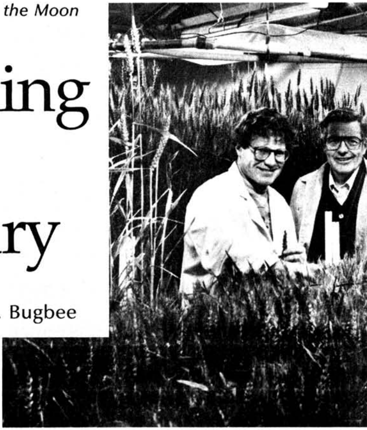
Preparations for New Year's Eve dinner on the Moon in the year 2020.

Space Farming in the 21st Century

by Frank B. Salisbury and Bruce G. Bugbee



The clock reads 20:00 Greenwich Earth time. This is the time we keep here in Luna City, since the lunar day, which is 29.530589 Earth days long, doesn't match many human biological cycles. In four hours the year 2020 will begin, and that calls for a celebration. I might stroll along the tunnel called Main Street to the Earth-observation port and take a good look at the planet that establishes our time keeping and that we recently called home. Then it would be nice to visit the mess hall, which tonight we'll call a restaurant because we have a choice of three menus, all prepared with food from the lunar farms where I work.

It seems strange to be walking along this dim tunnel, knowing that outside the Sun shines continuously for nearly 15 Earth days, and the surface can reach temperatures well over the boiling point of water on Earth. Light piped in through fiber optic illuminators brightens Main Street. It also seems strange, with the blinding sunlight outside, to see the Earth through the thick glass of the observation port against a star-studded, pitch-black, airless sky.

The View from Luna

There are several ports in the Earth-observation room, and each has a chair tilted just right for viewing. From the lunar station's location in the Moon's northern hemisphere and in the Sea of Serenity, the Earth appears about 60 degrees above the horizon, just a little west of due south. It stays in nearly the same spot, shifting only a few degrees during the lunar day. Navigation on the Earth side of the Moon is easy; Earth's elevation and azimuth tell where you are. During each lunar day all 12 constellations of the zodiac move behind the Earth toward the west. Tonight, on New Year's Eve, the Earth is in a different constellation than it was a year ago, because 12 lunar days don't exactly equal one Earth year.

Earth's diameter is about 3.67 times that of the Moon, so it has nearly 14 times the area, which is really something to see! How fascinating it is to watch it go through its phases, which provide an interesting clock to measure time during the lunar day. The Earth was full on Christmas day this year, so now it is nearing the end of its third quarter with most of its western half in shadow. The Sun is just now rising here in Luna City; it will be 14 Earth days before it sets. West of us at the zero lunar meridian, the average position of the Earth in the sky is due south, and at high noon of the lunar day, the Earth is new with only a thin crescent of light on the side next to the nearby Sun, which is much smaller (it's the size of the Moon viewed from Earth). One or two times each year, the Earth moves in front of the Sun for a few hours, producing a partial to total solar eclipse (a lunar eclipse from Earth's vantage point). When the eclipse is total, Earth is surrounded by a halo of reddish light refracted through Earth's atmosphere (a "sunset" all the way around the Earth). At lunar midnight on the zero lunar meridian, the Earth is always full, completely illuminated.

It is possible to see the Earth rotate on its axis by watching for an hour or two in the observation room, and the position of the continents will be slightly different (about 12 degrees) if one observes the Earth at the same time each Earth day. With the low-powered telescopes in the Earth-observation room, it is fascinating to follow the Earth's weather on the side that faces the Moon at any given moment. Living here can lead to some homesickness for planet Earth, but our special views provide much compensation.

Dinner in Luna City

It's time to go to the restaurant for the last lunar meal of 2019. The menu (Table 1) gives us choices for three days. We had to choose which day's menu we wanted when we

Authors Frank Salisbury (right) and Bruce Bugbee survey the wheat crop in their greenhouse at the Utah State University, which provides a controlled environment for plant experiments in preparation for space farming. The plant scientists are looking at the effect of light levels, day lengths, temperature, and so on, on efficiencies of plant growth. High-pressure sodium lamps provide a high irradiance day and night, equivalent to about half that of sunlight. Thermostats and fans provide a uniform temperature. Plants are fed automatically with a nutrient solution.

ordered breakfast, so that our diet is carefully balanced. The menus are impressive, considering that our colony is less than 10 years old and reached its originally assigned 100 occupants only about 5 years ago. Now, there are 250 people living here. We are all basically vegetarians, though not necessarily by choice! A small livestock colony, consisting of animals that live mostly on plant parts not eaten by humans, has been established, but the colony is too new to produce much meat. Most animals are now used for breeding, but there are extra eggs from the chickens. Although water is costly and scarce on the Moon, a small aquaculture system has been established with tilapia (an African catfish), carp, and trout—species that also consume organic material not eaten by humans.

Except for a few special ingredients imported from Earth, the items on the menu (Table 1) were prepared exclusively from crops grown in the lunar farms (Tables 2 and 3). Many other crops will also be developed as Luna City grows. We are always improving our repertoire.

The lunar farms are extremely efficient. Thanks to 50 years of research on Earth, it is possible to grow a wide variety of crops, each producing far more per unit area than in terrestrial agriculture. It took a large investment of time and money to establish the farms; large masses of equipment and raw materials (carbon dioxide, water, minerals, initial food for the workers) had to be transported from Earth. Producing food on the farms is expensive now, but it is far cheaper than the cost of transporting it from Earth. In a few years, money saved by growing our food on the Moon will equal the initial investment; we will have reached the economic breakeven point.

