Bioregenerative life-support systems[1-3]

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ABSTRACT Long-duration future habitation of space involving great distances from Earth and/or large crew sizes (eg, lunar outpost, Mars base) will require a controlled ecological life-support system (CELSS) to simultaneously revitalize atmosphere (liberate oxygen and fix carbon dioxide), purify water (via transpiration), and generate human food (for a vegetarian diet). Photosynthetic higher plants and algae will provide the essential functions of biomass productivity in a CELSS, and a combination of physicochemical and bioregenerative processes will be used to regenerate renewable resources from waste materials. Crop selection criteria for a CELSS include nutritional use characteristics as well as horticultural characteristics. Cereals, legumes, and oilseed crops are used to provide the major macronutrients for the CELSS diet. A National Aeronautics and Space Administration (NASA) Specialized Center of Research and Training (NSCORT) was established at Purdue University to establish proof of the concept of the sustainability of a CELSS. The Biosphere 2 project in Arizona is providing a model for predicted and unpredicted situations that arise as a result of closure in a complex natural ecosystem. *Am J Clin Nutr* 1994;60:820S–4S.

KEY WORDS CELSS, cereal, controlled ecological life-support system, legume, oilseed, recycling, vegetarianism

Long-duration habitation of space

When the manned space program evolves to the point that it involves a considerable number of people operating at great distances from Earth for long periods of time, the present approach of storing essential ingredients of human life support, or resupplying them, must give way to regenerative means. Physicochemical technologies for air revitalization and water reclamation can operate for long periods of time in space (1, 2) but the continuous provision of human food remains a challenge. Many life-support scenarios depicted for long-term space habitation implicate a central role for plant life. Even though edible biomass production for a vegetarian diet is the driving force for considering plants in a major life-support role in space, the fact that plants also can purify air and water is another plus. However, the concept of transparent, greenhouse-like habitats supporting plant and human life on the lunar surface probably is unrealistic. For one thing, the airless moon is subject to bombardment by meteorites and lethal solar flares, as well as by cosmic or galactic radiation. Transparent surface structures on the moon would afford no protection from particle impacts or radiation events and would need provision for photoperiod control during the 2-wk-long lunar day as well as high-intensity plant-growth lighting during the equally long lunar night. Habitats either will be located underground, bunkered heavily with regolith (soil), or constructed of thick-walled lunar "concrete" that is resistant to solar flares and micrometeorites.

Surface units also would be compartmented such that individual habitation modules can be isolated rapidly from others should a section be hit by something that could create one of the many craters that scar the lunar surface. Canopies of crop plants growing within opaque structures would be illuminated either by plant-growth lamps energized by electricity generated from photovoltaic cells during the lunar day and/or by nuclear reactors that would provide electrical power during the lunar night. Fiber optic or light-pipe transmission of photosynthetically active solar radiation to underground plant-growth areas also might be utilized to make use of available solar radiation. Early Mars colonists may convert their landing craft into surface habitats with inflatable greenhouses attached. Although Mars has an ultra-thin, mostly carbon dioxide atmosphere and is much farther from the sun than is the moon, there still will be danger from solar flares and meteor showers. Advanced bases likely will take advantage of the eroded martian terrain and will be bermed or dug into hillsides.

The controlled ecological life-support system concept

In anticipation of extended-duration, manned missions to Mars, including transit to and from the Red Planet, the National Aeronautics and Space Administration (NASA) has developed a research program in its Life Sciences Division to explore the feasibility of using bioregenerative cycling in combination with physicochemical recycling of certain life-support ingredients. The goal of this NASA program is to develop a controlled ecological life-support system (CELSS) that ultimately would operate totally independently of resupply from Earth. A major structural challenge for a CELSS will be the maintenance of a pressurized volume against the vacuum of space, as on the moon, or against a very thin, low-pressure atmosphere, as on Mars, with little or no outward leakage.

