Review Article

Biosphere 2’s Lessons about Living on Earth and in Space

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Biosphere 2, the largest and most biodiverse closed ecological system facility yet created, has contributed vital lessons for living with our planetary biosphere and for long-term habitation in space. From the space life support perspective, Biosphere 2 contrasted with previous BLSS work by including areas based on Earth wilderness biomes in addition to its provision for human life support and by using a soil-based intensive agricultural system producing a complete human diet. No previous BLSS system had included domestic farm animals. All human and domestic animal wastes were also recycled and returned to the crop soils. Biosphere 2 was important as a first step towards learning how to miniaturize natural ecosystems and develop technological support systems compatible with life. Biosphere 2’s mostly successful operation for three years (1991-1994) changed thinking among space life support scientists and the public at large about the need for minibiospheres for long-term habitation in space. As an Earth systems laboratory, Biosphere 2 was one of the first attempts to make ecology an experimental science at a scale relevant to planetary issues such as climate change, regenerative agriculture, nutrient and water recycling, loss of biodiversity, and understanding of the roles wilderness biomes play in the Earth’s biosphere. Biosphere 2 aroused controversy because of narrow definitions and expectations of how science is to be conducted. The cooperation between engineers and ecologists and the requirement to design a technosphere that supported the life inside without harming it have enormous relevance to what is required in our global home. Applications of bioregenerative life support systems for near-term space applications such as initial Moon and/or Mars bases, will be severely limited by high costs of transport to space and so will rely on lighter weight, hydroponic systems of growing plants which will focus first on water and air regeneration and gradually increase its production of food required by astronauts or inhabitants. The conversion of these systems to more robust and sustainable systems will require advanced technologies, e.g., to capture sunlight for plant growth or process usable materials from the lunar or Martian atmosphere and regolith, leading to greater utilization of in situ space resources and less on transport from Earth. There are many approaches to the accomplishment of space life support. Significant progress has been made especially by two research efforts in China and the MELiSSA project of the European Space Agency. These approaches use cybernetic controls and the integration of intensive modules to accomplish food production, waste treatment and recycling, atmospheric regeneration, and in some systems, high-protein production from insects and larvae. Biosphere 2 employed a mix of ecological self-organization and human intervention to protect biodiversity for wilderness biomes with a tighter management of food crops in its agriculture. Biosphere 2’s aims were different than bioregenerative life support systems (BLSS) which have focused exclusively on human life support. Much more needs to be learned from both smaller, efficient ground-based BLSS for nearer-term habitation and from minibiospheric systems for long-term space application to transform humanity and Earth-life into truly multiplanet species.

1. Introduction

The term biosphere was first used by Eduard Suess in 1875, but not until the work of Vladimir I. Vernadsky in the 1920s was our modern understanding of the biosphere formulated. He saw that the biosphere, rather than being just a lucky and passive passenger, has profoundly altered the Earth’s surface through its 4-billion year history. Vernadsky’s The Biosphere (1926) outlined the force of life in including ever more matter as it spread and evolved. He also realized that humans have become a “geological force” through our vast technological systems and foresaw the development of a sphere of intelligence (the noosphere) to move the biosphere and the technosphere into greater harmony [1, 2]. More recently, the term “Anthropocene” has been advanced for our current geologic era to recognize the impact of the human population and their technologies [3, 4].
This modern understanding of the biosphere and the critical need to address human impacts on its functioning come amidst a growing alienation and disconnect of people from the ecological realities of their lives (e.g., "nature deficit disorder").

2. Historical Context of the Biosphere 2 Project

The Biosphere 2 project was started in 1984 and after years of design, ecological and engineering research, construction of the facility began in 1987. The project created the Biosphere Research and Development Center which included quarantine and bioaccession greenhouses: the Biosphere 2 Test Module, a small closed system chamber, tissue culture and analytic laboratories; and other facilities. Two experimental closures were conducted, the first from 1991 to 1993, and the second in 1994. These were the initial experiments of the planned hundred year lifetime of the facility, before a change in ownership/management resulted in Biosphere 2 ceasing to be a fully closed ecological system supporting people.

At the time of the project, the Russians were the leaders in space life support and closed ecological system research, both at the Institute of Biophysics (IBP) at Krasnoyarsk operating the Bio-3 facility and at the Institute of Biomedical Problems (IBMP) in Moscow. Both institutes cooperated extensively, seeing that Biosphere 2 could take the field to the next level, a Vernadskian biospheric one. To create energetically and informationally open but virtually materially closed systems would allow precise monitoring of the system and the potential to track subtle and small changes over time [5, 6].

