Lunar Farming: Achieving Maximum Yield for the Exploration of Space

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So, you want to visit the CELSS farms here in Luna City? I’m a farmer in that facility, and I’d be happy to show them to you. Perhaps we can complete our visit before midnight, when the year 2020 begins. (Because the lunar day is 29.530589 Earth days long, we keep Greenwich Earth time here.) As a matter of fact, we can celebrate New Year’s Eve with a meal in the mess hall based almost entirely on food from the CELSS farms. What is the significance of the CELSS acronym, you ask? It stands for Controlled Ecological (or Environment) Life-Support System. Fundamentally, it is a bioregenerative life-support system (which could be called BLISS!).

On our way to the farms, let’s make a brief stop in the Earth-observation room. From our location here in the Sea of Serenity, Earth hangs in a black sky 60° above the horizon and slightly west of south. It is always there! With a diameter 3.67 times and an area almost 14 times that of the moon as it appears from Earth, Earth is truly a spectacular sight in the sky. It is fascinating to watch it go through its phases. The Earth is always full at lunar midnight, and it was full on Christmas this year (2019). When the sun appears close to the Earth, the Earth is a thin crescent: a new Earth. Once or twice a year, the sun moves behind the Earth, producing an eclipse. The sun’s rays, refracted by Earth’s atmosphere, form a red ring around the Earth; a circular sunset, one might say, that produces a red glow here on the moon. It’s fascinating to watch the Earth rotate and to observe cyclones and other storms moving across its surface.

As everyone knows, our CELSS farms in Luna City are based on photosynthesis in which carbon dioxide, water, and minerals are transformed with the help of light energy into food and oxygen. The water transpired by the plants is condensed and purified in various ways, but even that proved to be more difficult than we had expected; now our plants do a better job of filtering the water as it passes through them into the atmosphere. There is no physical/chemical way to recycle food.

It was always clear from basic principles that plants and microorganisms could play an important role in a recycling system in a space craft, on the moon, or on Mars, but could they compete with physical/chemical processes combined with periodic resupply from Earth? A study carried out in 1981 suggested that the launch weight of a CELSS would amount to equal the launch mass of a physical/chemical system combined with resupply after about 7 years. By 1986, we had learned enough about optimizing plant growth so that a subsequent calculation suggested a break-even time (see Fig. 1) of only a little less than 3 years (Mason, 1980; Oleson and Olson, 1986). Putting some of the principles that we have alluded to into practice, as well as others I’ll be telling you about as we tour the CELSS farms, allowed the construction of Luna City beginning about 15 years ago. We have about 250 people living here now, and all of them eat a carefully balanced diet, most of it coming from the lunar farms. These farms include a wide variety of crops and even a small livestock colony with a few chickens and fish (tilapia, carp, and trout) that eat the plant materials that are not well-suited for humans.

A group at Purdue Univ., West Lafayette, Ind., (Hoff et al., 1982) studied various crops according to a series of criteria related to their suitability for a CELSS farm (Table 1). Table 2 lists the crops with the highest scores based on these criteria. Many of them, plus a few others that proved to be as good or better (based on more recent information), are grown in our lunar farms.

The lunar CELSS farms

Let’s visit the farms. I’ll explain things as we go. Way back in the 1980s, when these things were being planned, artists depicted what they imagined the future farms would be like (Paine, 1986). Huge glass domes sat on the moon’s surface with field crops and orchards growing underneath. It was a beautiful dream, but it was incompatible with the facts of the lunar environment (Mendell, 1985). Radiation from solar flares that come at intervals is lethal to humans and plants that are not suitably protected. With a lunar day lasting 29.53 Earth days, plants that depend on sunlight would have to survive about 15 days of darkness interspersed with 14 days of light. While experiments showed that many plants could actually tolerate such a cycle, they were certainly not very productive in these conditions (G.M. Lisovskii, Institute of Biophysics, Krasnoyarsk, USSR, personal communication). The vacuum of space on the lunar surface made large transparent structures extremely difficult to build. If pressure on the inside of such a structure

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Frank B. Salisbury

Plants produce a pleasant and familiar environment for us Earthlings. An important part of the CELSS system combines inedible plant parts and other waste with oxygen from photosynthesis to produce carbon dioxide, water, and minerals, partially completing the cycle. Of course our bodies are also part of the system, as we breathe oxygen and consume the food and water that is produced, releasing CO₂ as we respire.

Before our CELSS was fully developed, we had only physical/chemical methods of waste disposal available, and their limitations prevented a complete recycling. Lithium hydroxide (LiOH) was used to remove CO₂, but it did not provide oxygen and thus was not part of a recycling system. (Lithium peroxide had the potential of releasing O₂ as it absorbed CO₂, but its use also presented problems.) Most wastes were simply dried and stored or sometimes jetisoned. Water was condensed and purified in various ways, but even that proved to be more difficult than had been expected; now our plants do a better job of filtering the water as it passes through them into the atmosphere. There is no physical/chemical way to recycle food.