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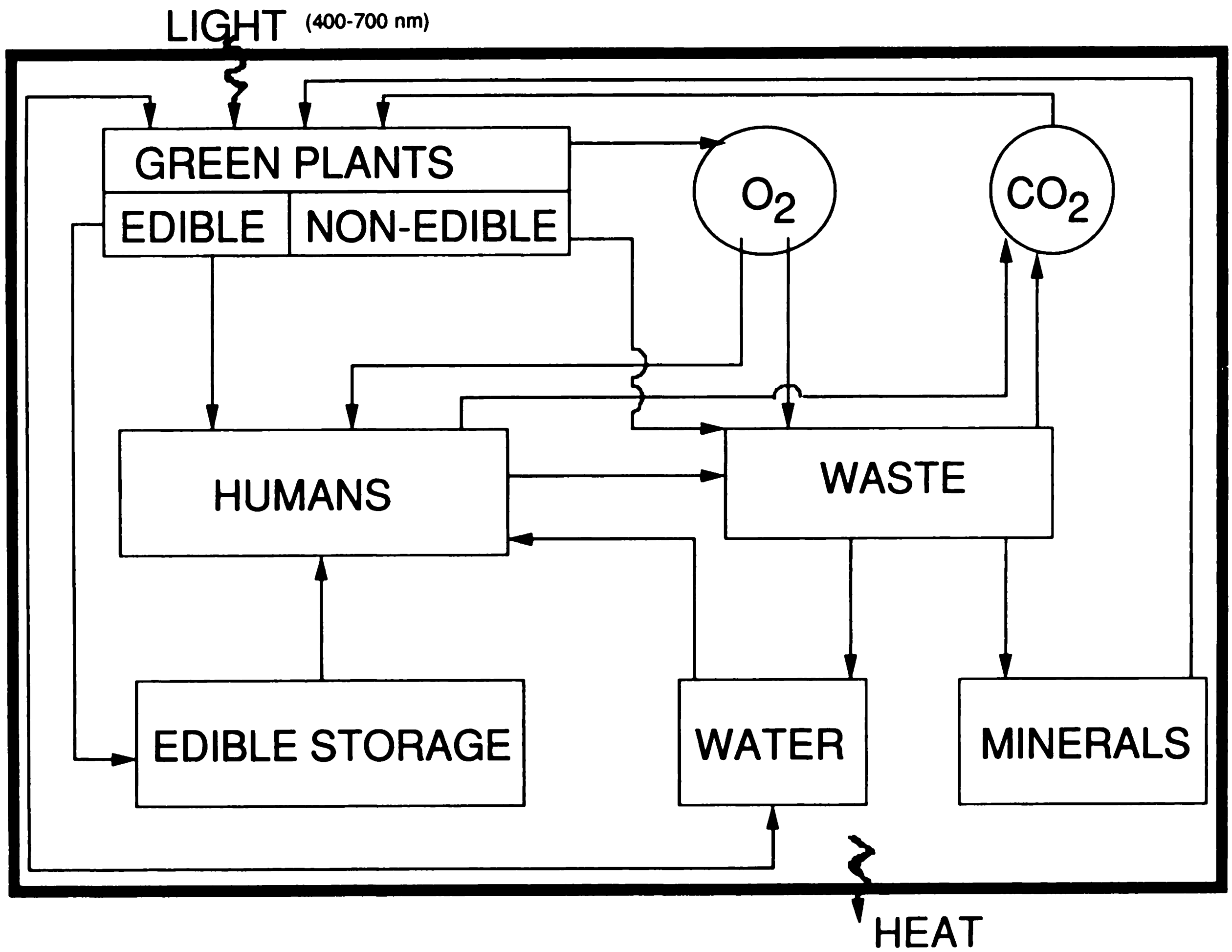

FIG 1. A sustainable bioregenerative life-support system for space (from reference 3).