As a biospheric laboratory, Biosphere 2 included a range of terrestrial and aquatic/marine areas based on major biomes as well as a farm and human habitat with kitchen, crew rooms, recreation space, laboratories and workshops. The project faced enormous engineering and ecological unknowns. Was it possible to create resilient synthetic ecologies including food webs in “biomes” limited to areas of 0.2 hectares or less? Could appropriate environmental conditions be maintained for systems as diverse as tropical rainforest, savannah, coastal/fog desert, mangrove/marsh and coral reef ocean systems, and a food growing area (Figure 1)? The strategy of “species-packing” was employed, i.e., including far more species than might be expected to persist, and included numerous species that could fill each ecological niche, since no one could predict the number of species which might be lost adapting to new conditions. The crew intervened to “defend” biodiversity, functioning as surrogate keystone predators, combatting invasive plants, and cutting seasonally active savannah grasses given the absence of large animal grazers. The coral reef system survived despite the change from the tropics to temperate seasons and light. Limiting acidification from elevated atmospheric carbon dioxide required extensive chemical buffering, and nutrient removal methods were used as well as physical removal of algae. Biosphere 2’s ocean, with the world’s largest human-created coral reef, provided critical experimental data to predict the impacts of global warming and ocean acidification [7, 8].

self-organized ecologically to become more like a chaparral ecology than the original domination of succulents and cacti. The fact that there is so much that is unknown about basic ecological and biospheric processes was a major motivator in creating the Biosphere 2 laboratory [9–11].

Biosphere 2 has been described as the greatest experiment in ecological self-organization [12]. It also exemplified what John Allen, Biosphere 2’s inventor, called “The Human Experiment” [12]. It was no surprise to project designers and biospherian crews that there would be plenty of unexpected challenges and emergent phenomena. This included the widely reported and at first unexplained decline in atmospheric oxygen. In spite of Biosphere 2’s size and complexity, and in spite of critics who contended that causal mechanisms would be impossible to prove, the mystery was solved with creative use of carbon isotope tracking, and an inspired suggestion to check if absorption of CO₂ by unsealed concrete inside Biosphere 2 was a primary sink for the oxygen [13].

The Institute of Ecotechnics, a major scientific consultant to Biosphere 2, helped organize a series of international workshops on closed ecological systems and biospheric research. The first was held at the Royal Society in London in 1987, the second at IBMP in Moscow and at IBP in Krasnoyarsk, Siberia, in 1989, the third at Biosphere 2 in 1992 and the last at the Linnean Society of London in 1996. Leaders in the field from many space agencies including NASA, ESA, Russia, and Japan participated in the workshops. At Krasnoyarsk, the workshop participants gave the name of “biospherics” to the new study of biospheres, large and small, natural and designed [10].

For more of the publications on Biosphere 2, see Marino and Odum (1999) who edited a collection of nearly two dozen papers for the journal, Ecological Engineering (later published by Elsevier), online at https://ecotechnics.edu/publications and in the references in Nelson (2018), “Pushing our Limits: Insights from Biosphere 2”.

3. Roadblocks to Biospheric Research and Changing the Human-Biosphere Relationship

Amongst the obstacles to research relevant to a new paradigm for the human-biosphere relationship are those that arise from narrow definitions of science.
Some of the controversies that Biosphere 2 ignited stemmed from the perception of the project’s core creative team as “outsiders.” This occurred despite the many high-level scientists and institutions which contributed to Biosphere 2’s design and research studies.

Biosphere 2 was originally intended to function as a quiet research facility, while we found out more about how to design and manage minibiospheres. As a privately funded venture, the intention was to recoup capital investment by creating further biospheres for world cities, major universities, and theme parks since they could be used for advancing the science of biospherics and as public and educational resources. The premise of Biosphere 2 was inherently optimistic: that a minibiome could be engineered and operated to include wilderness biomes while satisfying humans needs. That plus the excitement of real-time science underway at Biosphere 2 struck a chord with people everywhere. Biosphere 2’s architects, determined to make the world’s first minibiospheric laboratory also a beautiful symbol, used traditional forms (stepped pyramids, Babylonian barrel vaults) along with modern forms like spaceframe and geodesic domes to create a stunning facility (Figure 2). Suddenly, the previously obscure word “biosphere” was reaching huge numbers of people around the planet. Biosphere 2 was a compact laboratory for studying fundamental processes and properties of our global biosphere, and people could relate to it as a model of how our biosphere works, from rainforest to ocean, farm to people [10].

Biosphere 2 was controversial. Any project that is truly cutting edge and a leap into the future is bound to be so. Rebecca Reider, in the book she published from her Harvard history of science studies of Biosphere 2, discerned four ways that Biosphere 2 differed from customary expectations for science.

