphasis on canopies rather than individual plants. The first step for space experiments is to develop a relatively stress-free environment for plant growth, something that has so far never been achieved. High light levels are essential, and there must be time enough to complete a significant portion of a life cycle. Optimal atmosphere and nutrients must be provided. Such responses as germination, orientation of roots and shoots, photosynthesis and respiration, floral initiation and development, and seed maturation and viability will be studied.

THE PURPOSE AND CHALLENGE OF A CELSS

In developing a CELSS plant-production facility, and thus in CELSS research with plants, the challenge is to obtain maximum crop yield per unit area (or volume) with minimum inputs of mass and energy. It is imperative to calculate the efficiency of the system in terms of food energy produced per unit input of light energy. The maximum yields achievable per unit area (or volume) and the light energy required to produce them must be determined. With this knowledge, engineers can design future CELSS systems with appropriate light sources.

The mass of the system is a problem for the engineers. Energy required to operate the system beyond the light energy used to irradiate the plants is also largely an engineering matter. Plant researchers allow themselves to use equipment of any size and energy requirement, knowing that clever engineers should ultimately be able to optimize the mass and functional-energy needs.

WHAT CELSS RESEARCH HAS TAUGHT US SO FAR

The plant scientists reporting at this conference have been studying these things with NASA support for nearly a decade. Much has been learned. For one thing, we can calculate the potential crop yields on the basis of photosynthetic efficiencies, and then we can compare the yields that have been achieved with the theoretical ones (1). The theoretical efficiencies depend upon a number of factors. We have used the model discussed by Dr. Bugbee at this meeting. It involves the amount of light absorbed by the plants, the quantum efficiency of the photosynthetic process, the respiration efficiency (percentage of the photosynthetic products that are used up in maintenance respiration necessary for growth and to keep the plant alive -- a somewhat variable factor that makes the final calculation of efficiency also somewhat variable), and the harvest index (edible biomass as a percentage of total biomass -- also a variable figure that depends upon species, cultural practices, and what an astronaut is willing to eat). Ignoring the harvest index for the moment, and assuming that maintenance respiration might be somewhat less in controlled and optimized environments than it is in the field, we arrive at a figure for photosynthetic efficiency of about 15 percent. If this is a valid figure, the food energy in the biomass will never exceed 15 percent of the light energy delivered to the plants.

In our research with wheat (1), we have found that the theoretical efficiency can be approached if the environment is optimized. The highest efficiency we have been able to measure is about 10 percent, but that is measured over the complete life cycle of the wheat plants. Much light energy is wasted during approximately the first 20 days while the plants are forming a canopy; more light energy is wasted during the final days after most of the leaves have senesced but before the grains are mature. This high efficiency is achieved when day and night temperatures are optimized (in Fig. 1, 20°C day and 15°C night), carbon dioxide is enriched to an optimal level (about 1,000 to 1,200 μmol mol^{-1}), irradiance is at an optimum level and spectral balance for maximum efficiency (about 400 μmol m^{-2} s^{-1}, mostly from high pressure sodium lamps), mineral nutrients are optimally supplied in a well-balanced nutrient solution, the daily period of irradiation is optimized (continuous light in our recent experiments), and plant densities are ideal (dense enough to rapidly form a canopy but not dense enough to reduce yields by competition; 2000 or more plants m^{-2}). Humidity and wind velocity also need to be optimized but seem to be somewhat less important than the factors just enumerated.

Our model has assumed that yield is a function of irradiance when everything else has been optimized, and results have born that out. In addition, we discover that efficiency as well as yield is a strong function of irradiance. This is illustrated in Figure 1 in which total biomass, seed biomass, and efficiency are plotted as functions of total daily irradiance. The highest yields were produced by an instantaneous irradiance equivalent to noon-day summer sunlight (2000 μmol m^{-2} s^{-1}) given continuously during a 20-h light period (4-h dark). This is about 2.5 times as much radiant energy as plants could receive anywhere on Earth. Within statistical error, and beginning above the light compensation level and at our lowest irradiance, biomass production increased in a nearly linear fashion with increasing irradiance. There was no sign of saturation. Efficiency, on the other hand, decreased linearly with increasing irradiance from about 10 percent at the lowest light levels to about 7 percent at the highest light level.

