THE LEGACY OF BIOSPHERE 2 FOR THE STUDY OF BIOSPHERICS AND CLOSED ECOLOGICAL SYSTEMS

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ABSTRACT

The unprecedented challenges of creating Biosphere 2, the world's first laboratory for biospherics, the study of global ecology and long-term closed ecological system dynamics, led to breakthrough developments in many fields, and a deeper understanding of the opportunities and difficulties of material closure. This paper will review accomplishments and challenges, citing some of the key research findings and publications that have resulted from the experiments in Biosphere 2. Engineering accomplishments included development of a technique for variable volume to deal with pressure differences between the facility and outside environment, developing methods of atmospheric leak detection and sealing, while achieving new standards of closure, with an annual atmospheric leakrate of less than 10%, or less than 300 ppm per day. This degree of closure permitted detailed tracking of carbon dioxide, oxygen, and trace gases such as nitrous oxide and ethylene over the seasonal variability of two years. Full closure also necessitated developing new approaches and technologies for complete air, water, and wastewater recycle and reuse within the facility. The development of a soil-based highly productive agricultural system was a first in closed ecological systems, and much was learned about managing a wide variety of crops using non-chemical means of pest and disease control. Closed ecological systems have different temporal biogeochemical cycling and ranges of atmospheric components because of their smaller reservoirs of air, water and soil, and higher concentration of biomass, and Biosphere 2 provided detailed examination and modeling of these accelerated cycles over a period of closure which measured in years. Medical research inside Biosphere 2 included the effects on humans of lowered oxygen: the discovery that human productivity can be maintained with good health with lowered atmospheric oxygen levels could lead to major economies on the design of space stations and planetary/lunar settlements. The improved health resulting from the calorie-restricted but nutrient dense Biosphere 2 diet was the first such scientifically controlled experiment with humans. The success of Biosphere 2 in creating a diversity of terrestrial and marine environments, from rainforest to coral reef, allowed detailed studies with comprehensive measurements such that the dynamics of these complex biomic systems are now better understood. The coral reef ecosystem, the largest artificial reef ever built, catalyzed methods of study now being applied to planetary coral reef systems. Restoration ecology advanced through the creation and study of the dynamics of adaptation and self-organization of the biomes in Biosphere 2. The international interest that Biosphere 2 generated has given new impetus to the public recognition of the sciences of biospheres (biospherics), biomes and closed ecological life systems. The facility, although no longer a materially-closed ecological system, is being used as an educational facility by Columbia University as an introduction to the study of the biosphere and complex system ecology and for carbon dioxide impacts utilizing the complex ecosystems created in Biosphere 2.The many lessons learned from Biosphere 2 are being used by its key team of creators in their design and operation of a laboratory-sized closed ecological system, the Laboratory Biosphere, in operation as of March 2002, and for the design of a Mars on Earth™ prototype life support system for manned missions to Mars and Mars surface habitats. Biosphere 2 is an important foundation for future advances in biospherics and closed ecological system research. © 2003 Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

The challenges of creating Biosphere 2, with its 1.2 hectare (3.14 acre) footprint and 180,000 m^3 (6 million ft^3) atmosphere, included engineering challenges such as the mechanical generation of winds (for pollination), waves (for the coral reef), and sealing of the system to a world record atmospheric leak rate of 10% a year. Outgassing of harmful materials had to be eliminated, and the atmosphere recycled without a toxic buildup of trace gases, including gases of special concern such as CO_2, N_2O, NO_x, hydrogen sulfide, ethylene, CO, methane, and ozone.