“Science’ could be performed only by official scientists, only the right high priests could interpret nature for everyone else...’Science’ was separate from art (and the thinking mind was separate from the emotional heart)...’Science’ required some neat intellectual boundary between humans and nature; it did not necessarily involve humans learning to live with the world around them. Finally, ’science’ must follow a specific method: think up a hypothesis, test it, and get some numbers to prove you were right” [14].

Narrow definitions of science exclude new and larger scale approaches that are vital for understanding our global biosphere, how humans interact with local and planetary ecosystems, and also the badly needed rethinking and redesign of many current elements of our technosphere. The insistence on specific, hypothesis-driven science reflects the current dominance of analytic, small-scale science rather than the systems level science needed for our pressing planetary ecological crises [15]. Science which excludes the heart and art is leading to even greater “scientific apartheid” than Lovelock [16] described. This is a prime reason there is still such a lack of even multidisciplinary scientific research. Most scientists are well aware of the passions that motivate their work. Emotions are critical tools in motivating us to do science that can be relevant to our global issues as well as helping make us whole human beings.

“Has a time of experimentation with large-scale Biospheres come? The tradition of using small-scale microcosms and growth chambers does not capture the essence of whole system responses, a scale that will affect humanity. Biosphere 2 will continue to stimulate the minds of those who have the vision to think beyond the veil of tradition. As much as anything else this technology, or conglomerate of them, may play a vital role in the emergence of new sciences due simply to the fact that this tool enables experimental work at a scale that rarely has been possible” [17].

3.1. A Technosphere in the Service of Life. Biosphere 2 functioned so well because engineers and ecologists worked closely together. This is unusual since ecologists had to learn enough engineering language to communicate their needs. Engineers had to reorganize their customary thinking since in this facility technology’s primary role was to support its life, which excluded any technology, process, or material which produced byproducts toxic or injurious to its diversity of organisms [9, 10].

The Institute of Eco technics was part of the history of much of the core creative team of Biosphere 2. Many, including myself, were cofounders of the Institute in 1973, taking as our aim a scientific discipline which would harmonize the worlds of ecology and technics. We started and helped manage a number of innovative demonstration projects in challenging biomes around the world, in areas of ecological and cultural crisis where conventional approaches had not worked [18]. Our aim was to achieve top line improvement of the ecology (as measured by increase of biomass and biodiversity) along with viable economics (bottom line) so the projects could be self-sustaining. Biosphere 2 was an excellent ecotechnics research laboratory, since innovative approaches would be needed to: insure the health of the biomes, achieve water and air regeneration, prevent pollution, design a productive agriculture without use of toxic chemicals and recycle nutrients and wastewater. Biosphere 2 made advances in soil biofiltration to control buildup of trace gases and used constructed wetlands as a method of returning nutrients to the farm’s soil [19–21].
Redesigning our planetary technosphere along similar lines is clearly needed since it is obvious that our current technical infrastructure and ways of doing “business as usual” have seriously degraded air, water, soil, and the health of both humans and the biosphere itself.

3.2. Viscerally Connected: The Biospherian Experience. We did not anticipate that humans in closed ecological systems would so profoundly experience their total connectedness with the living world. After engineering tests, human experiments were conducted in the Biosphere 2 Test Module, a 480 m$^3$ facility with a footprint of 6.1 m $\times$ 6.1 m, plants from the various biomes included in Biosphere 2, a constructed wetland for treating human waste, and a cropping area [22]. Its first test subject, John P. Allen, noted during his three-day closure experiment in 1988:

“Already a strange partnership has started building between my body and the plants. I find my fingers stroking, feeling the soft rubbery texture of the spider plant, knowing it’s picking up outgassing products...Notice my attention turning more and more to the condition of the plants...I’ve always had the sense of plants being alive, responsive, even a living symbol. But now they’re necessary...and since they’re necessary, I look out for them” [12].

I spent 24 hours in the Test Module, and the amazing experience inspired me to start training as a biospherian crew candidate. The metabolic connection between you and the rest of the living organisms in such a small facility is unmistakable and almost immediately felt. You know that its living things are keeping you alive and healthy, and what is remarkable is that this knowledge is felt viscerally, a bodily mindfulness of your interdependence. What a joyful realization! [10].