The Lunar Farms

Growing food on the Moon is expensive for several reasons. For one thing, we can't depend on light from the Sun as the source of energy for photosynthesis. The lunar night is nearly 15 Earth days long, and when the Sun shines it is difficult to use the sunlight directly to irradiate our crops. Even if an Earth-type greenhouse could be made leak proof, it could never contain an atmospheric pressure sufficient for both plants and the humans who take care of them. With a vacuum outside, lunar structures must be strong enough to withstand internal pressures of 6,000 to 10,000 kilograms per square meter. It is possible to build partially transparent walls strong enough to resist those pressures as well as micrometeorite bombardment (for example, the many small ports of heavy glass as in the Earth-observation room), but it is expensive. Furthermore, solar storms produce dangerous radiation on the lunar surface, and long exposure to the hard cosmic rays of space is deleterious to us and to the plants in the lunar farms. Hence, most of Luna City is at least 3 meters underground.

The designers of the lunar farms decided to use artificial lights supplemented with some sunlight piped in through fiber optic cables. These have large parabolic collecting reflectors that track the Sun and focus sunlight on the outside end of the cable; inside are spreaders and diffusers that irradiate the plants. This works well and saves electrical power during the part of the lunar day when the Sun is visible in the sky.

In the 1980s, there was talk of building solar collectors at the lunar poles where some people thought that the Sun never set, but the Moon's equator is tilted 6.7 degrees to the plane of the lunar orbit, and this plane is tilted 5 degrees to the plane of the Earth's orbit; hence, each pole is tipped away from the Sun for a little less than half of each Earth year and would then be in continual darkness.

Fortunately, electrical power is not a serious problem. The achievement of low-cost fusion power in the early part of this century provided the solution. A highly efficient fusion reactor produces power for all the lunar colony, including the farms.

There are many problems in operating farms besides the sources of power and light. One is the excessive transpiration (evaporation) of water from the plants. This greatly exceeds the pure-water needs of the colony, but it is relatively easy to condense the water vapor in coils that are shaded from the Sun but exposed to the cold blackness of space. The coils radiate the heat of condensation released by the condensing water; they drop tens of degrees below freezing if moist air doesn't circulate through them. Most of the water is recycled to the plants, but some is bled off for use by the colony.

Toxic organic gases generated by plants, humans, and machinery would build up in the confined atmosphere if they were not destroyed by oxidation in catalytic converters. These had their most extensive development by the automobile industry on Earth, where they were built to control atmospheric pollution from automobile exhausts (back in the days when most automobiles were powered by internal combustion engines). Thus, condensed water is also pure enough for nearly all uses.

Of course, the lunar farms do much more than produce food for Luna City: In the process of photosynthesis, they remove the carbon dioxide (CO_2) produced by respiration of the human and animal occupants and by other activities of the colony, and they release the oxygen (O_2) that the humans and animals require. Photosynthesis does not always equal respiration, however. If the farms are doing exceptionally well, for example, CO_2 may become depleted in the atmosphere as the carbon atoms are tied up in vegetable matter; O_2 then builds up. There is some automatic feedback because as CO_2 goes down, so does the rate of photosynthesis, but if the CO_2 drops too low, the plants will starve.

To keep things in proper balance, there are several things that can be done. If O_2 gets too high and CO_2 too low, oxidation (burning) of excess organic wastes can restore the proper levels. In an opposite situation, light levels on the plants can be increased to increase photosynthesis, increasing O_2 and decreasing CO_2. Luna City also maintains a supply of compressed (liquified) gases in tanks to use as a *buffer* against sudden leaks. Other "buffers" include stored supplies of food, seed, chemical nutrients for the plants, and a system to break down water by electrolysis to produce O_2 and hydrogen gas (H_2), which could then be combined with excess CO_2.

The same balances between photosynthesis and respiration are also important on Earth, but the atmosphere, ocean, and soil provide huge buffers that absorb added gases or other materials and supply gases and materials that become depleted. The buffers in Luna City are miniscule compared to those on Earth, so they must be managed with special care. The Earth's ecology allows for short-term human mistakes, but ecology in Luna City is unforgiving. Learning to recycle on the Moon has contributed to our understanding of how Earth's buffers react to perturbations.

Another balance that must be maintained in the lunar farms is between the plants and the pathogenic organisms that can cause plant diseases. Bacteria and fungi survive and sometimes grow almost anywhere, and if some fungal or bacterial disease should ravage one or more crops, it could be disastrous. Yet such problems have been quite minor. We thoroughly clean the growing areas between crops and rotate crops to avoid the build-up of particular pathogens that are adapted to any one crop.

The CELSS Life-Support System

Food production is only part of the solution to the problem of living on the Moon. The other parts are also complex and demanding of time and resources—although less demanding of electrical power than the farms. The four aspects of balancing our lunar ecosystems—food production, food preparation, waste disposal, and technological control—are really subsystems of what is called a CELSS, a controlled-environment life-support system.

Food preparation combines most aspects of the highly complex food technology of Earth in a few processing plants and kitchens. Many raw plant products must be processed to produce oils, flour, sugar, and a variety of other things. Plant roots, stems, and leaves that normally are not eaten by humans are digested by microorganisms or otherwise processed to obtain edible products. Cellulose, for example, is broken down into glucose (a simple and common sugar), which is used directly or fermented to produce many other products, including alcohol. Once initial processing is complete, food is prepared in kitchens much as on Earth.