Biosphere 2 also required the creation of a sustainable high yield agriculture soil-based system, complete recycling of animal, crop and human wastes, complete recycle of water, and nearly complete recycle of the atmosphere. A decrease of less than 300 ppm a day of oxygen occurred due to take-up by some interior concrete walls of CO_2 whose source carbon came from the agriculture soil and a 3-4 ppm/month increase of N2O occurred since there was no stratospheric radiation to decompose it. From the Biosphere 2 experience it is now known to plan for these factors. The agricultural system supplied all vitamins (except vitamin D because of lack of UV through the glass spaceframe structure of Biosphere 2), enzymes and amines needed as well as normative amounts of proteins, carbohydrates, and fats. A regime and ambience for the biospherians to maintain top health was designed.

The great wealth of scientific research conducted in Biosphere 2 can only be selectively and briefly surveyed in a paper of this length, so we include some of the most important references at the end of the paper, and include quotations from some of the more striking observations made on Biosphere 2 to give a flavor of the excitement, controversy and new thinking that Biosphere 2 researchers experienced.

SELF-ORGANIZATION AND LONG-TERM SYSTEMS SCALE EXPERIMENTS

Biosphere 2 operated in an essentially materially-closed ecological system mode from September 1991 to September 1994 when the new managers of the facility terminated the second crew's experiment. While three years was merely the commencement of the planned century of experimentation, it was enough time for dramatic changes (such as the dominance in the desert of vegetation better adapted to the higher moisture levels that prevailed) and self-organization processes to occur in all the biomic areas. We must remember in this context, that Biosphere 2 had dramatically accelerated cycling times – e.g. a residence time for CO_2 that at 3-4 days is hundreds of times faster than that in the global biosphere (Nelson et al, 1993). So three years of self-organization inside Biosphere 2 were perhaps far more significant than three years of outside research.

"Examination of the ecosystem within Biosphere 2, after 26 months of self-organization...[showed] features of self-organization....the self-organizing system appeared to be reinforcing the species that collect more energy (maximum power principle)...species diversity of plants was approaching normal biodiversity...the observed successional trend (carbon dioxide absorption by carbonates and high net production of "weed species vegetation") if allowed to continue, was in a direction that would eventually generate enough gross production to match respiration of the soil, which was gradually declining. Thus the self-organizational development of a human life support was successfully underway...the smaller, faster Biosphere 2 is a good model for studying the biogeochemical dynamics of our earth. It would be a shame if interests in the smaller scale divert this opportunity to understand what a large-scale system does adapting to a continuing regime" (H.T. Odum, 1996)

"The mission of this venture is not generally understood by the scientific community. The mission of this experiment is not traditional, reductionist, discipline-oriented science, but a new, more holistic level of ecosystem science that has been called "biospherics." Biosphere 2 is as much a human experiment as a scientific one. When you consider that nothing on the scale of Biosphere 2 has been attempted before (NASA'S designs for regenerative life support are entirely different, and much smaller) and how little we really know about how our Biosphere 1 (Earth) works, a measure of success will have been achieved if the biospherians come out alive and healthy this fall after the 2-year isolation. Certainly the experiment will have improved our understanding of human-biosphere interrelations and helped answer the question of how much natural environment must be preserved for life support, and it will have provided a basis for improving the design next time around" (E.P. Odum, 1993)

The examination of the metabolism and atmospheric cycles within Biosphere 2 provided a wealth of insights into global patterns, confirming the original goal of Biosphere 2 as a new way of understanding our previously unique experience of a biosphere (Biosphere 1, the Earth's planetary-scale biosphere)."The metabolism in Biosphere 2 turned out to be a good analog for that of the whole planet Earth...The study of Biosphere 2 provides the important insight that long range oxygen levels on Earth are partly controlled by the cycles of calcium and carbonate, and that only by considering the interaction of these biogeochemical cycles can we gain a realistic understanding of planet homeostasis and feedback mechanisms. Biosphere 2 because of its analogous properties to

the Earth, provides the opportunity to investigate the potential implications for the global carbon and oxygen budgets that may result from climate forcing and a changing atmosphere...The holistic perspective provided by Biosphere 2, so necessary to understand system level responses within the enclosure, will help shape the emerging interdisciplinary approach to understanding Earth" (Engel and Odum, 1999).