Similar experiences were felt by all eight biospherian crew members during the first two-year closure experiment in Biosphere 2 from 1991 to 1993. In such a vastly larger facility, the experience does not manifest as quickly, but living inside there were almost continual reminders of how tightly connected the humans are to this living world, a perception far more bodily centered than simply intellectually thinking and knowing. It was with some wonder that our bodies “got it”; understanding that our health and the health of this miniworld are the same. This leads to a heightened consciousness of everything you do. There are no anonymous or small actions—everything has a consequence, and the reaction time is much faster because you are living in a small world.

Amongst the most exciting elements in any small closed system—from Controlled Environmental Life Support Systems (CELSS) program plant growth chambers to larger ones capable of human life support—is the change in the concentration of life. Their far smaller buffer sizes (atmosphere, soils or hydroponic media, water reservoirs) result in acceleration, sometimes enormous, of cycles and a dramatic increase in atmospheric fluctuations. Atmospheric CO$_2$ could vary by 500–700 ppm per day in Biosphere 2, and atmospheric residence time was measured in hours not years since the whole system was in sunlight during the day while respiration dominated during dark hours [23, 24] (Figures 3 and 4). Water cycles were also accelerated, in some cases, by orders of magnitude (Tables 1 and 2).

My biospherian teammates and I referred to the green plants inside Biosphere 2 as our “third lung.” We became atmospheric managers to limit the rise of CO$_2$ during low-light seasons. Our strategies included pruning plants that could quickly regrow, storing (sequestering) the cut biomass,
turning off compost and worm bed operations, and planting wherever possible to capture more “sunfall.” Sunlight was a limiting factor since the glass spaceframe and structural shading reduced incident sunlight by over 50%. We were grateful and ever aware that our “green allies” and the countless soil and water microbes helped purify water, cleaned our air, and produced fresh and healthy food from our farm [10].

The variety of roles that we had to carry out also deepened our connectedness. These included farming in a regenerative system, which used no toxic chemicals and recycled nutrients and water, maintaining technical equipment, intervening when necessary to defend biodiversity, monitoring and collecting data, and conducting research in association with outside scientists. Most of the crew celebrated our mini-world with poems, paintings, music, documentary films, and in writing. We even convened two “interbiospheric arts festivals” to share with outside artists and musicians.

Though, like almost all people in ICE (isolated, confined environments), there were significant issues with group tensions during the two-year experiment; there was never any subconscious sabotage of other people’s work or research nor of Biosphere 2 itself. This facility was so obviously our life support system that it was unthinkable that anyone would damage it. Realizing that it was our “life boat” led to a high degree of mindfulness about any action we considered undertaking. The beauty of the world we were living in and our physical and emotional bonding with it were sources of great satisfaction and helped hold the crew together despite internal frictions and simultaneously negotiating an external power struggle [10, 25] (Figure 5).

3.3. The Legacy of Biosphere 2 to our Long-Term Future in Space. One of our motivations for creating Biosphere 2 was seeing that our ability to explore space through astronautics—advanced rocketry—was developing at great speed, while our ability to support humans in their essential needs of regenerating water, air, and producing food, lagged far behind.

Tsiolkovsky, the visionary who conceived rockets, had seen long before spaceflight was possible that to live in space humanity would need to create space greenhouses. “Just as the Earth’s atmosphere is cleaned by plants with the help of the Sun, so our artificial atmosphere can be renewed...the plants we take along with us during the journey can work uninterruptedly for us.” This early vision of how elements of our biosphere could function to clean the air, produce oxygen, regenerate water, and grow food was a crucial part of his conviction that humans were destined to leave our planetary cradle, the Earth, to expand in space [26].

Biosphere 2’s creators are deeply appreciative that our expansion into space and our ability to generate water, air, and produce food will be incremental and for a long period severely limited by weight, power, and volume limitations [27]. Biosphere 2 advanced the idea that since we know so little about how to create the more complex, ecologically diverse and resilient environments that are psychologically and emotionally necessary for human life, it was important to begin a ground-based experimentation program. Only through many iterations, many mistakes and learning experiences, will we begin to understand how such minibiospheres function.

| Table 1: Earth’s biosphere carbon ratios of biomass, soil, and atmosphere compared to Biosphere 2. This results in dramatically different carbon cycling and atmospheric residence [10, 49], data from [50–52]. |
|---------------------------------|---------------------------------|
| **Ratio of biomass C : atmospheric C** | Earth | Biosphere 2 |
| 1 : 1 (at 350 ppm CO₂) | 100 : 1 (at 1500 ppm CO₂) |
| **Ratio of soil C : atmospheric C** | 2 : 1 | 5000 : 1 |
| **Estimated carbon cycling time (residence in atmosphere)** | 3 years | 1-4 days |

| Table 2: Water fluxes and residence times in Biosphere 2 compared to the Earth’s biosphere [32, 53–55]. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Reservoir** | **Earth residence time** | **Biosphere 2 estimated residence time** | **Acceleration of cycle compared to Earth** |
| Atmosphere | 9 days | ~4 hours | 50 times |
| Ocean/marsh | 3000–3200 years | ~1200 days (3.2 years) | 1000 times |
| Soil water | 30–60 days | ~60 days | Similar |