Recycling of indigestible plant compounds, leftover foods, and human wastes proceeds in several steps. First is the digestion of residues by microoganisms. We try to conserve and extract as much fixed nitrogen (nitrate, ammonium, amino acids) as possible so it can be recycled to the plants.

Wastes that remain after microbial processing are broken down by a wet oxidation process in which they are oxidized in water at high temperatures and under high pressures. This breaks down the organic molecules into H_2O, CO_2, and inorganic salts. Further processing is then required to balance the contents of the resulting solution so it will be a suitable nutrient for plants. This means, among other things, fixing some of the nitrogen that was released as free gas (N_2) in the waste disposal process. Nitrogen fixation is carried out by microorganisms including those in the nodules of legume roots such as soybeans and peas, but some must also be reduced to ammonium by chemical means. Oxidation of nitrogen gas to nitrate is also possible, but it requires more energy.

Waste processing is in some ways simpler than it is on Earth but in other ways more complex. Wet oxidation is simple and quick, but complexities arise because of the processing of the resulting solution that is required to remove toxic ions and to provide an appropriate balance of inorganic plant nutrients. All in all, the system works well.

Control systems are necessary to integrate food production, food preparation, and waste disposal, which includes the regeneration of plant nutrients as well as purification of the atmosphere and control of its composition. As noted, the control is complex because the buffers are extremely small relative to those of the Earth. We compensate for our lack of large size with a greater degree of intelligent control—typically that of small, programmed computers.

Plant Diversity

In the planning stages, some scientists thought that plant diversity in space could be greatly reduced. Potatoes and soybeans, for example, supply nearly all the nutrients needed by humans, and it was thought that these crops could be combined with algae and yeast to produce raw materials, and food technology would do the rest. As it turns out, there are compelling reasons to use as many different plants

Table 1
MENUS FOR THREE DAYS IN LUNA CITY, 2019 A.D.*

DAY ONE

Breakfast

Fresh strawberries, 1 cup
Cooked wheat cereal, 1 cup
    with filberts (pecans), ¼ cup
    and raisins, ¼ cup
Hot beverage (cereal or soybean base)

Lunch

Stuffed tomato
    large raw tomato
    onion, chopped, 1T
    celery, sliced, ½ cup
    corn (maize), ¼ cup
    fresh mushrooms
    cooked bulgar wheat, ½ cup
    french dressing, 2 T
    lettuce, ½ cup
Bran muffins, 2
Margarine, 2 tsp
Jelly, 1 T
Oatmeal cookies, 2

Dinner

Oriental stir-fried vegetables
    celery, chopped, ½ cup
    broccoli, ½ cup
    bean sprouts, ½ cup
    fresh mushrooms, ½ cup
    pea pods, ½ cup
    cabbage, ½ cup
    peanuts, ¼ cup
    cooking oil, 1 T
    tofu, ½ cup (pinto beans)
    soy sauce, 2 T
Brown rice, 1 cup
Raspberry cobbler
    raspberries, 1 cup
    crust (sugar cookies), 2

Nutritional Status

Total calories:	2,452.8
Protein:	65.5 g
Fat:	100.5 g
Percent of calories from:	
Fat:	36.9
Protein:	10.7
Carbohydrate:	56.8

Supplies 100% or more of the recommended daily allowances (RDA) of all but the following: Calcium (supplies about 70%); Zinc (about 68%); Vitamin A (about 90%); Vitamin B_{12} (about 8%). (In Luna City, Vitamin B_{12} is supplied to everyone in tablet form.)

DAY TWO

Breakfast

Wholewheat soy pancakes
    pancakes (regular), 4
    wheat germ, 1 T
    soybeans (or pinto), ½ cup
Pineapple fruit sauce, ½ cup
Margarine, 4 tsp.
Hot beverage, cereal or soybean base

Lunch

Vegetable dumpling soup
    onion, 1 T
    carrots, ½ cup
    celery, ¼ cup
    cooked tomatoes, ½ cup
    beef flavored bouillon, 1 cup
    seasonings (brought from Earth)
    potato, ¼ cup
    dumplings (biscuits), 2
Cornbread, 1 square (8 cm)
Margarine, 2 tsp
Cabbage salad
    cabbage, ½ cup
    salad dressing, 1 T
    honey (bees in the Lunar Farms for pollination)

Dinner

Baked catfish, pearl barley casserole
    catfish or other seafood flakes, 90 g
    pearl barley, cooked, 1 cup
    white sauce, 2 T
Minted peas, ½ cup
Margarine, 2 T
Spinach salad
    spinach, raw, 1 cup
    soy curd (or pinto beans), ½ cup
    sunflower seed, ¼ cup
    oil/vinegar dressing, 1 T
Banana crepes
    pancakes, 2
    banana, fresh, 1 medium
    cream cheese (imitation), 1 T

Nutritional Status

Total calories:	2,471.7
Protein:	80.1 g
Fat:	105.1 g
Percent of calories from:	
Fat:	38.3
Protein:	13.0
Carbohydrate:	51.0

Nutrients below 100% RDA: Zinc (about 80%); Preformed niacin (over 90%); Vitamin B_{12} (over 90%).