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times the world record for the field.

A decrease in efficiency accompanied the increase in yield with increasing irradiance (Fig. 2). Nevertheless, efficiency at the lowest irradiance was 10%, integrated over the entire life cycle. Photosynthetic efficiencies (conversion of light energy to chemical bond energy) during the period of maximum growth must have closely approached the calculated maximum efficiencies for photosynthesis, ≈13%, suggesting, as indicated above, that only light was limiting and that all other environmental factors were at or close to their optimum levels.

The data on yield and efficiency point up some important CELSS trade-offs (Fig. 3). Less light means a higher efficiency of photosynthetic conversion and thus a somewhat lower power requirement, but more light means a smaller farm. In our experiment, at the highest light levels, a human being could be provided with food on a continuous basis in a CELSS farm only about 13 m² in area, about the size of an office! Even with a safety factor of as much as 4 to allow for other crops that might be less productive or have a lower harvest index, or both, and even for an occasional crop failure, a CELSS farm should not have to exceed ≈50 m²/person. At this rate, a farm the size of an American football field (5000 m²) could support about 100 people.

According to the law of limiting and optimum factors, when everything is at its optimum, plants can achieve maximum yield. We can define stress as any condition that results in less-than-maximum yield. Because our wheat yielded five times the world-record, we must conclude that the wheat plants in that world-record field were under stress. However, the situation is not quite so straightforward. Table 4 shows yields of wheat in the record field compared with yields of our CELSS wheat. It turns out to be difficult to estimate the world-record yields because we do not know the length of the life cycle nor the density of planting. The reasonable estimates shown in the table suggest that, while the CELSS wheat canopy yielded nearly five times as much as the world-record canopy, individual plants may have yielded only slightly less in the world-record field. In short, the high yields that we obtained in a controlled environment occurred because the high planting density allowed good use of the resources that considerably exceeded their counterparts in the world-record field: 2.5 times as much total light as wheat plants could possibly have received in the field, 3.6 times as much CO₂, virtually no water stress, optimized mineral nutrients, and an ideal temperature. The dense canopy allowed full use of these resources. There is no way to know how much light was absorbed by the individual plants in the CELSS canopy compared with those in the world-record field, but the data in Table 4 suggest that each individual plant in the CELSS canopy may have received even less light than comparable plants in the field (because they were packed together so tightly), and that the

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Fig. 2. Average crop growth rate (total biomass and biomass of seed, which is edible grain) and percent efficiency (chemical-bond energy of total biomass as percent of input light energy) as a function of irradiance applied to wheat plants in a controlled environment. Irradiance is shown as instantaneous photosynthetic photon flux (PPF: flux of photons that are effective in photosynthesis; 2000 µmol·m⁻²·s⁻¹ = full sunlight) and PPF integrated over the 20-h day (Bugbee and Salisbury, 1988).

Fig. 3. Illustrating trade-offs between farm size and power requirement for a CELSS, based on yield and efficiency as a function of irradiance (PPF). Farm size is calculated directly from the yield curve, based on an assumed energy requirement of a human of 11,700 kJ·day⁻¹ and an energy content of oven-dried wheat of 15,000 kJ·kg⁻¹. Power requirement is calculated from the efficiency curve, but includes some assumptions about the efficiency of conversion of electrical to light energy.

Table 4. Data on world-record and CELSS wheat yields. Were world-record wheat plants under stress?

Data on world-record wheat (Kittitas County, Washington, U.S.A., 1965):¹
Cultivar: Gaines, winter wheat.
Field size and yield: English units: 2.2 acres, 27,600 pounds, 209 bushels per acre.
SI units: 0.89 ha, 12,517 kg = 1406 g·m⁻².
Assume growing season is 100 to 120 days, yield=12 to 14 g·m⁻²·day⁻¹.
Seed yield per plant:
Assume 200 plants/m²: 7 g/plant.
Assume 600 plants/m²: 2.33 g/plant.
Daily yield: 0.0194 to 0.07 g/day per plant.
Utah CELSS wheat (Bugbee and Salisbury, 1988), yields:
Cultivar: Yecora Rojo, hard red spring wheat.
Growing conditions: growth chamber (0.8 m²; harvested area = 0.225 m²); 20C day, 15C night; 2000 µmol·s⁻¹·m⁻²; CO₂ = 1200 ± 30 µmol·mol⁻¹ (ppm), hydroponic medium.
Seed yield:
4760 g·m⁻² in 79 days = 60 g·m⁻²·day⁻¹.
2000 plants/m² = 2.37 g/plant.
Daily yield: 0.03 g/day per plant.
Compilation: It is impossible to know the amount of light absorbed per plant in the two situations.

be tied up in the organic matter; there were with 20% to 40% in the field (Bugbee and 2021).