**Figure 5:** A feast day inside Biosphere 2 as the biospherian crew gather to celebrate and eat food grown in the intensive agricultural biome. Since the farm was inside a tightly sealed and recycling system, no toxic chemicals could be used, irrigation and wastewater were recycled, year-round harvests made it one of the world’s most productive half acres (0.2 ha) [10, 56]. The low-calorie, high nutrition biospherian diet was also intensively studied for its health impacts [57].
My role at Biosphere 2 was Director of Earth and Space Applications, so I attended space conferences and interacted with researchers from space agencies around the world as well as the broader scientific community. Many at first were skeptical of Biosphere 2, though following the first closure experiment and seeing that dramatic ecological surprises occurred and appreciating that the slow decline of oxygen was only observable because the facility had achieved the remarkable air tightness of less than 10% per year leak rate, changed many minds (Figure 6) [5]. Space bioregenerative life support researchers were enthused that Biosphere 2 had given such high visibility to the issues of long-term habitation in space and once they realized that we knew full well that space conditions would preclude a structure anything like Biosphere 2 [28]. We were trying to launch not the facility but the significant idea that building biospheric systems was necessary for open-ended human expansion into space. I like to put it into a pithy phrase: humans cannot exist without biospheres—and that will be true in space as well as it has been on Earth.

"Pioneering the Space Frontier", the report of the U.S. National Commission on Space (1986), chaired by Thomas Paine, the administrator of NASA during the Apollo moon landings, saw the necessity of the work begun at Biosphere 2. Their report states

"A biosphere is not necessarily stable; it may require intelligent tending to maintain species at desired levels. Earth supports a biosphere; up to now we know of no other examples. To explore and settle the inner Solar System, we must develop biospheres of smaller size, and learn how to build and maintain them... The builders of Biosphere 2 have several goals: to enhance greatly our understanding of Earth’s biosphere; to develop pilot versions of biospheres... and to prepare for the building of biospheres in space and on planetary surfaces, which would become the settlements of the space frontier [29]."

Learning how to design, build, and live in biospheres is critical not only to our future on Earth, but also to our future as a space-faring civilization.

3.4. Bioregenerative Life Support Systems for Space. Weight and volume restrictions due to launch costs from Earth will severely limit the size and scope of near-term bioregenerative life support systems. Until in situ resources for creating soils can be utilized for moon or Mars habitation facilities, hydroponic or aeroponic systems will provide a more feasible approach to growing plants in space. The plants would also provide food while accomplishing water purification and some resupply of oxygen. Estimated daily requirements to support one person in space include 4577 g for drinking water and water in food preparation; washing water at 18,000 g and water in food 128 g, while oxygen is only 805 g and food 855 g dry weight [30]. Water is purified during evapotranspiration. Control of humidity inherently results in condensation of evaporated water which recycles the largest use of the water system. Direct human use for drinking, washing, and toilets requires much smaller quantities. As capabilities and use of in situ resources increase, cropping areas can be increased, and methods of high-yield production such as aquaponics, which lends itself to closed loop recirculation as is required for bioregenerative life support in space, could produce fish as well as vegetables, to supply more of the diet for space crews and base dwellers [31]. The more biomass produced by plant photosynthesis, the more oxygen will be supplied and air purified, though for safety and redundancy, these should be complemented with physical-chemical approaches and storage of vital supplies.

The experience of Biosphere 2 underlines the importance of tight sealing of space habitats since losing the life-sustaining oxygen component of the atmosphere necessary for plant growth and human well-being would be fatal. William F. Dempster, Biosphere 2’s system engineer, developed its sealing and leak-detection technologies, including its expansion/contraction “lungs” to prevent the varying internal air temperature and humidity and fluctuating outside barometric pressure from exploding or implooding the virtually airtight structure [32, 33]. He reviewed the challenges of building air-tight structures for human habitation and crop production on Mars. There, the very large pressure difference between a livable inside atmosphere and Mars’ very low surface pressure means use of variable volume lungs would be irrelevant and even the tiniest of holes results in large losses of vital atmosphere (Table 3). For example, if the Mars base has an air volume of 1000 m³, a single 1 mm diameter hole would require the whole atmosphere to be replenished every 80 days, almost five times the entire atmosphere every year. In addition, occupants and other life forms must be shielded from dangerous radiation since the Moon...
and Mars lack Earth’s ozone layer which protects its surface. One solution is using enough regolith to shield interiors from radiation hazards. Anchoring structures is also a daunting problem on the surface of Mars and may argue for the desirability of underground locations for the base [28].