DAY THREE

Breakfast

Cantaloupe, half
Granola, 60 g
Margarine, 1 T
Honey, 1 T
Hot beverage

Lunch

Toasted pumpernickel bagel
    with peanut butter, 2 T
Fresh green salad
    lettuce, ½ cup
    cucumber, ¼ cup
    tomato, ½ cup
    spinach, ½ cup
Blue cheese dressing, 2 T
Brownie, 1

Dinner

Enchiladas, 2
    refried beans, ½ cup
    soybean oil, 1 T
    beef flavored soybean granules
    corn tortilla, 2 medium
    lettuce, ½ cup
    tomato, ½ cup
    cheese spread, imitation, 60 g
Corn chips, 22 g
Fresh fruit salad, 1½ cups
    watermelon wedge
    cantaloupe, ¼ cup
    grapes, ½ cup
    imitation sour cream, 1 T
Lemon meringue pie, ⅐ pie

Nutritional Status

Total calories:	2,288.9
Protein:	64.1 g
Fat:	104.2 g
Percent of calories from:	
Fat:	41.0
Protein:	11.2
Carbohydrate:	51.4

Nutrients below 100% RDA: Zinc (about 60%); Potassium (about 90%); Pantothenic acid (over 90%).

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*These menus were prepared by Georgia C. Lauritzen, assistant professor, Nutrition and Food Science Department, Utah State University, based on the plants listed in Table 3 and the assumption that some flavorings and other staples would be supplied from Earth. Because of the reduced gravity on the Moon, Lauritzen assumed that caloric requirements would be somewhat reduced, to about 2,500 kilocalories per day.

as possible (Tables 2–3). The marvelous synthetic capabilities of different plants make a vast host of molecule types that provide not only nutrition but the sheer pleasures bestowed by diverse flavors. Furthermore, plants by their very presence confer a psychological stability on the space inhabitants. We are a long way from home, but the presence of familiar plants softens the impact of this separation.

Table 2
CRITERIA USED FOR EVALUATION OF CROPS

Use or Nutritional Criteria	Cultural Criteria
Energy concentration	Proportion of edible biomass
Nutritional composition	Yield of edible plant biomass
Palatability	Continuous harvestability
Serving size and frequency	Growth habit and morphology
	Environmental tolerance
Processing requirements	Photoperiod and temperature needs
Use flexibility	Symbiotic requirements
Storage stability	Response to CO_2 and irradiance level
Toxicity	
Human use experience	Suitability for soilless culture
	Disease resistance
	Familiarity with species
	Pollination and propagation

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 3 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.

Source: Hoff et al. 1982

Another approach was considered during the last third of the 20th century: complete *in vitro* synthesis of food from CO_2, H_2O, and minerals. The Japanese had a project in the 1980s in which they used enzymes isolated from organisms to make food (Nitta 1986). As it turned out, synthesis of artificial food required equipment more complex than the lunar farms, and the energy input was almost as great as that needed to drive photosynthesis. Either the equipment had to be as automated as a functioning green plant, or highly trained personnel were required to operate somewhat simpler equipment. Synthetic food was not practical; plants do the job very well.

Creating an Artificial Environment

Our lunar farms depend upon completely artificial environments. Gas composition and pressure must be accurately established (especially the level of CO_2), air speed must be controlled to facilitate convective heat exchange without mechanically damaging the plants, and temperature and humidity must also be controlled at levels suitable for maximum plant growth and yield.

Artificial light. There has been much discussion over the past decades about the relative merits of natural versus artificial light for use in a CELSS. On the Moon, the argument remains alive, because bright sunlight is available at least half of the time.

So far, lamps and much else must be brought from Earth to resupply our lunar farms, although we manufacture many items and hope soon to make lamps. There are several ways to produce energy for manufacturing on the Moon: fission or fusion, solar cells, and thermodynamic processes dependent upon the extreme temperature gradients available on the Moon (an indirect way of using solar power). Yet, it is the fusion power plant that really makes our Luna City possible and will make it possible to grow in size.

Gravity. Gravity is an important factor that differs on Earth, the Moon, and a spaceship. When a spaceship is in free fall, accelerational forces (equivalent to gravity) approach zero (but do not quite achieve it because of movements within the spacecraft). Lunar gravity is about one sixth of that on the Earth's surface. Plants and animals, including humans, are adversely affected by near-zero gravity, especially after long exposures. Plants will grow and produce harvestable materials under such conditions, but the yields are reduced compared with those on Earth, and it is somewhat more difficult to supply mineral nutrients in solution to the roots; solutions must be confined to keep them from floating around in the microgravity environment.

The upright form of plants on Earth is a response of the gravity-sensing system within the plants, a highly complex system that was still not understood by the late 20th century. Plants also grow toward a source of light, which is used to keep many plants oriented when they are weightless, but not all plants respond sufficiently to light in this way. Soybeans, for example, have straight stems and grow upright on Earth but become vine-like when they are weightless, even when they are illuminated from a stable light source.

There is plenty of available surface on the Moon, so the size limitation is dictated only by the cost and mass of materials necessary to build the structures that will contain the artificial environments. It is not too difficult to provide fairly large underground volumes, although that means producing more oxygen from minerals on the Moon. This is a relatively simple and inexpensive procedure, however, so it has never demanded tightly cramped volumes for the lunar farms. Nevertheless, the plants are usually grown in layers to best utilize the volume. Each layer has its own lights and nutrient system.