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gradually into a true soil as organic matter

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ics (Bugbee and Salisbury, 1989). Nutrient

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accurate control in a hydroponic system, and

root-zone oxygen can be kept at suitable level-

els. Water potential never drops low enough
to be stressful, and pH can be controlled ac-

urately. The proof of the approach lies in the

root : shoot ratio. If the plant can obtain

ample water, nutrients, and oxygen, rela-

tively little of its biomass is partitioned to

the roots. Indeed, a wheat crop in a good

hydroponic system may have only 3% or 4%
of its dry biomass as roots; this compares with

20% to 40% in the field (Bugbee and

Salisbury, 1988).

A critical point in designing a CELSS is

the concept of buffer size. On Earth, CO

in the atmosphere is buffered by all the CO

and carbonates dissolved in the hydrosphere,

other substances must be maintained by ac-

tive control rather than depending on buff-

ering. This applies to the nutrient medium,

oxogen levels, and virtually everything that

is critical for growth of plants in the CELSS

and for the well-being of the human inhab-

itants.

Plant pathogens can be a problem in a

CELSS, partially because planting densities

and atmospheric humidities are typically very

high. The problems are minimized by com-

partmentalizing the environments, an ap-

proach that is also needed to provide optimum

environments for different crops. Resistant

cultivars are used, but chemical control is a

problem in the closed environment. Ultra-

violet and ionizing radiation are used in the

duct work to keep pathogen levels down. We

also construct artificial microbial communi-

ties that provide the proper balance of or-

ganisms to help control pathogens, and we

use the most modern monitoring techniques,

including infrared observations, monoclonal

antibodies, and other biotechnology sys-

tems.

Back in the 1990s, we wondered whether

we should have a large crop variety or just

a few staples such as soybeans, potatoes, and

wheat, calling upon food technology to cre-

ate many foods from these basic plant ma-

terials. We soon realized that plants make

many tasty, nutritious molecules, and that a

variety of plants offers certain psychological

advantages that, while they are not easy to

measure, are nevertheless real. Thus, we have

the large variety of crops noted (Table 2).

The total CELSS

Our lunar CELSS has four functioning

parts: 1) A plant-production facility with

higher plants and algae; 2) food technology

kitchens; 3) waste processing and recycling

facilities; 4) control systems.

We have been discussing several aspects of

the plant-production facility. The primary

goal of the kitchens is to provide a balanced,

attractive diet that includes ample food en-

ergy. A secondary goal is to use inedible

plant parts. For example, the cellulose in straw

is broken down by cellulase enzymes ob-

tained from fungi, and the resulting glucose

is used in various ways (including some fer-

mentation into alcohol!). Another secondary

goal is to recover as much nitrogen as pos-

sible before unused plant parts are sent to

the recycling facilities, where much fixed ni-

trogen is released to the atmosphere. First,

soluble salts are removed by soaking the plant

material in water, then other processes (de-

veloped in the late 1990s) are also applied.

Blue-green algae (cyanobacteria) are used to

fix some of the nitrogen lost in food prepa-

ration and waste recycling.

Science fiction authors have suggested that

we might emulate plants by synthesizing food

from scratch: from carbon dioxide, water, and

minerals. Research in this field was going on

as early as the mid-1980s, particularly in

Japan, where purified enzymes were being

used (Nitta, 1987). But machinery and en-

ergy costs proved to be very high, and again

it was realized that plants do an excellent and

relatively inexpensive job.

Our waste disposal system uses both phys-

cal/chemical and biological techniques. While

it is difficult to synthesize food and only plants

can really do it, it is less difficult to go in

the opposite direction and break it down.

In-

cineration is one approach, with the ash being

converted to plant nutrients, but the smoke

is a problem that must be solved with filters

and catalytic converters. Research was just

beginning in the 1990s. Super-critical water

oxidation is another approach. At 374°C and

above, and pressures of 22 MPa or above,

water, organic liquids and solids, gaseous

oxygen, and nitrogen all become miscible

with each other. The organics are oxidized,

and the ash settles and can be converted to

plant nutrients. Such a system requires con-

siderable energy, but we recover some of

this energy with a turbine in the effluent

stream.

As we’ve noted already, loss of fixed ni-

trogen is a problem. We use chemical nitro-

gen fixation (the Haber-Bosch process), but

this requires much energy. Thus, we also use

biological nitrogen fixation with free-living

microorganisms, as well as Rhizobium nod-

ules on legumes.

The waste disposal trade-offs involve en-

ergy and carbon. If plenty of energy is avail-

able (as from a nuclear reactor), physical

systems are basically a good choice. Other-

wise, biological waste disposal systems can

be used, but they tie up much carbon, which

allows oxygen to build up. Remember that

all the carbon must come from Earth.