Our Biosphere 2 experience also taught valuable lessons about the importance of sufficient photosynthetically active radiation (PAR) for plant crop production. Only around half of outside sunshine reached our intensive agriculture system because of the glass spaceframe structure. Numerous studies have demonstrated that crop yield is highly correlated with incident PAR. Supplemental lighting was installed in Biosphere 2 for the second closure experiment in 1994. That plus use of crops and crop cultivars better suited to lower light may have helped that crew reach 100% production of their diet vs 83% for the first 2-year closure [34]. The energy required for artificial lights to entirely grow crops or to supplement sunlight can be very large. There is an inherent trade-off between using high-intensity lighting to enhance crop production and thus reducing the required size of the agriculture versus the power costs of lighting. Figure 7 demonstrates these relationships using experimental data from very high yield wheat cultivars [27].

Numerous other factors need significantly more research before they can be reliably used in actual space settings. For example, experiments a group of Biosphere 2 researchers conducted in the Laboratory Biosphere showed that different crops have quite distinctive and divergent patterns of CO₂ fixation and the reciprocal production of oxygen [35, 36] These metabolic rates, with their attendant impact on the small volume atmospheres of near-term space vehicles and bases, also vary depending on the crop’s stage of growth from germination to senescence and the concentration of CO₂. A balanced diet from space crops will undoubtedly include a variety of crops including root tuber crops, leafy greens, vegetables, legumes, and grains, so balancing their CO₂ needs and fixation rates and averting excessive production of oxygen will be critical issues to resolve.

Other challenges include learning to manage interactions between elemental cycles. Accelerated cycling times are inherent in small closed ecological systems, even at Biosphere 2’s scale, because ecological buffers and reservoirs are also limited. There is a greater concentration of living biomass to atmosphere than on Earth. The danger of buildup of toxic elements in air and water, or of sequestering and thus making

| Hole diameter (mm) | 100 m³ | 1000 m³ | Volume of Mars base (m³) | 10,000 m³ | 100,000 m³ | 1,000,000 m³ |
|-------------------|--------|---------|-------------------------|-----------|-----------|-------------|
| 0.1               | 46.3   | 4.63    | 0.463                   | 0.046     | 0.005     |             |
| 0.2               | 185    | 18.5    | 1.85                    | 0.185     | 0.019     |             |
| 0.5               | 1,158  | 116     | 11.6                    | 1.16      | 0.116     |             |
| 1                 | 4,634  | 463     | 46.3                    | 4.63      | 0.463     |             |
| 2                 | 18,535 | 1,854   | 185                     | 18.5      | 1.85      |             |
| 5                 | 115,846| 11,585  | 1,158                   | 116       | 11.6      |             |
| 10                | 463,385| 46,338  | 4,634                   | 463       | 46.3      |             |

TABLE 3: Replenishment rates (percent of the internal atmosphere per year) to maintain the atmosphere of a human habitation/crop production facility on Mars with varying size holes. Methods of leak rate calculation and table from [28, 33].

![Figure 7: The trade-offs between power required for supplying light energy and required farm size to feed inhabitants of a space base.](image-url)

The challenges of humans living so remotely and in small groups in space cannot be ignored. There is extensive literature on what can and often does occur in exploration teams, Antarctic bases, and even space simulation experiments. Some of these have had to be canceled because of in-fighting, sexual jealousy and aggression, and subconscious sabotage of

unavailable essential elements in soils, sediments, or biomass, is far greater in synthetic ecologies. Learning how to ensure system fluxes remain within acceptable boundaries for health and that nutrient and other cycles are completed are vital for the persistence of bioregenerative life support systems for space habitation [11].

Some of the innovative ecological engineering approaches used in Biosphere 2 may prove useful in the long-term space future. Soil microbes and plants can purify air of buildups of potentially toxic trace gases, and constructed wetlands can treat and recycle wastewater and its organic nutrients while increasing diversity of plants including food-producing crops [19, 20]. Such approaches may lessen the reliance on systems that require sophisticated technology, power supply, consumables such as chemicals and technically trained maintenance.