IMPORTANT CELSS TRADE OFFS

If these results, obtained with wheat, are valid for other species as well, they suggest some important trade offs in the design of a future CELSS. First, it is obvious that more light means a smaller farm. At our highest light level, we harvested about 60 g m^{-2} d^{-1} of edible wheat. Assuming that a human can function with the energy provided in 780 grams of wheat per day (or its equivalent in other foods), this much food energy (11,700 kJ = 2800 kcal) could be provided in a CELSS farm of only 13 m^2 $person^{-1}$. This assumes that the crop can always be produced at maximum efficiency. An actual CELSS will incorporate a safety factor and will be designed for crops besides wheat. With a safety factor of about 4, with which I might be almost comfortable, the CELSS farm would be about 50 m^2 $person^{-1}$.

Second, less irradiance means higher photosynthetic efficiency and therefore a smaller power input. This is illustrated in Figure 2. (The power input is based on estimates of light-output efficiencies for sodium vapor lamps housed in highly efficient reflectors.) Although farm size per person decreases with increasing light, the power per person increases by about 50 percent. Thus, if the CELSS farm is located where size is less important than power (on the lunar surface, perhaps?), the farm can be larger and the power supply somewhat smaller. If area or volume are critical (as in an orbiting space station or a space craft on the way to Mars), it will be important to have a large power supply so the farm can be proportionately smaller. Much electrical power is required to produce the light needed to grow plants. The entire contemplated power supply of space station Freedom would be required, for example, if its astronaut occupants were to be fed exclusively from a CELSS farm. Thus, it is clear that large sources of power will have to be developed if CELSS farms are to be used in the future, or ways will have to be devised to utilize the relatively inexpensive light energy from the sun. (The cost of solar energy will be reckoned as the cost of the equipment required to utilize it.) Of course solar energy won't be available on the lunar surface during about 15 earth days of the approximately 29-day lunar day (except close to the lunar poles?).

SPECIAL CELSS PROBLEMS FOR SPACE EXPERIMENTS

Although our CELSS research has so far been conducted on the Earth's surface, a CELSS operated beyond the Earth's atmosphere in the foreseeable future will have to contend with microgravity (space station or spacecraft), lunar gravity, or Martian gravity. Can we achieve maximum crop yields in these gravity conditions? To find out we need to do space experiments. To study lunar or Martian levels of gravitational acceleration, we will either have to go to the moon or Mars or use a centrifuge in the space station. Thus CELSS research in space will probably be initiated with experiments carried out in microgravity. The discussion so far should make it obvious that experiments designed to study primarily CELSS problems will place much emphasis on yield, quality, and the interaction of irradiance and crop area. All steps in the life cycle of a crop plant could affect yield and quality:

1. Germination.
2. Orientation of roots and shoots.
3. Growth and differentiation of roots and shoots.
4. Photosynthesis and respiration.
5. Floral initiation and development.
6. Pollination and fertilization.
7. Seed maturation and viability.

All plant scientists interested in space biology would like to study these steps. Indeed, this could be done in the often discussed seed-to-seed experiment. If we knew that a plant could grow from seed to seed in microgravity, there would seem to be no obvious show stoppers in development of a CELSS for space exploration. But what if plants will grow from seed to seed in microgravity but yield only 10 percent as much as they do on Earth? This would surely be an unexpected show stopper. Thus the process of photosynthesis and other developmental steps that lead to the harvested product must be the crucial topics of study in CELSS space experimentation.

WHAT CAN WE EXPECT?

Considering that it has been possible to do experiments with plants in space for over a quarter of a century, it is discouraging to realize how little has been done. This is especially true of the United States' space program in which well-conceived plant experiments can be counted on the fingers of one's hands. Furthermore, none of these experiments has utilized sufficient light to be of interest from the special standpoint of CELSS. Soviet scientists have carried out many more space experiments with plants, but their experiments have also left much to be desired from the standpoint of CELSS (although most of their plant experiments were justified from that very standpoint!). In an article published in the 1987 Annual Review of Plant Physiology (2), Thora W. Halstead and F. Ronald Dutcher summarize what is known about the response of plants to the space environment, particularly to microgravity. The following paragraphs are a brief summary of their summary.