TOWARDS A NEW EXPERIMENTAL SCIENCE OF ECOLOGY AND BIOSPHERICS

Biosphere 2 marked the creation of the world's first "biospheric laboratory" where a number of ecosystems patterned after natural biomes (e.g. rainforest, desert, savannah, fresh-water and salt-water marsh and coral reef oceanic system) were included in the closed system as well as an agricultural and human habitat (living) system (Allen, 1991; Nelson, et al, 1993). "Biosphere 2 provides, for the first time, the possibility of conducting controlled, large-scale ecosystem ecology experiments. Modern Physics emerged when Galileo conducted experiments that yielded numerical data. Biosphere 2 provides a setting for the same type of transformation in ecology as occurred in physics." (Morowitz, 1994). A critique of much ecological research is that it is on too small a timeframe (frequently 1 year or less) and too small an area (often under 10 m^2). In contrast, Biosphere 2 was originally intended and designed as a 100-year long-term experiment.

"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" (Marino and Odum, 1999).

GOING BEYOND THE HOLISM/REDUCTIONISM DIVIDE

From the start Biosphere 2 was exciting and controversial. It was unusual for such a large-scale project to be privately financed; and when it caught the world's imagination, and received widespread media attention, it became subject to the kinds of jealousy with which some academics regard celebrity even if unsought. With the exception of the project's world-class scientific consultants and advisors (e.g. Sir Ghillean Prance, H.T. Odum, Richard Harwood, Keith Runcorn, Clair Folsome etc.), many of the managers who worked with John Allen, the inventor of Biosphere 2, were not all traditionally trained academic scientists though they had a great deal of complex ecological project experience. But perhaps that's why something new and challenging was attempted. H.T. Odum commented, "The original management of Biosphere 2 was regarded by many scientists as untrained for lack of formal degrees, even though they had engaged in a preparatory study program for a decade, interacting with the international community of scientists including the Russians involved with closed systems. The history of science has many examples where people of atypical background open science in new directions, in this case implementing mesocosm organization and ecological engineering with fresh hypotheses"(Odum, 1996).

In addition, because of Biosphere 2's total systems approach, it was perhaps inevitable that it would fall into the running antagonism that unfortunately divides those primarily oriented to holistic, or "top-down" approaches, as opposed to the more analytical, reductionist, "bottom-up" approach. The irony was that of course Biosphere 2 enlisted the help of both science and engineering, for such a challenging project required great precision and knowledge at the smaller as well as larger scale.

"When journalists asked establishment scientists, most of whom were small scale (chemists, biologists, population ecologists), they got back the small scale dogma that system-scale experiments are not science...Some people with this level of interest recommended Biosphere 2 be used as they have used growth chambers for 60 years to study small things with many replications, relate trees to carbon dioxide, study species dynamics etc. How do you explain to people whose lives have been dedicated to organismic or population scale that what is more important on an ecological mesocosm scale is the whole self-organizing process. The real world of Biosphere 1 and Biosphere 2 has several scales of size all interacting together: light fields, biodiversity, water regime, biogeochemical cycles, nested oscillations, genetic and ecological information processing selecting special abilities of different species to adapt and be reinforced...A very destructive practice in science occurs when a scientist knowledgeable about science of scale A selects (in ignorance) a specialist dedicated to science of scale B as competent to judge work in a third scale C. The microbiologist writing a column on Biosphere 2 in Science honestly believed that the only first class basic science for Biosphere 2 would be studying small-scale micro scale mechanisms. A priori, all scales of science may be of equal importance, but there have been large research funds

for the small scale and very little for experiments at a large enough scale to be relevant to the global atmosphere...There is no sure way to test theories and models of mesoscale self-organization except by seeding and running mesoscale systems. Science at one scale cannot validate that at the next scale" (Odum, 1996).