On Mars, where a new colony is being established, the problems of agriculture will be similar to those of Luna City, but some will be less severe. Mars has a thin atmosphere (less than 1 percent of atmospheric pressure on Earth) that offers some shielding from micrometeorites but offers almost no protection from radiation. However, it contains ample CO_2 (about 20 times that on Earth), and water is scarce but obtainable. Oxygen will be produced from silicate rocks as it is on the Moon, but there is virtually no nitrogen in the atmosphere.

A day on Mars is similar to that of Earth (24 hours, 37 minutes, 23 seconds), so natural light might be used to grow plants, although the irradiance levels in Mars's elliptical orbit are only about 36 to 52 percent of those at the Earth-Moon distance from the Sun.

Space farming must always be as efficient as possible. In artificial environments, there is no constraint imposed by the seasons. After a harvest, the system is immediately cleaned and the next crop planted, so our measure of productivity is yield per unit volume *per day*. A high final yield is less valuable if it takes a long time to get it. Of course, there are many other features to consider, such as nutrient content, flavor, and the other items listed in Table 2.

Many factors determine the size of the different space farms. It is truly amazing how small these farms can now be. To appreciate this, you need to compare what we have on the Moon now with what was known back in the 1980s when research was just getting going. The calculations made then proved valid, but there were many unforeseen breakthroughs in technology that have greatly improved efficiency and ease of operation.

Some History of the CELSS Concept

It was clear from the first dreams about space travel that we would have to know how to produce our own food and recycle our wastes in a Moon colony and during the long trips to the stars and the outer planets. Sometimes, an author of science fiction would suggest that the food could be chemically synthesized: The space traveler would punch in the right codes, and a machine would put together carbon, hydrogen, oxygen, nitrogen, and other elements to make a fine meal. Scientists were working on such an approach at least as early as the 1970s and 1980s.

As soon as space exploration began, government agencies started to support research on the CELSS concept. NASA supported some projects in the early 1960s to study growth of plants under controlled conditions, but most of NASA's emphasis at that time was on algae as the means to convert light energy into food energy by photosynthesis. The idea was not far behind a purely chemical approach: Once the algae had combined carbon dioxide, water, and nitrogen compounds to make proteins, fats, and carbohydrates, food technology could take over to make it as tasty and nutritious as might be desired.

By the end of the 1960s, NASA was no longer supporting research with higher plants, and algal research had also been disappointing. Ways to make algae truly tasty and nutritious were clearly far in the future, and besides, it looked like a bacterial system (with *Hydrogenammonas*) might be the way to go. But that also failed to reach fruition,

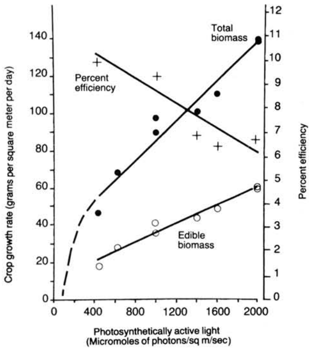
The Soviets began CELSS research at about the same time as NASA did, but they never stopped (Ivanov and Zubareva 1985). This was mostly because of the dedication of a single Soviet scientist, Iosif Gitelzon, in Krasnoyarsk, Siberia. By 1985, Gitelzon's group was testing what they had learned by sealing two volunteers into a simulated spaceship farm called Bios 3, where they stayed for five months, producing 80 percent of their food needs and regenerating all their oxygen and water. Only electricity and TV programs were supplied from the outside. They grew crops under artificial light (xenon lamps) in an area of 60 square meters and a total volume of 315 cubic meters. They grew wheat, chufa (a species of sedge with edible tubers), peas, dill, kohlrabi, turnips, leeks, table beets, cucumbers, and other plants, and they encountered some difficulties with potatoes and tomatoes.

Table 3
CROPS GROWN ON THE MOON IN THE YEAR 2019[1]

Common Name	Estimated Value[2]
Leguminous crops	
Bean, dry or field	29
Bean, green or snap	29
Bean, mung	29
Pea, garden	30
Pea, pigeon	28
Pea, southern, cow	29
Pea (sugar, Chinese)	29
Peanut	35
Soybean	34
Salad crops	
Celery	31
Cucumber	29
Lettuce, leaf	38
Mushroom	28
Parsley	28
Tomato	37
Leaf and flower crops	
Broccoli	28
Cabbage, head	29
Chard	34
Collards	33
Dandelion	28
Kale	34
Mustard greens	31
Spinach	30
Sugar crops	
Sorghum	28
Sugar beets	37
Sugar cane	34
Nut crops	
Filbert	30
Root and tuber crops	
Beet, garden	29
Potato	35
Sweet Potato	32
Taro	30
Grain crops	
Barley	30
maize (corn)	32
Oats	29
Rice	36
Rye	32
Wheat	38
Fruit crops	
Banana	35
Canteloupe	36
Grape, European	34
Pineapple	32
Raspberry	28
Strawberry	39
Watermelon	28
Herbs and spices[3]	
Anise	
Basil	
Caraway	
Chili peppers	
Dill	
Garlic	
Mint	
Mustard	
Oil crops[4]	
Soybeans	
Peanuts	
Sunflower	
Rape seeds	
Seed cotton	

Notes

1. Extracted from: J.E. Hoff, J.M. Howe, and C.A. Mitchell (1982) in a report prepared for NASA Ames Research Center. Exotic crops will probably also be considered for use in a CELSS (Vietmeyer 1986), but they are not considered in this article.
2. See Table 2 for a description of criteria used in crop selection.
3. Herbs and spices were listed but not evaluated in the Hoff et al. study. The selection here is arbitrary.
4. It is important to grow some crops just for the oil, although oil-seed crops were not considered as such in the Hoff et al. study. The ones shown here all have high yields and would be suitable for growth in controlled environments. Soybeans and peanuts are also an excellent source of protein as well as oil.