Figure 1 schematically depicts the essential components of a CELSS. The dark boundary depicts a mass-impermeable barrier within which biomass recycles in its various forms. Only energy enters or leaves a CELSS: light or electrical power is input to energize plant-growth lamps and machinery and waste heat is output to preserve temperature equilibrium. Human life-support needs provide the justification for creating a CELSS, but photosynthesis is the reason a CELSS will work. Chlorophyll traps the energy of photosynthetically active radiation in the chemical bonds of carbohydrate precursors that can be metabolized to any biochemical constituent of living things. The edible portion of plant biomass can be consumed directly or processed into more palatable foods with shelf lives. Of course, photosynthesizing plants also scavenge carbon dioxide from the air and release oxygen as a byproduct. These gas-exchange fluxes are opposite those of aerobic respiration, so plants and humans complement each other with respect to carbon, oxygen, and energy metabolism. Plants, of course, also transpire large quantities of highly purified water vapor from stomatal pores in the leaves, even if the roots are immersed in treated sewage. In a CELSS, organic wastes generated by humans or from various bioconversions would be oxidized to carbon dioxide, water, and minerals by enzymatic or physicochemical reactions, which would consume just as much oxygen and energy as liberated by photosynthesis in the first place.

Therefore, it is important when planning a CELSS to select or develop candidate crop species that have as low a proportion of nonedible biomass as possible, or to develop bioconversion technologies that create safe, nutritious, palatable food products out of residue or waste. Although Figure 1 illustrates the basic recycling pattern for biomass conversion in a CELSS, it is greatly oversimplified. There actually are multiple paths of biomass conversion for each step depicted in the CELSS schematic. Critical path analysis is required to determine the most efficient path from the standpoint of kinetics, energetics, and operational power and labor requirements, and these parameters need to be determined for all energy-consuming bioconversions that follow the primary events in photosynthesis, including food processing, waste management, and other forms of resource recovery.

Crop selections for a CELSS

One of the most important considerations in developing a sustainable CELSS involves selection of appropriate candidate crop species, especially because a first-generation CELSS likely will provide a mainly vegetarian diet (**Table 1**). One set of selection

TABLE 1
Candidate species selection criteria for a controlled ecological life-support system (CELSS) based on nutritional use (criteria numbered 1–9) and horticultural characteristics (criteria numbered 10–21)[1]

Selection criterion
1. Energy content
2. Nutritional composition
3. Palatability
4. Serving size and frequency
5. Processing requirements
6. Use flexibility
7. Storage stability
8. Toxicity
9. Human use experience
10. Proportion of edible biomass
11. Yield of edible biomass
12. Continuous vs determinate harvestability
13. Growth habit and morphology
14. Environmental stress tolerance
15. Photoperiodic and temperature requirements
16. Symbiotic requirements and restrictions
17. Carbon dioxide and light intensity response
18. Suitability for soil-less culture
19. Disease resistance
20. Familiarity with species
21. Pollination and propagation

[1] From reference 3.

TABLE 2
Plant species recommended for a "generous" controlled ecological life-support system (CELSS) diet scenario[1]

Leguminous crops	Herbs and spices (*continued*)
Dry bean (navy, pea)	Pimiento pepper
Green bean (garden)	Mint
Mung bean	Parsley
Garbanzo (chickpea)	Grain crops
Dry pea (split)	Barley
Sugar pea (podded, Chinese)	Corn (maize)
Peanut	Oat
Soybean	Rice
Root and tuber crops	Rye
Garden beet (red)	Wheat
Carrot	Leaf and flower crops
Potato	Broccoli
Sweet potato	Chinese cabbage
Taro	Head cabbage
Salad crops	Cauliflower
Celery	Chard
Leaf lettuce	Kale
Onion	Spinach
Tomato	Fruit crops
Sugar crops	Banana
Sugar beet	Grape
Sugar cane	Strawberry
Herbs and spices	Cantaloupe
Chive	Stimulant crop
Garlic	Tea

[1] From reference 3.

criteria involves nutritional considerations, such as energy content of the harvested part and its nutritional value. Other important nutritional considerations include the time, effort, and power needed to process edible biomass into food products that not only are safe and palatable, but that people will not tire of. Another important set of selection criteria are horticultural. Species with a large proportion of edible biomass (ie, have a high harvest index) are desirable because there is less nonedible residue to submit to the waste stream for processing. Knowing the actual yield of edible biomass per unit growing space per unit time also is important to minimize the agricultural area needed within a CELSS. Do we want bushes or vines? Do we want everbearing or rapid-cycling crops? Do they need to be self-pollinating? Should they be long-day or short-day requiring for flower initiation? Inclusion of woody species such as dwarf fruit trees probably is unrealistic because of biomass holdup (metabolically inactive storage) as lignocellulose for long periods of time. Long juvenile periods and chilling requirements to break seasonal dormancy cycles are other reasons why woody plants would be unrealistic. However, characteristics such as adaptability to hydroponic culture and responsiveness to yield-optimizing factors such as carbon dioxide enrichment are likely to be important cultural selection criteria for crops in a CELSS.