1. **Germination.** Several species of seeds have been germinated in space. There were no problems with the seeds that were tested, and we do not expect problems with other species.

2. **Orientation of Roots and Shoots.** In microgravity plus darkness, roots and shoots both grow in the direction they assume when they emerge from the seed. This has been observed with

several species. Shoots of many species orient toward the light (phototropism). This is especially true for monocots, but some dicots (e.g., soybeans) have not oriented strongly toward the light in microgravity. Roots are not phototropic and have grown out of the soil in several experiments.

When weightlessness is simulated by rotating plants about a horizontal axis on a clinostat, the most obvious symptom is a downward bending of leaves, called epinasty. Thus it is surprising that the Soviet literature never mentions epinasty of dicots in space, and the point has seldom been discussed by American researchers. Nevertheless, the classic experiment in Biosatellite II with pepper plants showed epinasty in microgravity comparable to that observed on a clinostat, and some photographs of space-grown seedlings also show epinastic leaves.

3. **Growth and Differentiation.** Growth of some species was inhibited: pine, oat, mung bean. Yet hypocotyls of lettuce, garden cress, and Arabidopsis thaliana were longer in microgravity than those grown on a flight centrifuge. This is one example of several kinds of conflicting data from space experiments.

Maize root caps removed just before a flight did not regenerate in microgravity as they do on Earth (within 48 h). A few other effects on differentiation have also been reported.

Many cytological effects have been observed. In several cases, cell division was reduced or inhibited. Yet there were other cases where cell division did not appear to be affected. Damaged chromosomes were observed in many species but again, not always. There has been much discussion about whether these effects were caused by space radiation, microgravity, or an interaction of the two. Equivalent radiation doses on Earth do not cause such effects, so it is likely that radiation, if it is responsible, is interacting with microgravity.

Abnormal nuclei, endoplasmic reticulum, ribosomes, mitochondria, plastids, dictyosomes, and cell walls have also been observed in space-grown plants. Again, however, these abnormalities have failed to appear in other plants grown in space.

4. **Photosynthesis and Respiration.** To the best of my knowledge, these processes have not been measured in space. (We hope to do so!) Nevertheless, a disintegration and destruction of grana along with a disorientation of the intergrana and a shrinkage of membranes comprising grana stacks has been observed in chloroplasts from pea and other species, as have a lack of starch and reduced chlorophyll. These observations lead to an expectation of decreased photosynthesis -- except that such effects have not appeared in all species and in all experiments.

5. **Floral Initiation and Development.** The Soviets, who are the only ones who have grown plants for relatively long periods in microgravity, reported that death often occurred at the flowering stage. This was true for wheat, peas, and several other species. Yet the Soviets were able to grow Arabidopsis thaliana from seed to seed. They observed some aborted ovules and a markedly reduced germination percentage of the seeds that had been produced in space. Seedlings that grew from seeds that did germinate were often abnormal although the next generation consisted of normal seedlings. Thus the Soviets have achieved the seed-to-seed experiment but not without encountering several problems and some failures in early attempts along the way.

6. **Pollination and Fertilization.** I know of no experiments designed to study these important phenomena, but the seed-to-seed experiment with Arabidopsis prove that pollination and fertilization can be achieved in microgravity. (In our pending flight experiments, we will look first at photosynthesis and respiration; then we hope to emphasize floral initiation and development as well as pollination, fertilization, seed maturation, and seed viability.)

7. **Seed Maturation and Viability.** Again, we have the Arabidopsis experiment to suggest that viable seeds can mature in microgravity.

Although much remains to be learned, it is clear that plants may respond to microgravity in many ways besides having their gravitropic responses upset. While germination seems to be insensitive to microgravity, growth may or may not be affected, and mitosis and cytokinesis appear to be quite sensitive to microgravity or to a combination of microgravity and slightly increased radiation. Chromosomal damage is especially prevalent. Differentiation is influenced in several ways, and polysaccharide metabolism including photosynthesis could be affected; this would be especially true if organelle membranes are sensitive as might be the case.