John Allen, the original Research Director during the closure years of Biosphere 2, put it thus: "Four basic ways uneasily co-exist in science to deal with understanding complex systems: One, prolonged naturalist observation, description of observed regularities and classification of parts, making a naive realist description of the field of study. A second, by analyzing component parts of the object of study, formulating restricted hypotheses, and then, holding all else other than the chosen part as constant as possible, measure changes produced by measured impacts. The third way is to accept complexity as an irreducible element, and then to search for the organized structure that enables us to examine the entity as a whole, to ascertain its specific laws or regularities. The fourth way is to put into an operating model a synthesis of these three approaches, together with test principles of engineering, to test the validity of the existent thinking's predictive powers, and to provide a fecund base for new observations. This full interplay of observation, analysis and structuring to make a working apparatus in order to test and extend our knowledge of biospherics is the approach we used to create Biosphere 2. This interplay of all four scientific approaches is required to study Earth's biosphere, the most complex entity yet encountered (Allen, 1996).

Yet despite the fact that the current managers of Biosphere 2, Columbia University, acknowledge that the facility was created with superb and innovative ecological engineering and offers unique opportunities for scientific research[1], they continue to disparage the original creators and research conducted at Biosphere 2. Worse yet, the current managers of Biosphere 2 have refused to give some of the original researchers access to data stored in the computer archives at the project, and are following a path which will lead to the loss of the invaluable record of how Biosphere 2's ecosystems developed, and key environmental data on water, air and soil/agricultural systems. This data should be made available to both the original researchers and to the worldwide scientific community.

Our hope is that large-scale biospheric laboratories like Biosphere 2 and its eventual successor systems may be an area in which both systems levels thinkers and scientists focused at other levels of interest can come to understand that they are not competing, but represent different approaches in the quest for understanding, the mission of science.

DESIGNING ENVIRONMENTAL TECHNOLOGIES FOR A HEALTHY WORLD

Technically, the large scale and complex apparatus had to be tended, maintained, and improved with using no more than ten per cent of the Biospherian labor time. The scale of the technical systems can perhaps be appreciated by the following partial inventory: "120 operating pumps, 50 air handlers, several miles of electrical wires and pipes, water storage tanks, computer controllers, video systems, communications systems, filters, an algae-based nutrient removal system for the ocean and marsh, rainfall irrigation, heating and cooling exchangers, desalination systems, lights, a chemical recycler for atmospheric carbon dioxide, diving equipment, composting equipment" (van Thillo et al, 1999). A five level system of data collection and analysis of changes in water, atmosphere, light, temperature, soils, biomass, biodiversity, health of humans, animals, and plants, and diets had to be functioning, assessed, and responded to on a continuous basis. Observation and measurements of changes in the ecology of the seven major biomic systems and their thirty separate bioregions had to be performed, interpreted, and acted on where necessary. The technosphere also required continuous monitoring of the sealing and of the complex systems for the hydrosphere and atmosphere circulation as well as providing all repairs and upgrades from within. To accomplish this, the technosphere contained its own machine shop.

The technical challenges and sophistication of Biosphere 2 were hailed in the journal Science as a "marvel of engineering" and rated as one of the 10 Ultimate Engineering Achievements by the Learning Channel of Discovery Television in 2002. The accomplishment of a leakrate of 10% annually is more than two orders of magnitude better