Our control systems respond to sensors lo-

cated throughout Luna City, their outputs

being fed to a central computer with a backup

system and an independent power supply.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Estimated value</th>
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<tbody>
<tr>
<td>Strawberry (Fragaria × ananassa)</td>
<td>39</td>
</tr>
<tr>
<td>Watermelon (Citrullus lanatus)</td>
<td>28</td>
</tr>
<tr>
<td>Herbs and spices*</td>
<td></td>
</tr>
<tr>
<td>Anise (Pimpinella anisum)</td>
<td></td>
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<tr>
<td>Basil (Ocimum basilicum)</td>
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<tr>
<td>Caraway (Carum carvi)</td>
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<tr>
<td>Chili peppers (Capsicum annuum)</td>
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<tr>
<td>Dill (Anethum graveolens)</td>
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<tr>
<td>Garlic (Allium sativum)</td>
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<tr>
<td>Mint (Mentha arvensis)</td>
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<td>Mustard (Brassica nigra)</td>
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<tr>
<td>Oil crops*</td>
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<tr>
<td>Cotton seed (Gossypium hirsutum)</td>
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<tr>
<td>Peanuts (Arachis hypogaea)</td>
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<tr>
<td>Rape seed (Brassica napus)</td>
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<tr>
<td>Soybeans (Glycine max)</td>
<td></td>
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<tr>
<td>Sunflowers (Helianthus annuus)</td>
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</tbody>
</table>

*Extracted from: J.E. Hoff, J.M. Howe, and C.A. Mitchell (1982). The authors are at Purdue Univ., West Lafayette, Ind., and the report was prepared for NASA Ames Research Center, Moffett Field, Calif. Exotic crops will probably also be considered for use in a CELSS (Vitek, 1986), but they are arbitrarily not considered in this article.

See Table 1 for a description of criteria used in crop selection.

Herbs and spices were listed but not evaluated in the Purdue study. The selection shown here is completely arbitrary.

It is important to grow some crops just for the oil, although oil-seed crops were not considered as such in the Purdue study. The ones shown here all have high yields and would be suitable for growth in controlled environments. Soybeans and peanuts are also shown as food legumes; they are an excellent source of protein as well as oil.

Table 2. continued.
We use intrinsic feedback loops when possible: If CO$_2$ drops and oxygen rises, we oxidize more wastes, for example. If oxygen begins to drop while CO$_2$ builds up, we increase the light on the plants to increase photosynthesis. Nevertheless, leaks are a constant problem, so some control is provided by gasses released from storage.

To reduce the human workload, it is essential for the CELSS to make maximum use of automation and robotics. This allows most of the inhabitants of Luna City to be engaged in activities other than farming. Some study the geology of the moon, observe the universe (astronomy), do other scientific research, process lunar regolith for oxygen, mine the regolith for helium-3 (for fusion reactors), and engage in other activities.

So far, we have been talking about a Lunar CELSS; the one-sixth of Earth’s gravity makes things much simpler than they are in a microgravity space craft. Some of my colleagues are in a spaceship out among the asteroids prospecting for minerals. An initial goal was to simplify some of the engineering by operating the spaceship in microgravity. (Although the term microgravity is now widely used, we usually deal with *mili* gravity on a space craft. Crew activities and functioning machinery produce random accelerational forces of about 10^(-2) times Earth’s gravity.) There are problems with handling solutions in microgravity, but these can be managed. Plant gravitropism is also a bit of a problem. Generally, plants orient their stems and roots in relation to the gravitational field, but they can also orient their shoots (usually not their roots) toward a point source of light. By the 1980s, several other adverse effects of microgravity on plants had been reported (Halstead and Dutcher, 1987), but some of these were artifacts of the poor environments used to grow the plants in space. However, animals also responded poorly to microgravity, and humans were as sensitive as any other animal. Calcium loss from bones was a problem (Roux, 1983). The obvious solution was to spin the spacecraft and produce an artificial gravity. Thus, my colleagues out among the asteroids are not living in a microgravity environment after all. The only microgravity CELSS is a small, experimental one in the Space Station Freedom, which is orbiting Earth.

Other colleagues of mine are establishing a colony on the surface of Mars. Although it’s a long trip to get there, conditions are somewhat more benign than they are on the moon. There is a thin atmosphere (about 1% of earth’s atmosphere), which allows parachute landings. There is also about 20 times as much CO$_2$ in that atmosphere as in Earth’s atmosphere. Irradiance levels vary with the seasons and in the highly elliptical orbit of Mars around the sun from about 37% to 52% of the irradiance here on the moon. The Martian day is just a little over 24 h, which is certainly advantageous, and, while water is difficult to obtain on Mars, it is present. There is oxygen in the silicate rocks, the same as here on the moon. Temperature fluctuates drastically between day and night, but is always very cold (−75°C at night to 20°C at noon in the summer on the equator at the soil surface). Several characteristics on earth, in the space station, on the moon, and on Mars are compared in Table 3.