THE EFFECT OF INCREASING LIGHT ON PLANT PRODUCTIVITY AND EFFICIENCY

The productivity of plants increases with increasing light, but the plant's energy efficiency decreases with increasing light. The goal in a CELSS is the use of as much light as possible without saturating the system so that there is maximum growth and maximum use of light. In this Utah experiment with wheat, there is no sign of saturation, even at the highest level, which equals full summer sunlight for 20 hours per day. The dashed line represents light values too low to produce much biomass.

Excessive oxygen was removed by burning nonedible biomass in a catalytic furnace. When the catalysts went bad, oxides of nitrogen began to build up, which was noticed when the plants reacted adversely. The catalysts were then replaced, and the air became fresh again. Earlier versions of Bios "spaceships" used the algae *Chlorella* for air purification, but it was "difficult to cook," so they gave it up.

NASA again became interested in the late 1970s. Workshops were held, and initial projects were funded in 1980. By 1986, quite a bit had been learned by the NASA contractors, who studied food preparation, waste disposal, and control systems as well as four projects on plant productivity, although the amount of support was miniscule compared with other NASA-supported projects. (About $10 million had been spent during the first six years of the project.) A major effort was initiated in 1985 at the Kennedy Space Center in Florida to scale-up some of the results obtained with plant-growth chambers in the four production projects. A large pressure chamber (a vertical cylinder about 8 meters long and 4 meters in diameter), which had been used to test space vehicles in the Apollo program, was outfitted so about 22 square meters could be used for plant growth. The goal was to enclose the atmosphere and eventually to recycle wastes. Wheat plants were first put in the chamber on Dec. 1, 1986.

There was also an independent project in France (Andre, et al. 1986), and the Japanese were supporting several projects (Nitta 1986). Strong support was presented for the CELSS concept in the report of the National Commission on Space (1986). CELSS had begun to come of age.

Crop Physiology

The goal in the early years of the four NASA plant-production projects was to see just how much food could be produced in a limited area and how much energy it would take to produce it. Here was a real challenge for the science of *plant physiology,* the study of how plants function, and especially its applied subfield of *crop physiology.* If the goal was to increase yields to some theoretical maximum in a given space and with a given amount of energy, the obvious approach was to learn about everything that limits yield and quality of harvested crops and to find ways to overcome the limitations. The idea was to eliminate, in so far as possible, all *stress factors.*

Plant physiologists had learned enough about photosynthesis by 1980 to make a good estimate of maximum theoretical yield. The calculation depends on the efficiency with which light energy is converted by photosynthesis to the chemical-bond energy of foods. Let's examine the process of photosynthesis and the stress factors that might limit it. (The calculations are summarized in Salisbury and Ross 1985; see also Rosinsky 1986.)

Photosynthesis and the limits on yield. Light is the ultimate limiting factor. Plants can't produce more chemical-bond energy in food than they absorb from the light that irradiates them—and, since they will never be 100 percent efficient, they will convert only some fraction of that absorbed energy to food. Based on what was known in the 1980s about the chemistry of photosynthesis and measurements with dense algal cultures irradiated with relatively dim red light (so every photon was used in photosynthesis), it was possible to suggest that photosynthesis could reach a maximum of 33 percent efficiency. (That is, 33 percent of the absorbed light energy could end up as food energy.) However, higher plants irradiated with low levels of white (full-spectrum) light were only about 18 percent efficient. At higher light levels, only about 14 percent could be achieved; in typical agricultural fields, efficiency was often around 1 to 2 percent.

One way that physicists think of light is as consisting of particles of energy called photons or quanta. Plant physiologists had learned that it takes at least 8 photons of light energy to combine 1 molecule of CO_2 with 2 molecules of H_2O, releasing 1 molecule of O_2 and another molecule of H_2O, and producing 1 carbon unit (CH_2O) in a carbohydrate molecule. Calculations based on 8 photons predict an efficiency of 33 percent in red light. Red photons have less energy than blue photons, so the highest efficiencies are achieved with red light. In general, light quality—its color—is important in photosynthesis; blue and red are most effective, green less so.

It was also known that photosynthesis can be *saturated.*

When light levels are low, adding more photons leads to more photosynthesis, but at some high light level (depending on the species and other factors), the photosynthetic mechanism becomes saturated so that additional photons do not increase the rate of photosynthesis. The goal in a CELSS is to use as much light as possible, so the process will go as fast as possible, without saturating the system so that light is wasted.

Light-utilization efficiency depends partly on how the leaves are arranged. If the plant has horizontal leaves, the top leaves get too much light and are inefficient. Only a few layers down, the light is too low for photosynthesis to work efficiently, and most of the food the shaded leaves produce is used to keep them alive. The light level where photosynthesis just equals respiration (the process that goes on in the light or the dark and uses food to support the plant's functions) is called the *compensation point* (or the *compensation light level*). It is important to keep as many leaves as possible photosynthesizing well above the compensation light level.