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the mission and each other’s work. Biosphere 2 certainly was a key case study with its physical separation of eight people for two years. While there was some factionalism, exacerbated by a power struggle on the outside, the crew was determined to last the full duration of the planned closure experiment and to produce as much scientific research as possible. Having enough room for privacy is important as is having natural elements like plants to work with. Accounts of space station astronauts and cosmonauts have underlined the psychological benefits of having other life forms aboard. Gardening and time in natural environments has even become recognized as an important therapy relieving stress. What also helped keep the Biosphere 2 crew together and working seamlessly even in the midst of personal and group dynamic tensions was the realization that the facility was literally our life support system. Anything that damaged Biosphere 2’s living or technical systems could also endanger the health of the crew, so subconscious sabotage was unthinkable and never occurred [10, 25]. These realizations will be even more profound for human exploration crews or inhabitants off-planet where there is no airlock through which they can safely leave. Space dwellers will undoubtedly fall in love with their crops and world; thinking and acting to keep them healthy will be a priority which overrides personal and group divisions and pulls them together as a team.

3.5. Differing Approaches to Designing Space Life Support Systems. Research on bioregenerative life support systems (BLSS) designed for space has focused on ways to simplify the natural complexity of ecology to maximize efficient production of the essentials of life support, minimizing volume and weight required and to enable tight cybernetic and human control. In both the Soviet space program and in NASA, the earliest systems used only algae tanks which regenerated air and water but did not fulfill food needs. So, crop plants were introduced, and research investigated ways of maximizing harvest yields using crop breeding, lightweight hydroponics, and high levels of light. The Bios-3 facility in Siberia was the most advanced BLSS through the 1970s, producing much of the crew diet, recycling liquid human wastes, regulating CO₂ levels, and removing volatile organic compounds (VOC) by heating inedible crop wastes in a thermocatalytic converter [37].

After Biosphere 2, Japan built the CEEF (Closed Ecological Experimental Facility). Their design approach has been to research and develop several separate compartments which are then integrated with the capacity to monitor and regulate flows from one module to another. CEEF includes a Closed Plant Experiment Facility, the Closed Animal and Human Habitation Experiment Facility, and the Closed Geohydrosphere Experiment to study wetland and terrestrial ecosystems. Short week-long experiments have been conducted including two people, domestic goats, and food crops [38].

Currently, the most advanced work is being done in China and by the European Space Agency (ESA). In the former, there is a group led by Prof. Shuangsheng Guo, at the China Astronaut Research and Training Center in Beijing, and another group largely based at Beihang University, led by Prof. Hong Lui, developing the Lunar Palace (Permanent Astrobasis Life-support Artificial Closed Ecosystem) facility. ESA’s flagship BLSS program is the MELiSSA (Micro-Ecological Life Support System Alternative) project.

It is instructive to compare the purposes and design criteria of Biosphere 2 with these efforts focused strictly on near-term life support systems suitable for space exploration. Because of that goal, these BLSS systems aim at perfecting the smallest and simplest life support systems, choosing processes which minimize mass, volume, energy needs, and crew time while maximizing efficiency, reliability, and degree of closure in regenerating air, water, and producing food. Unlike these other BLSS research efforts and facilities, CEEF includes terrestrial and marine ecosystems because of their desire to track radioactive elements through the environment and study issues relevant to global climate change. All the other facilities include only what is needed for supporting humans. MELiSSA’s design was inspired by the recycling of a freshwater terrestrial ecosystem, so their subcompartments include waste degradation by thermophilic anaerobic bacteria, then processing by photoheterotrophic bacteria, nitrification using nitrifying bacteria, air revitalization (photosynthesis with microalgae), food production using higher food crops, and the crew compartment [39].

Tests at the Lunar Palace facility have included successful 105 and 370 day experiments, with crews of two and three. The integrated BLSS includes a higher plant cultivation area using stacked beds to reduce area needed, nitrogen recovery from urine and bioconversion of plant and human wastes into soil-like substrate, animal protein production through use of yellow mealworms (Tenebrio molitor L.), and control of problematic trace gases through use of an electrostatic precipitator, activated charcoal, and a catalytic reactor. Control of oxygen between 19.5 and 21.5% and CO₂ between 500 and 5000 ppm is accomplished by cybernetic manipulations of heating units in the waste bioreactors, lighting regime for the plants and crew activities [40–42].

Prof. Guo’s group is researching better methods of plant crop intracanopy lighting and other components needed in a BLSS in ground-based and spaceflight conditions. They have conducted a thirty-day experiment with two people and a 180 day experiment with four crew members. In the latter, 4 compartments grew crops, 2 were for crew habitation, and 2 were for life support and a resource cabinet. Their CELSS Integrating Experimental Facility (CIEF) used activated carbon for air purification and plant growth systems that included both hydroponics and a solid medium [43]. All these BLSS facilities use recently developed LED lights for crop growth as a more energy-efficient approach.