**What we knew about plant productivity by 1990**

NASA was interested in the CELSS concept as early as 1960, but, after sporadically supporting some research for a few years, NASA lost interest. Beginning in about 1978 to 1979, this interest was rekindled, and various plant productivity and other projects were supported during the 1980s. [Wheat, Frank B. Salisbury and Bruce G. Bugbee, Utah State Univ.; potatoes, Theodore (Ted) W. Tibbitts, Univ. of Wisconsin, Madison; lettuce and, recently, a few other crops, Cary A. Mitchell, Purdue Univ.; soybeans, David Raper, North Carolina State Univ.; sweetpotatoes, a more-recently funded team at Tuskegee Institute; and two smaller projects on algae (Salisbury and Bugbee, 1988).] The level of support was relatively low (probably less than $30 million for the total period—compared with a cost of nearly 10 times that much for a single launch of the space shuttle). The Soviets also began supporting CELSS research around 1960, but they continued their efforts until the present.

The Soviet program was located at various institutes around the Soviet Union, but the Institute of Biophysics in Krasnoyarsk in central Siberia was especially active (Ivanov and Zubareva, 1985). In the early 1960s, the Soviets began their studies with the alga *Chlorella*, but they discovered that it “made but poor food for man” (Terskov et al., 1986). They then began to use higher plants, emphasizing wheat, chufa nut sedge (related to purple nut sedge, the world’s worst weed; it has an oil-containing tuber), and several other vegetables. They made many advances in growing these crops in controlled environments, and several of these advances have been applied in Soviet agriculture, particularly in the far north. Yosev I. Gitleson was Director of the Institute of Biophysics and Genry M. Lisovsky was Deputy Director. In 1972, the group constructed Bios-3. They carried out experiments with the facility from 1972 to 1985. Two or three volunteers from the Institute were sealed in the unit for 4 to 6 months at a time, with a total experiment time of about 2 years.

Bios-3 consisted of welded, stainless-steel plates enclosing a volume of about 300 m$^3$ and about 63 m$^2$ of growing space for plants. Only a few sealable ports connected the inside with the outside world, and the only input was electric current and television programs. They estimated the leak rate at about 30 to 150 liters·day$^{-1}$ (0.01% to 0.05%/day).

Bios-3 had four equal-sized compartments. Two of these were used for wheat, one for the other vegetables, and the fourth was further subdivided into living quarters, kitchen, laboratory, waste disposal systems, and the control console. Vegetables that were grown included table beets, carrots, dill, turnips, cabbage, radishes, cucumbers, peas, kohlrabi, leeks, and the chufa sedge. The plants supplied 80% of the caloric intake for the subjects, and the other 20% was taken in at the beginning of each run, primarily in the form of frozen meat. The subjects chose their own diets, which were virtually identical to their normal diets. They were under constant medical supervision, and their body weights stayed within ±800 g. Plants were grown hydroponically, and urine was added directly to the nutrient solution. Thermocatalytic filters were used to purify the air, and straw and other plant-waste products were burned in an incinerator. The ash and human solid waste were stored until the end of each run.

The system never achieved complete stability. Sodium accumulated in the nutrient solutions and in the plants. The microflora (bacteria and other organisms) were carefully monitored, but did not stabilize. Hence, the CELSS concept was demonstrated, but only for relatively brief intervals of time. An ideal CELSS required a much better waste disposal system.

Way back in Sept. 1989 and Apr. 1990 (when I was very young!), I was able to visit the Institute of Biophysics in Krasnoyarsk. The first opportunity was a meeting arranged primarily with the scientists at Biosphere-2, and the second meeting involved people from NASA. We Americans and a few others from Western Europe (in the first meeting) found the scientists in Krasnoyarsk to be not only

| Table 3. Space environments. | Location |
|---|---|---|---|---|
| Factor | Earth | Space station | Moon | Mars |
| Gravity | 1.0 | <0.001 | 0.165 | 0.38 |
| Day length | 24 h | 90 min | 29,530 ± 89 days | 24 h 39 min |
| Year | 365.25 days | Same | Same | 687 Earth days |
| Tilt of axis (season) | 23.5° | 1.5° | None | 1.0 kPa |
| Atmospheric pressure | 101.3 kPa | Artificial | None | 37% to 52% |
| Light (% of Earth) | 100% | 100% | 100% | 100% |
Plant productivity in a CELSS was quite different from that of CELSS and we won’t review the results (first obtained including eight male and female humans: Bios-3, however. About 4000 species (including eight male and female humans: “Biospherians”) were introduced in an attempt to duplicate seven of the earth’s biomes. (Earth was called Biosphere 1.) In addition to a massive cooling system (environmental control system) to maintain technological control systems to maintain balances and control conditions. Biosphere 2 proved to be an interesting experiment, but we won’t review the results (first obtained in the early 1990s) here.