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[1]:For example, "the Biosphere 2 facility is an exceptional laboratory for addressing critical questions relative to the future of Earth and its environment." Dr. Michael Crow, Vice-Provost of Columbia University Space Biospheres Ventures Press Release December 20, 1994;...[Biosphere 2 offers] unique opportunities for research in the areas of ecology and biodiversity, plant physiology and biogeochemistry. It appears to me that Biosphere 2, a unique, living "Earth" laboratory, has a bright scientific future." Dr. Bruno D.V. Marino, Harvard Professor and Columbia's Director of Science and Research at Biosphere 2, Space Biospheres Ventures Press Release, December 20, 1994..."This facility is light years ahead of any other....It's a gem."Bruno Marino Boston Globe, August 16, 1994. "One of the things Biosphere 2 has displayed to us over the years is its ability to control its own carbon cycle." Dr. Wallace S. Broecker Newberry Professor of Geology at Lamont-Doherty Earth Observatory, Columbia University Biosphere 2 Newsletter Vol 2 No 1, 1995 "The intellectual lure of the Biosphere is tremendous." Dr. Wallace S. Broecker Newberry Professor of Geology at Lamont-Doherty Earth Observatory, Columbia University Arizona Daily Star, November 13, 1995).

than some other closed system performance, e.g. the Kennedy Space Center Biomass Production Facility (a 3.5m diameter x 7.5m high chamber) and "some 1000 times the commercial building industry standard. The capability to sustain closure was demonstrated over a period of about 3 years with human inhabitants reflecting one of the most unique and sophisticated structural features of the facility distinguishing it from large greenhouses and phytotrons" (Zabel et al, 1999). To achieve this result required many innovations, including the first use of variable volume structures ("lungs") in a closed ecological system to deal with pressure differences between Biosphere 2 and the outside environment (Dempster, 1994, 1997, 1999). Columbia University which now manages the Biosphere 2 facility was not able to replicate these high engineering standards when it modified the facility for the purposes of its new research program: "Recent modifications, such as the separation between the wilderness biomes and the agricultural biome, have resulted in leak rates on the order of 1-2% per day, some 50 times higher than the leak rates attained during the periods of closure of the entire facility [1991-1994]" (Zabel et al, 1999). If such a leakrate had been the case during the three years of closure, the loss of oxygen could not have been tracked, nor would far more subtle changes such as the increase in nitrous oxide been observed. The current leakrate effectively destroys the capacity of Biosphere 2 to serve as an apparatus to investigate long term atmospheric gas balances in closed systems should that goal be pursued in the future.

Biosphere 2 technosphere's basic role was to support the life systems, e.g., to supply missing cyclic physical functions such as wind and tidal fluxes, and a cooling and heating system to mimic the Earth's climate system. Furthermore, no technology could be used inside Biosphere 2 if its outgases or byproducts were toxic or couldn't be absorbed and purified by the life systems. What a contrast with the situation prevailing in our global environment, where technology is used without serious attention paid to its integration and sustainability with the living biosphere it impacts. "[Many people] believe that the human society may successfully design nature to fit economic aspirations. What Biosphere 2 showed, in a short time, is the lesson that our global human society is learning more slowly with Biosphere 1, that humans have to fit their behavior into a closed ecosystem"(H.T. Odum, 1996)

RESTORATION ECOLOGY AND THE STUDY OF NEW BIOMIC ECOSYSTEMS

Amongst the most remarkable aspects of Biosphere 2 was the creation of artificial ecosystems, with areas from 1000-2000 m^2, patterned after a range of natural biomes from the tropical zones of the planet – from rainforest to coral reef. These synthetic yet biodiverse and complex ecosystems, provided an unprecedented opportunity to study ecosystem dynamics and test hypotheses, such as the relationship of coral bleaching with temperature, by changing the environmental conditions with Biosphere 2. The initial strategy followed was to maximize diversity by including a number of different landscape or sub-ecosystems within each biome (e.g. in the rainforest there were ginger belt and bamboo groves to buffer harsh sidelight, then lowland forest, varzea or stream ecosystem, and upland and cloud forest zones). Biosphere 2 was also "species-packed", deliberately overplanted with candidate species, to facilitate the process of self-organization and adaptation also to the accelerated cycling and unusual environmental factors inside this closed system. So it was anticipated that there would be significant species loss in the first few years or even decades, as we learned how ecosystems developed in this experimental facility.