There has been some misunderstanding of Biosphere 2 by those who compare it to these approaches to creating successful bioregenerative life support systems. The goals of Biosphere 2 were quite different from trying to simplify and construct the most compact, energy-efficient, and reliable system for air/water regeneration and food production focused exclusively on human life support. One major aim of Biosphere 2 was to pioneer a new kind of biospheric experimental facility of relevance to understanding basic processes of the Earth’s biosphere. So, just as CEEF did, it was
necessary to complement food production/waste recycling/human habitat with areas analogous to major Earth biomes. This dictated the inclusion of tropical rainforest, savannah, desert, mangrove marsh, and coral reef oceanic areas since biomes are the building blocks of a biosphere [44, 45].

Similarly, since we wanted the intensive agricultural biome of Biosphere 2 to be relevant to global farming, the system was soil-based rather than hydroponic or aeroponic, and open to sunlight. That way, the soils could help with trace gas removal and could also be a model for how to achieve relatively high productivity per area while maintaining soil health and fertility. Because sunlight was reduced passing through the spaceframe and by structural shading, food production was limited by relatively low levels of photosynthetically active radiation, unlike most BLSS systems which operate with high levels of lighting to reduce the area needed for food crops, and by vertical arrangement of plant production growing beds.

Despite a great number of unknowns, Biosphere 2 was able to successfully replicate quite varied biomic areas and maintain enough diversity so that they have proved useful for experimentation relevant to issues of global climate change and threats to biodiversity. Contrary to many predictions, Biosphere 2’s wilderness areas were not overrun by invasive “weed” species but maintained quite different ecologies under one roof. Although there were some significant problems and surprises during the three-year period when it was operated as a closed ecological facility, this biospheric laboratory prototype has taught important lessons to help improve the design of future ground-based minibiospheres. Its approach which utilized species-packing and ecological self-organization with the technologies required to maintain each biome’s requirements for temperature/humidity range, rainfall regime, etc. and to use human intervention sparingly as needed to prevent large biodiversity losses, largely achieved its goals. This was somewhat surprising since the first two-year closure experiment was the “shake-down” mission. Instructive for future biospheric facilities was learning how important starting with soils mature enough to have better balances of C:N, so that soil respiration does not exceed photosynthesis in its early operation. This became a major cause of the decline in atmospheric oxygen. Later studies showed that Biosphere 2’s farm soils stabilized within less than five years after the initial two-year experiment [46].

Biosphere 2’s relevance to space life support is not competitive with nor in contradiction with the necessities driving BLSS researchers. Its importance lies in having changed how we visualize ultimately living full and rich lives in space, when compact hydroponic cropping areas and waste and insect production areas can be expanded to include some of the beauty and diversity that humans have always had on planet Earth - and may also require in space.

As space bioregenerative life support becomes more robust, we can envision a gradual expansion to more ecologically diverse assemblages. For example, fruit trees would provide greater diversity to the diet, small woodland areas, ponds and water features etc. would enhance the psychological pleasures and ecological resiliency of space life. Eventually, minibiospheres can be envisioned in humanity’s long-term space future. Therefore, it is vitally important to initiate small and large-scale experiments on Earth and to learn more about how such synthetic ecologies function. In the process, we will learn how to better design them to prevent surprises and collapses. Such experimentation will also deepen our understanding of basic processes that underlay Earth’s biosphere and give birth to the newly emerging field of comparative biospherics.

4. Conclusions

Since 2006, Biosphere 2 has been owned and managed by the University of Arizona. Though no longer a closed ecological system, it is a facility where ecological systems analogous to Earth’s biomes are experimentally manipulated and researched. It continues its life as an important scientific laboratory and is also used for student and public education and inspiration.

Biosphere 2’s early life as the world’s first minibiosphere stands as a landmark event in the fields of biospherics and closed ecological systems. The detailed record of how diverse ecological systems were designed, created, and then adapted to unique environmental conditions is remarkable [47, 48]. The extensive network of environmental sensors and analytic laboratory analyses coupled with data on every critical element of the minisystem provides a detailed account of ecosystem metabolism and development during the self-organization process.

The human experience of being so viscerally connected, dependent on, and responsible for helping to maintain a small world’s health is increasingly relevant to our need for a global response to the critical ecological challenges we face on Earth. Biosphere 2 was also a watershed project which has dramatically expanded our visualizations of what living off the planet will entail. In both cases, the key to success will be learning to be responsible biospherians, helping manage our planetary and off-planet biospheres.

Conflicts of Interest

The author declares there are no conflicts of interest.

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