WHAT CAUSES THESE RESPONSES?

Having surveyed the many responses that have been observed in the relatively few experiments, and noting the often conflicting results, it becomes apparent that we must look for the causes of the discrepancies. Although the situation is complex, five immediate possibilities come to mind:

1. Microgravity.
2. Radiation.
3. The growth chamber environment.
4. Interactions of these.
5. The stresses of launch and landing.

Except for complications of launch and landing stresses, microgravity and radiation have been fairly constant in most of the experiments carried out with plants so far. The growth-chamber environment, on the other hand, has varied greatly, particularly in the Soviet experiments and to a somewhat lesser extent in the American studies. Thus we are entitled to be especially suspicious of chamber environments as possible causes for many of the effects that have been observed. And if chamber environments prove to be responsible, it will be possible to avoid some deleterious effects by providing suitable growth environments. Two aspects of the plant-growth environment in microgravity experiments might have influenced results.

First, environmental factors may not have been optimized for the most ideal plant growth. The United States' experiments have never had enough light to provide an adequate rate of photosynthesis, and these low light levels could lead to other effects besides reduced photosynthesis. Growth and differentiation are known to be highly sensitive to the light environment, both irradiance levels and spectral distribution, not to mention photoperiod. Although light might have been the most limiting factor in the experiments already carried out and thus the most important factor to be considered for future experiments, atmospheric conditions have often been far from ideal. For example, it is likely that ethylene and perhaps other gasses built up in the plant growth unit used in American experiments. Furthermore, we have no assurance that nutrient or water conditions were as good as they should be for ideal plant growth.

Second, microgravity interacts with other factors of the environment. Because gravitational drainage does not occur through the plant substrate, it is difficult to provide ample water with sufficient root aeration. Furthermore, convection caused by temperature (density) differences does not occur in fluids in microgravity, so movement of both air and water must be by forced convection. All these problems must be solved before CELSS flight experimentation can be meaningful.

THE MOST CRITICAL PROBLEMS FOR CELSS FLIGHT EXPERIMENTS

The most critical problem so far has been opportunities for flight. How can we solve the problems if we never get to go? When we do get to go, we must have adequate growth facilities. We must find ways to provide adequate light! Furthermore, we must have adequate space to grow plants in at least limited canopies as they will surely be grown in a CELSS farm. Initial experiments might utilize individual plants, but somewhere fairly early in CELSS flight experimentation, canopies of plants must be used. In addition, we must have sufficient time for a significant portion of a growth cycle, and we must solve the problems of nutrient flow systems and of atmospheric control.

It should now be apparent that CELSS flight experimentation is more demanding than research in other fields of gravitational biology. Because it is absolutely essential to have adequate light, power sources must be found. These may have to depend on nuclear reactors in spite of public aversion to them. I'm told that NASA is developing safe nuclear reactors for space experimentation. Perhaps space studies in CELSS plant production wont be completely feasible until such sources are available.

Probably the most serious challenge facing us at the moment is public relations. Because NASA administrators as well as the public were well aware of what could be achieved by telescopes beyond the Earth's atmosphere, the Hubble Telescope came into being. It seems critical for us to make NASA administrators and the public aware that long-term goals such as a lunar colony or a station on Mars cannot be reached without incorporating the CELSS concept. We need to get this message across with high visibility programs such as the Kennedy Space Center Breadboard Project. It is incumbent upon each of us to take every opportunity that is presented to tell our story to the public. Interviews by the Associated Press can certainly interrupt one's day, but without them a truly viable CELSS program, including space experimentation, may not develop within our lifetimes. Eventually, as its importance is realized, it will come into being, but if this is to happen soon we must become personally involved in the effort to make it happen.