Plant productivity in a CELSS

Because of the extreme limitations on mass and energy (it costs several thousands of dollars to launch 1 kg of mass into space), space farming must be highly efficient. Crops must be harvested as soon as they are mature, and as soon as one crop is harvested the next one is planted in its place. Thus, the measure of productivity is yield per unit area per day, usually grams per square meter per day. Eventually, volume had to be taken into consideration, but to a considerable extent that was an engineering problem rather than an agronomic one.

Figure 1 is a generalized dose-response curve. Essential elements or environmental factors can be limiting when they are present in less-than-optimum amounts. Once the optimum has been achieved, further increases in the factor often lead to no further increases in yield; this is luxury consumption. When concentrations or intensities are too high, yields may be decreased; this is toxicity. Justus Liebig stated the principle in 1840: “The growth of a plant is dependent on the amount of ‘food stuff’ presented to it in minimum quantities.” Victor Shelford, in 1913, generalized the concept further, including the idea of super-optimal or toxic quantities: “Each and every plant species is able to exist and reproduce successfully only within a certain range of environmental conditions.”

With these ideas in mind, one approach is to establish all environmental factors at their optimum levels, except light, which can then be varied. The environmental factors that must be considered include water, carbon dioxide, temperature, nutrient medium, planting density, and genetics (cultivar). Based on what is known about photosynthesis, it is possible to make calculations about expected yields based on the light that is absorbed. If actual yields are close to the expected ones, then it can reasonably be assumed that all environmental factors are close to their optimum levels, with productivity being limited only by the light energy that is absorbed.

A small calculation illustrates some of these points and puts the question of CELSS yields into perspective. One hundred grams of oven-dry wheat has about 1500 kJ (370 kcal). Let us say a human needs 11,700 kJ·day−1; this could be satisfied by 780 g of oven-dried wheat/day. If the farm has an area of 15 m², then it must produce 52 g·m²·day−1 of oven-dry wheat or its caloric equivalent to support one human.

The Utah wheat project

The project was initiated in 1981 with Bruce G. Bugbee as a postdoctoral fellow; in 1987, he became principal investigator. Three small (0.8-mi growing area), state-of-the-art growth chambers were purchased and modified for this research. These chambers provided irradiance levels equivalent to half of sunlight in two chambers and full sunlight in one chamber (2000 µmol·m⁻²·s⁻¹). Temperature, humidity, and air velocity were controlled, carbon dioxide was enriched (usually to 1200 µmol·mol⁻¹), and plants were grown in a flowing-liquid hydroponic medium. There was also a greenhouse bay with enriched CO₂, relatively accurate temperature control (water running over the glass), and supplementary light from high-pressure sodium lamps. In 1990, a walk-in growth room was added in which near-solar light levels from high-pressure sodium lamps were combined with accurate temperature control in an area larger than that available in the growth chambers (~9 m²).

The greenhouse bay was used largely for cultivar trials, and, by 1990, more than 1000 cultivars had been tested in controlled, optimized environments. The goal was to combine high productivity with short height (35 cm or less), and some effort was expended to find uniculm types (so planting densities could be high, quickly forming a canopy). Several strains that were uniculm in the field formed profuse tillers in the optimized environments. There was a great difference in yield depending upon cultivar, with some cultivars yielding two or three times as much in controlled environments as others, although nearly all were high-yielding cultivars in the field.

Initial studies used a relatively high temperature (27°C) to shorten the life cycle and thus produce a smaller number in the denominator and a larger number for yield per square meter per day. The life cycle was decreased from ~120 days in the field to ~59, and yields were certainly encouraging: 24 g·m⁻²·day⁻¹ compared with a world-record yield of ~12 to 14 g·m⁻²·day⁻¹. Unfortunately, however, the harvest index was only ~24% compared with 45% in the field. Because of the relatively high temperatures, heads were simply not filling with grain. Hence, temperature was reduced to 20°C day/15°C night, and a short dark period (4 h) was added and combined with a high planting density (2000 plants/m²) and irradiance from 400 to 2000 µmol·m⁻²·s⁻¹), maintained at a constant level for the 20-h photoperiod (Bugbee and Salisbury, 1988). The life cycle increased to 79 days, but the yield on a daily basis almost tripled to 60 g·m⁻²·day⁻¹ (at the highest irradiance)! This was almost five
equalled atmospheric pressure at sea level on Earth, it would exceed that on the outside by 10,332.3 kg·m$^{-2}$. Of course, such pressure differences are the rule in any pressurized spacecraft (and in pressurized aircraft), but their size and shape make the engineering problems much easier to solve. A large transparent dome, tens to hundreds of meters in diameter and pressurized for humans inside, poses infinitely more formidable engineering problems. Hence, Luna City is mostly underground. Tubular modules were brought from earth and covered with about 3 m of lunar regolith. The modules are interconnected, but capable of being individually and rapidly sealed against sudden leaks, which could be disastrous to Luna City. Small leaks are unavoidable, so the atmosphere of Luna City must be continually regenerated from the lunar regolith itself (it is relatively easy to obtain oxygen from the regolith) or brought in pressurized containers from Earth at great expense. Because there is virtually no carbon on the moon, carbon or carbon compounds, including certain foods (especially meat), must be brought from Earth with some regularity.