There are likely no perfect crop selections for a CELSS, but the fewer species that are used, the more important human nutritional considerations will become in those selections. The National Research Council has determined that Americans consume too much dietary protein and fat and should decrease their protein intake from the current 25% of total energy to ≈15%, decrease fat intake from 38% to 30%, and increase complex carbohydrate consumption from 37% to 55% to make up the balance (4). Hypogravity and other space conditions may alter protein and energy dietary requirements, but more nutrition research must be done with humans exposed to prolonged hypogravity conditions in space before we will know what dietary guidelines are most appropriate. It is believed now that traditional legume-and-cereal-based vegetarian diets will be pursued for a CELSS: for example, oily legumes such as soybeans and peanuts and nonoily legumes such as cowpeas, dry beans, or garden beans will be used together in proportions that are appropriate to minimize fat intake; wheat and/or rice will be used to lower total protein intake and to achieve amino acid complementarity of the cereal-legume protein mix; and complex carbohydrates will be provided by white potato and sweet potato as well as by cereals. Vegetable (chard, cabbage, and/or broccoli) and salad (lettuce, tomato, and sprout) crops should be included for vitamins, minerals, fiber,

TABLE 3
Proximate analysis of original controlled ecological life-support system (CELSS) candidate species[1]

Species	Composition		
	Carbohydrate	Protein	Lipid
	% of dry wt		
Soybean	38	38	20
Wheat	82	14	2
Potato	85	10	1
Sweet potato	89	6	1
Lettuce	58	22	5

[1] From reference 5.

and psychological augmentation (freshness, texture, flavor, variety, etc) of the diet. A 36-species "generous" diet shown in **Table 2** is desirable for variety but probably will not be realistic for a CELSS. However, small amounts of herbs and spices certainly could be grown for condiments, garnishes, and for heightening interest in food. The main dietary challenge of a CELSS is not so much to provide a variety of species, but to create a variety of palatable dishes from the species selected. Mars pioneers quickly would tire of eating bowls of beans and cereals. They will want pasta, tempeh, tofu, yogurt, cheeses, beverages, tasty desserts, and recreational stimulants (herbal tea?). The proximate composition of CELSS candidate species for which most optimum productivity research has been done to date is included in **Table 3.**

Research and training in bioregenerative life support

The NASA Specialized Center of Research and Training (NSCORT) in Bioregenerative Life Support, established at Purdue University in November, 1990, has begun work on several candidate species to provide additional flexibility in food processing. One "new" crop is a rapid-cycling, dwarf brassica (*Brassica napus*) that is related to mustard and is just a gene or two away from canola (6). The seeds of the dwarf brassica contain oil, protein, and carbohydrate. A nonoily legume under investigation by NSCORT is cowpea (*Vigna unguiculata*), which can be eaten either as a snapbean or as a dry bean. Cowpea foliage also is consumed in Africa either as a pot herb or as a raw salad green, so the potential harvest index of this legume can be quite high (7). Rice (*Oryza sativa*) is an alternative NSCORT cereal crop to complement wheat. It is a natural for hydroponic culture and, because its leaves remain green as the grain ripens, can be "rattooned" or cut back for a second crop on the same root system. The proximate composition of these three new candidate species gives additional flexibility in terms of mixing and matching edible biomass from different crops to formulate diets with predetermined composition of protein, fat, and carbohydrate (**Table 4**).