REFERENCES

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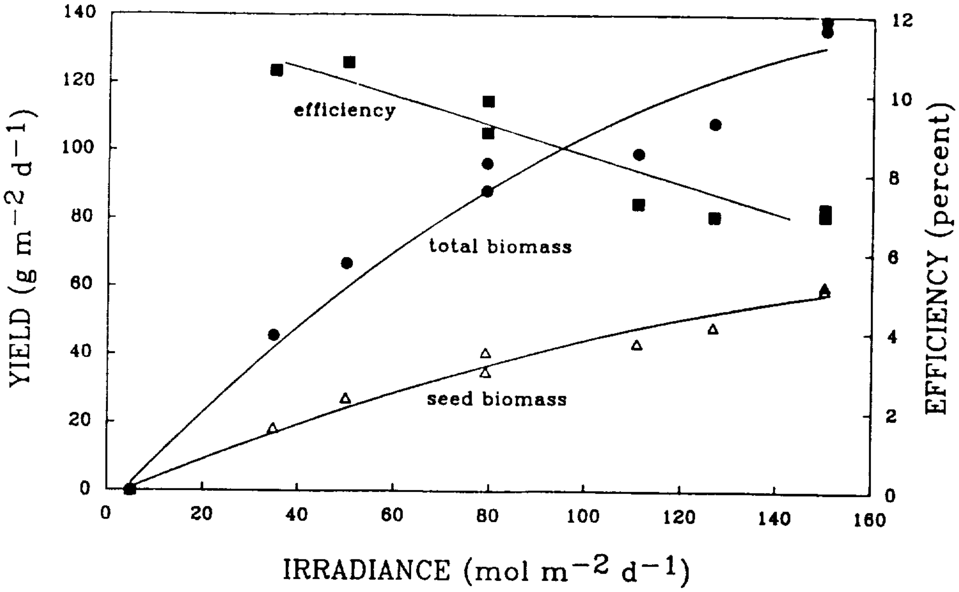

Figure 1. Yield and efficiency of wheat plants grown under different daily photosynthetic photon fluxes. Yields (biomass) were calculated by dividing final yields by the 79-day growth period of the crop. The highest irradiance is equivalent to noon, summer sunlight at the earth's surface, but provided for 20 hours each day (details in reference 1).

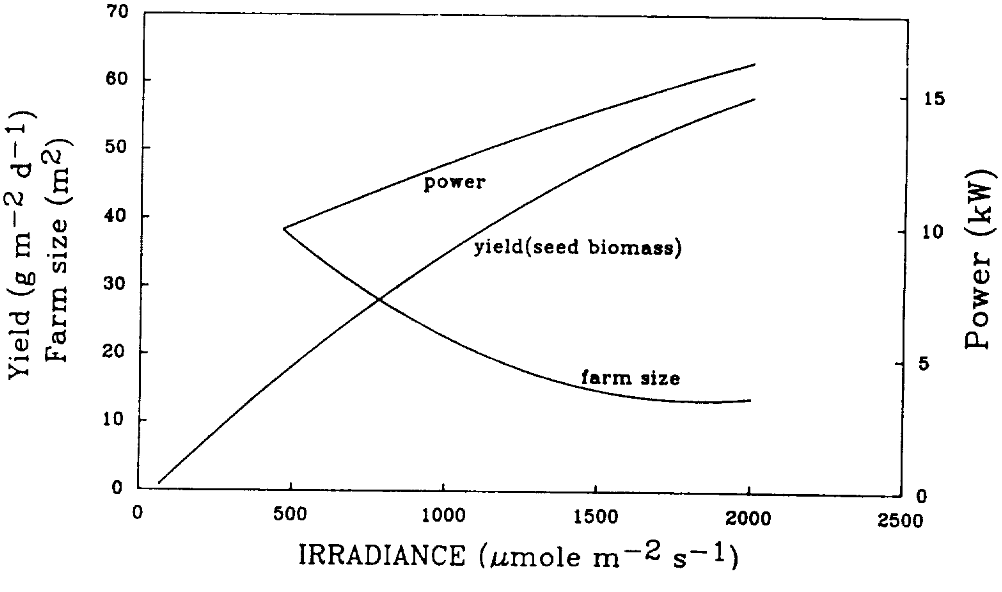

Figure 2. CELSS trade offs based on the experimental data presented in Figure 1 (but showing irradiance integrated for a second instead of a day). As irradiance increases, so does yield, allowing a smaller farm to support a given number of human beings. But as irradiance increases, photosynthetic efficiency decreases, so more light is needed to produce a given yield, and this requires more power.