Let me tell you about these CELSS farms. Most of the light for photosynthesis is artificial. The lamps are powered with a cold-fusion nuclear reactor manufactured in Utah! (Well, maybe it’s a hot-fusion reactor; I’ll have to check one of these days to be sure.) In spite of being underground, we try to use sunlight during the lunar day to save some power. It is collected in huge Fresnel lenses and brought into the farms via fiber optics (as in a system developed by the Himawari Company in Japan back in the 1980s). The system is about 60% efficient (60% of the light energy is transmitted to the plants). (Solar cells with batteries for storage are about 7% to 14% efficient.)

Transpired water is condensed in large coils that are exposed to the cold radiant environment of space but shielded from sunlight. With such a system, it is easier to condense the water than it is on Earth, where compressors are needed for cooling. Much of the water is recycled to the plants; some of it is purified further for use by the humans and animals.

Although plants photosynthesize somewhat better when oxygen is reduced to low levels, not enough is gained to make this approach worthwhile. If we used low oxygen levels, we farmers would have to wear masks with supplemental oxygen when we worked with the plants.

However, humans tolerate higher CO$_2$ levels than plants, so we must carefully monitor the rate at which gasses from the farms are circulated from the living and working quarters to the farms and back again. Carbon dioxide is held at about four times its ambient level in Earth’s atmosphere in the 1990s; this level promotes photosynthesis in much the same way as reduced oxygen. In the gas circulation system, toxic gasses are scrubbed out with catalytic oxidizers and active charcoal filters.

### Table 1. Criteria used for evaluation of crops listed in Table 2

<table>
<thead>
<tr>
<th>Use or nutritional criteria</th>
<th>Cultural criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy concentration</td>
<td>Proportion of edible biomass</td>
</tr>
<tr>
<td>Nutritional composition</td>
<td>Yield of edible plant biomass</td>
</tr>
<tr>
<td>Palatability</td>
<td>Continuous harvestability</td>
</tr>
<tr>
<td>Serving size and frequency</td>
<td>Growth habit and morphology</td>
</tr>
<tr>
<td>Processing requirements</td>
<td>Environmental tolerance</td>
</tr>
<tr>
<td>Use flexibility</td>
<td>Photoperiod and temp. needs</td>
</tr>
<tr>
<td>Storage stability</td>
<td>Symbiotic requirements</td>
</tr>
<tr>
<td>Toxicity level</td>
<td>Response to CO$_2$ and irradiance</td>
</tr>
<tr>
<td>Human use experience</td>
<td>Suitability for soilless culture</td>
</tr>
<tr>
<td></td>
<td>Disease resistance</td>
</tr>
</tbody>
</table>

Each crop was assigned a score for each criterion, the assignment often being arbitrary because of lack of data. Scores were totaled, and crops chosen for Table 2 were those that had a score of 28 or higher. The scores will change in response to future research, and several crops with scores of 27 or lower might be quite suitable for a CELSS.