The NSCORT at Purdue is quite interdisciplinary in its approach to bioregenerative life support. There are two projects on biomass production, one with higher plants, the other with blue-green algae. There are two molecular biology projects, one to improve the protein quality of rice, the other that of cowpea, both by using recombinant DNA technology. There are three projects in food science and human nutrition: the first emphasizes the development of novel food products for balanced vegetarian diets, the second is a compositional analysis of nutrients and antimetabolites in the candidate species, and the third emphasizes bioavailability problems with vegetarian diets and appropriate countermeasures. There is also a waste management project emphasizing in vitro enzymatic degradation of cellulose wastes and what to do with sugars produced by the process. Total systems analysis and dynamic modeling of a CELSS is being done in collaboration with the University of California at Berkeley.

Biosphere 2

Analogous to a CELSS in terms of closure is Biosphere 2, which is a private project located at Oracle, AZ, just north of Tucson (8). Biosphere 2 is a sealed, air-conditioned greenhouse occupying > 3 acres, with a "lung" (expandable-contractible air-tight bellows) mechanism to minimize pressure differential between inside and outside, and therefore minimize leakage. There are multiple biomes within Biosphere 2, including a rainforest, a savannah overlooking an ocean, a salt marsh, and a desert. One biome is an intensive agriculture area where the human inhabitants cultivate food crops. A few animals and fish are raised for milk, eggs, and occasional meat to supplement the mainly vegetarian diet. Human wastes are cycled through tanks where they fertilize water hyacinths and other aquatic species. The aquatic plant biomass is then composted to return carbon dioxide to the atmosphere. The habitat has a kitchen well-stocked with creative vegetarian cook books and several crew members wrote their own recipes during the first 2-y mission. The crew members rotated cooking duties and came together at mealtime. Crew quarters are designed and decorated to promote psychological well-being during the long period of enclosure within Biosphere 2. The first crew lost considerable body weight from closure in September, 1991, to exit in September, 1993. The fat content of their diet at one point was < 9% and they frequently fantasized about snacks. However, the physician in the group felt they were healthier than when they entered the enclosure even though they became visibly thinner. Many interesting nutritional, physical well-being, and psychological health issues involving closure, group dynamics, and diets should come out of the initial and subsequent Biosphere 2 missions. Future lunar and Martian habitats likely will not be as expansive or Earth-like as Biosphere 2 and human issues that emerge from the Biosphere 2 experience may be greatly amplified under real space conditions.

A space-deployed CELSS will use a combination of physicochemical and bioregenerative approaches for controlling essential parameters within space habitats. "Brute force" may have to be employed by computer control systems if components of certain CELSS subsystems go out of bounds or behave chaotically. Environmental controls within a CELSS will be "active," whereas the Biosphere 2 approach tends to wait for "passive" equilibration of factors within a small, closed ecosystem, which may not happen.

TABLE 4
Proximate analysis of seeds of new NASA Specialized Center of Research and Training (NSCORT) candidate species for a controlled ecological life-support system (CELSS)

Species	Composition		
	Protein	Fat	Carbohydrate
	% of dry wt		
Brassica	24	46	24
Cowpea	26	2	69
Rice	8	0.5	91

References

1. Janik D, Crump W, Macler B. Problems in water recycling for space station and long duration life support. Niles, MI: American Society of Automotive Engineers, 1989. (SAE Technical Paper Series publication 891539.)

2. Janik D, DeMarco J. Engineering testbed for biological water/air reclamation and recycling. Niles, MI: American Society of Automotive Engineers, 1990. (SAE Technical Paper Series publication 901231.)
3. Hoff J, Howe J, Mitchell C. Nutritional and cultural aspects of plant species selection for a regenerative life-support system. NASA Contract Rep 1982; 166324.
4. National Research Council. Recommended dietary allowances. 10th ed. Washington, DC: National Academy Press, 1989.
5. Watt B, Merrill A. Composition of foods. Washington, DC: US Department of Agriculture, 1963. (USDA handbook no. 8.)
6. Williams P, Hill C. Rapid-cycling populations of *Brassica*. Science 1986;232:1385–9.
7. Bubenheim D, Mitchell C, Nielsen S. Utility of cowpea foliage in a crop production system for space. In: Janick J, Simon J, eds. Advances in new crops. Portland, OR: Timber Press, 1990:535–8.
8. Nelson M. Using a closed ecological system to study Earth biosphere. Bioscience 1993;43:225–36.