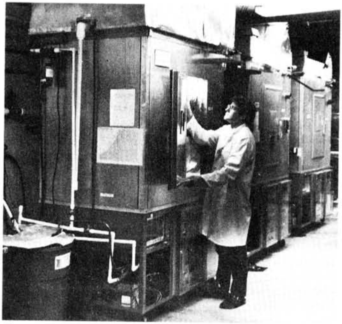
If the leaves are nearly vertical, like grass leaves, the light comes in almost parallel to the leaves, so each leaf has a fairly uniform irradiation from top to bottom, and there is little shading. Therefore, a little light is spread over the entire leaf, and even at high irradiance levels no part of the leaf is much above saturation. So grasses like wheat and rice are ideal for a CELSS.

Light acts on plants in special ways besides photosynthesis. Plants have a number of delicate pigment systems that respond to light and control various growth processes. For example, plants will bend toward a blue light but not a red light, and they even measure the relative length of day and night, coupling a pigment that absorbs mostly red light with a biological clock. The response to day length can determine how soon and how many flowers form, for example, and it can further influence the rate at which seeds or fruits develop. Because the pigments absorb different colors of light, light quality can be very important in controlling these developmental processes. Such things can be critical to the yield and quality of harvested products, so crop physiology applied to a CELSS depends significantly on knowledge about plant responses to light.

Water and carbon dioxide. Water and carbon dioxide are needed along with light in the photosynthetic process. Water must be supplied in ample amounts in a CELSS; on Earth, lack of water is probably the most important stress factor limiting yields.

Photosynthesis can be increased by increasing the available carbon dioxide, providing that light or some other factor is not limiting. This is not easy to arrange in an open field on Earth, but all environmental factors must be controlled in a CELSS anyway, so CO_2 is increased to its optimum level.

The situation is more complex than it might seem, however. When CO_2 is increased in the atmosphere around a plant, it causes the minute pores in the leaves (called *stomates*) to begin to close. This increases the resistance to diffusion of CO_2 into the leaf, but more gets in than would have if it had not been increased in the atmosphere, and photosynthesis of most plants increases. However, the closing stomates reduce the amount of water that evaporates from inside the leaves and diffuses out of the stomates in the process called *transpiration*. This is good, because it means that, in a CELSS, less water will have to be condensed and returned to the plants. Reduced transpiration, however, reduces the rate at which some mineral nutrients, especially calcium, are taken from the roots to the leaves, so more must be added in the nutrient solution.



Plant scientist Bruce Bugbee looks into one of three growth-chambers at Utah State University. The university has been experimenting since 1981 with yield and quality of wheat in controlled environments. Each growth chamber has about 1 square meter of growing space. Two have fluorescent lamps supplemented with high-pressure sodium lamps to produce an irradiance about half that of sunlight. The third has light levels equivalent to sunlight.

Air is mixed with carbon dioxide in a large tank on the wall and the nutrient solution for the plants is pumped in from an external reservoir.

The role of temperature. The situation with temperature is much like that with light or carbon dioxide. Each species, even each cultivar (agricultural variety), has a particular temperature or sequence of temperatures that, given a certain set of other environmental conditions, will lead to maximum yield and quality at harvest.

The role of soil nutrients. Water may be the most limiting factor in conventional agriculture, but adding proper soil nutrients—fertilizers—probably had the most profound effect on crop yields since the beginning of agriculture several thousand years ago and especially since the 19th century when we began to understand what it was that plants needed besides sunlight, water, and carbon dioxide. (The roles of light, H_2O, N, S, CO_2 were discovered in the late 18th and early 19th centuries.) In about 1860, three German plant physiologists (W. Pfeffer, Julius von Sachs, and W. Knop) recognized that healthy plants could be grown with their roots in solutions that contained a limited number of dissolved salts. This approach was applied from then on to learn the elements that are essential for plants and the amount and conditions that provide the best yields and quality of different species and cultivars.

Achieving Maximum Yields

The process of growing plants in nutrient solutions instead of soils came to be called hydroponics. All plants require six elements in relatively large amounts (the macronutrients: nitrogen, potassium, calcium, magnesium, phosphorous, and sulfur in descending order) and at least seven others in smaller amounts (the micronutrients: iron, boron, manganese, zinc, copper, molybdenum and chlorine). A few seem to benefit from the presence of sodium, silicon, and others.

To achieve maximum yields and quality in a CELSS, these elements must be provided in ideal amounts in well-aerated nutrient solutions. When this is done, roots are small (only 3 to 4 percent of the dry weight of wheat plants, for example), and tops are healthy and productive. The harvested end-products contain not only the mineral elements that were provided in the nutrient solutions, but also the carbohydrates, fats, proteins, and vitamins that are needed by the humans who will consume them. No plant grown in a rich, organic soil provides more nutrients required by humans than a plant grown hydroponically.

After all, plants don't make vitamins and other nutrients just for humans to eat; these substances are part of the plant's machinery for making more of itself. Typically, vitamins and minerals act as coenzymes, substances that activate the enzymes, the proteins that control all the chemical processes that make up life. The same is true in the bodies of the humans who eat the plants; it is just that plants make all these essential compounds from basic minerals, CO_2, and H_2O driven by light energy, while we animals make only a few and must obtain the rest from the food we eat.