### Table 2. Crops grown on the moon in the year 2019

<table>
<thead>
<tr>
<th>Common name</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leguminous crops</strong></td>
<td></td>
</tr>
<tr>
<td>Bean, dry or field (Phaseolus vulgaris)</td>
<td>29</td>
</tr>
<tr>
<td>Bean, green or snap (P. vulgaris)</td>
<td>29</td>
</tr>
<tr>
<td>Bean, mung (Vigna radiata)</td>
<td>29</td>
</tr>
<tr>
<td>Pea, garden (Pisum sativum)</td>
<td>30</td>
</tr>
<tr>
<td>Pea, pigeon ( Cajanus cayan )</td>
<td>28</td>
</tr>
<tr>
<td>Pea, southern, cow (Vigna unguiculata)</td>
<td>29</td>
</tr>
<tr>
<td>Pea (sugar, Chinese) (Pisum sativum)</td>
<td>29</td>
</tr>
<tr>
<td>Peanut (Arachis hypogea)</td>
<td>35</td>
</tr>
<tr>
<td>Soybean (Glycine max)</td>
<td>34</td>
</tr>
<tr>
<td><strong>Salad crops</strong></td>
<td></td>
</tr>
<tr>
<td>Celery (Apium graveolens)</td>
<td>31</td>
</tr>
<tr>
<td>Cucumber (Cucumis sativus)</td>
<td>29</td>
</tr>
<tr>
<td>Lettuce, leaf (Lactuca sativa)</td>
<td>38</td>
</tr>
<tr>
<td>Mushroom (Agaricus bisporus)</td>
<td>28</td>
</tr>
<tr>
<td>Parsley (Petroselinum crispum)</td>
<td>28</td>
</tr>
<tr>
<td>Tomato (Lycopersicon esculentum)</td>
<td>37</td>
</tr>
<tr>
<td><strong>Leaf and flower crops</strong></td>
<td></td>
</tr>
<tr>
<td>Broccoli (Brassica oleracea, Italica)</td>
<td>28</td>
</tr>
<tr>
<td>Cabbage, head (B. oleracea, Captiata)</td>
<td>29</td>
</tr>
<tr>
<td>Chard ( Beta vulgaris )</td>
<td>34</td>
</tr>
<tr>
<td>Collards (Brassica oleracea, Acephala)</td>
<td>33</td>
</tr>
<tr>
<td>Dandelion (Taraxacum officinal)</td>
<td>28</td>
</tr>
<tr>
<td>Kale (Brassica oleracea, Acephala)</td>
<td>34</td>
</tr>
<tr>
<td>Mustard greens (B. rapa, Perviridis)</td>
<td>31</td>
</tr>
<tr>
<td>Spinach (Spinacia oleracea)</td>
<td>30</td>
</tr>
<tr>
<td><strong>Sugar crops</strong></td>
<td></td>
</tr>
<tr>
<td>Sorghum (Sorghum bicolor)</td>
<td>28</td>
</tr>
<tr>
<td>Sugar beets (Beta vulgaris)</td>
<td>37</td>
</tr>
<tr>
<td>Sugar cane (Saccharum officinarum)</td>
<td>34</td>
</tr>
<tr>
<td><strong>Nut crops</strong></td>
<td></td>
</tr>
<tr>
<td>Filbert ( Corylus avellana )</td>
<td>30</td>
</tr>
<tr>
<td><strong>Root and tuber crops</strong></td>
<td></td>
</tr>
<tr>
<td>Beet, garden (Beta vulgaris)</td>
<td>29</td>
</tr>
<tr>
<td>Potato (Solanum tuberosum)</td>
<td>35</td>
</tr>
<tr>
<td>Sweetpotato (Ipomoea batatas)</td>
<td>32</td>
</tr>
<tr>
<td>Taro (Colocasia esculenta)</td>
<td>30</td>
</tr>
<tr>
<td><strong>Grain crops</strong></td>
<td></td>
</tr>
<tr>
<td>Barley (Hordeum vulgare)</td>
<td>30</td>
</tr>
<tr>
<td>Maize (corn) (Zea may)</td>
<td>32</td>
</tr>
<tr>
<td>Oats (Avena sativa)</td>
<td>29</td>
</tr>
<tr>
<td>Rice (Oryza sativa)</td>
<td>36</td>
</tr>
<tr>
<td>Rye (Secale cereale)</td>
<td>32</td>
</tr>
<tr>
<td>Wheat (Triticum aestivum)</td>
<td>38</td>
</tr>
<tr>
<td><strong>Fruit crops</strong></td>
<td></td>
</tr>
<tr>
<td>Banana (Musa x paradisiaca)</td>
<td>35</td>
</tr>
<tr>
<td>Muskmelon (Citrus melo)</td>
<td>36</td>
</tr>
<tr>
<td>Grape, European (Vitis vinifera)</td>
<td>34</td>
</tr>
<tr>
<td>Pineapple (Ananas comosus)</td>
<td>32</td>
</tr>
<tr>
<td>Raspberry (Rubus idaeus)</td>
<td>28</td>
</tr>
</tbody>
</table>

(continued)
slightly higher yield per plant (if it really was
slightly higher) may have been a response to
some of the other resources.

Some caveats
In this paper, I attempted to stay in char-
acter as a farmer on the moon in the year
2020, suggesting several features of a future
Lunar CELSS. In many cases there is simply
not yet enough information to be sure about
these matters, so my suggestions were edu-
cated guesses (as I tried to suggest by giving
dates that are still in the future in 1990). In
particular, the following areas still need con-
siderable research:

1) Will waste disposal systems be purely
physical/chemical, purely biological, or a
combination of both? The value of lithium
peroxide as a way to absorb CO$_2$
and release O$_2$ has not yet been ascertained.

2) Will natural sunlight be used in a
CELSS?

3) What are the effects of microgravity on
plant productivity?

4) Will we use a high diversity of crops
or only a few crops combined with advanced
food technology?

5) What role will algae play?

6) How much food will we be able to syn-
thesize directly from CO$_2$, water, minerals,
and some form of input energy?

7) How limited will our power supply be?

8) The postulated time for Luna City (2020)
with its 250 inhabitants now looks hope-
lessly optimistic, based on Congressional
budget actions during Sept. 1990.

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