As with temperature, carbon dioxide, and light, there are many subtle effects of nutrients. The machinery of photosynthesis, for example, is built of organic molecules that contain atoms of carbon, hydrogen, oxygen, and nitrogen. There are also atoms of magnesium (in chlorophyll), iron, phosphorus, potassium, sulfur, chlorine, manganese, zinc, and copper, and there may well be others. If any of these elements is present in insufficient amounts (and sufficient amounts are often extremely small), photosynthesis will not function adequately, and yields will be reduced. But too much of these elements can be toxic.

The mineral elements also play critical roles in establishing a suitable osmotic environment (the total concentration of dissolved substances) for the chemistry of cells. Potassium is especially important in this function. If the osmotic concentration of the nutrient solution is too high, for example, the plants won't be able to absorb sufficient water, and many processes within the plant depend on transfers of water and other substances that are influenced by the osmotic environment. Movement of the foods produced in the leaves to storage organs like tubers or seeds, for example, is driven by the process of osmosis, so internal osmotic conditions strongly influence the partitioning of foods (the relative portions that are transported to roots, stem, new leaves, tubers, developing seeds or fruits, and so on).

Calcium is kept at low concentrations in the cytoplasm of plant and animal cells, where most of the enzymatic action

Table 4

HIGH YIELDS OF WHEAT CROPS IN CONTROLLED ENVIRONMENTS

Experiment	**Days to harvest** d	**Edible dry biomass** g/sq meter	**Harvest index** %	**Maximum growth rate**[1] **(total biomass)** g/sq meter/day	**Average growth rate (edible biomass)** g/sq meter/day
High average field	120	500	45	?	4.2
World record	140	1,450	45	?	10.4
Soviet Bios[2]	60	1,314	?	?	21.9
Utah, 24-hour light, 27°C	57	1,053	32	100.0	18.5
Utah, 24-hour light, 17.5 to 22.5°C, 1°C/week; 1,200 plants/sq meter, irradiance level = 1,000 micromoles/sq meter/sec	59	1,423	44.4	100.0	24.1
Utah, 20-hour light; 20°/15°C, day/night; 2,000 plants/sq meter, irradiance level = 2,000 micromoles/sq meter/sec	79	4,760	44.1	200 (est.)	60.3

1. Measured for a short interval during the most rapid phase of growth.
2. Data for Soviet wheat are from summary tables in Salisbury and Bugbee (1987).

Here are the yields of the NASA-supported wheat project along with typical field yields. The important column is the one on the right listing yields of edible biomass. A yield of about 50 grams per meter per day allows a space farm as small as 15 square meters per person. The new results achieved at Utah State University in 1987–60 grams per square meter per day–are more than double the yields from previous trials. The higher yield was achieved primarily by using high planting densities along with full sunlight equivalent and optimal temperature.

Dr. Bugbee lifts up the rock wool base of the plant-support system to show the dense root system of 18-day-old plants. Note the reflection in the open door of the growing chamber. The inside walls of the chamber have mirror surfaces to maximize reflection of light.

is; otherwise it would tie up phosphate ions, which are critical to much of the biochemistry of cells. In plants and animals, the calcium reacts with a special protein called calmodulin (and with related proteins that are less understood) to regulate many important biochemical and developmental processes. In plants, calcium also influences the structures of cell walls and membranes.

I have already noted how CO_2 levels can interact with the mineral nutrition of a plant by influencing the rate of transpiration and thus the rate at which minerals are moved from the roots to the tops of plants. Humidity also influences transpiration, as you would expect, so it interacts with the plant's mineral nutrition. All these things had to be considered in designing a CELSS that had maximum productivity.

Cultivars. The last factor I'll discuss is at least as important as all the rest: the genetics of the plants that were used. A specific crop variety with a specific set of genes that have been assembled by breeding and selection is called a *cultivar*, and the cultivar that is used in a CELSS can make a large difference in the yields and quality of harvestable products. It was found, for example, that when several wheat cultivars were grown together in a controlled environment, certain ones yielded three or four times as much as others. In conventional agriculture, all would yield about the same. Clearly, much could be gained by breeding special cultivars for controlled environments. Most available cultivars had been produced in environments that had relatively low levels of nutrients, total light energy per day, CO_2, and often even water.

With that background, we could calculate the potential yields in a CELSS and compare it with what had been achieved by the mid-to-late 1980s (Salisbury and Bugbee, in press): With a continual photosynthetic efficiency of 14 percent and light at about half that received at the Earth's surface, taking into account the time it takes for a crop to form a dense canopy of leaves, and assuming that about half the crop (for example, wheat) can be eaten, a figure of 15 square meters becomes a reasonable estimate for the theoretical minimum size of a space farm operated to support a single human being. Such a farm would have to produce about 52 grams per square meter per day of edible food. In the 1980s, the world record yield of wheat in the field was about 14 grams per square meter per day, but the NASA-supported CELSS project on wheat at Utah State University routinely obtained 15 to 24 grams per square meter per day during most of the years after it was initiated in 1981.

Then in 1986, experience gained during the previous years was applied to make some modifications in the techniques, producing a yield of 60 grams per square meter per day, almost triple the previous high yields! These results are summarized in Table 4. Even with a safety factor of 2 to 4, these figures predicted that our lunar farm would only have to be about the size of an American football field to support a lunar colony of 100 people, and so it turned out to be!

Well, all this talk about food and food production has made me more than ready for New Year's Eve dinner, 2020. Maybe next year, some of you will join me here in Luna City!

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