Assessments after the initial two-year closure validate the success of the process. "Southwest Florida mangrove forest vegetation was successfully transplanted into a mesocosm within Biosphere 2. Dense stands of mangroves with characteristics comparable to natural Florida mangrove forests developed from the small seedlings and saplings initially installed in the mesocosm...the fact that the mesocosm mangroves lack an understory is one indication that they are good models of natural mangrove forests and that they can be used to learn more about mangrove ecosystem structure and function" (Finn et al, 1999). "Initial [rainforest] dynamics seem to approach those in other tropical rainforests.The different light and CO_2 regimes may alter biogeochemical cycling; hence the Biosphere 2 rainforest is a suitable platform for innovative research" (Leigh et al, 1999)

The 3.5 million liter (900,000 gallon) coral reef was one of the most audacious and difficult systems to create and maintain in Biosphere 2. The coral reef proved remarkably responsive to changes in atmospheric composition, light levels and climatic conditions, requiring skilled and frequent management intervention. A detailed in-situ mapping of the coral reef biome in October 1993 after the two-year closure counted 863 living stony corals, 123 colonies of living soft coral, out of which 87 coral colonies were judged to be new recruits (Alling and Dustan, unpublished data). "Even though there are some peculiar characteristics of the Biosphere 2 coral reef, the coral reef biome functions as a recognizable coral reef community. The Biosphere 2 coral reef system offers an excellent opportunity to test questions of how environmental factors influence processes at community and organismal scales" (Atkinson et al, 1999).

The current managers of the facility, Columbia University, primarily use these unique ecosystems created at Biosphere 2 in their research focused on global warming and CO_2 enhancement of the atmosphere. However, observations by the authors of the Biosphere 2 system since change of research direction indicate that the health of the biomic areas is seriously in decline. Perhaps another lesson from our Biosphere 2 experience relevant to all life systems, from restoration ecology to maintaining the health of Earth's biosphere, is suggested: that humans who are living with and dependent on crops and ecosystems for their life support are vital for their care.

INTENSIVE HIGH-YIELD ECOLOGICAL AGRICULTURAL SYSTEM

The agricultural system of Biosphere 2 aimed at developing high-yield, high diversity food systems which did not use toxic sprays (since they would have quickly poisoned both the closed system and its inhabitants) and which would maintain soil fertility, thus laying the basis for a sustainable future. Despite some problems occasioned by unusually cloudy conditions because of El Nino, unexpected crop pests, and a learning curve for biospherians becoming resourceful "subsistence farmers" – the system overall worked surprising well.

"Analysis performed after 18 months of operation of the Intensive Agriculture Biome showed that the main problems at the time were high salinity in one of the plots and denitrification in the rice paddies...Otherwise, nutrient recycling techniques and soil management strategies had maintained adequate levels of soil fertility during the 2 years of closure and were not limiting to crop production (Silverstone et al, 1999), "The crop diversity achieved in Biosphere 2 demonstrated the health and aesthetic advantages of a soil system versus a strictly hydroponic one in which a small number of crops are grown... the overall rate of crop production for the 0.22 ha [around half acre] area...sustained both crews [Missions 1 and 2]. Overall production rates in Biosphere 2 exceeded those characteristic of fertile agricultural soil in the most efficient agrarian communities...Crop yields were markedly higher for Mission 2 than for Mission 1 due in part to experience and improvements based on the first closure....High productivity and biodiversity were due to many factors including high resolution climate control, hyper-intensive agricultural practices, selection and planting of food crops adapted to humid, tropical and sub-tropical conditions, nutrient recycling, intensive pest management, and the super ambient levels of atmospheric CO_2...The IAB [Intensive Agricultural Biome] of Biosphere 2 has the potential, with system improvement, to be a high-yielding, self-sustaining agricultural mesocosm suited for a variety of research endeavors...Our work shows that a facility like Biosphere 2 offers the possibility to investigate key research issues in crop production through a combination of experiment and modeling techniques. Because of its large experimental area and tight environmental control, experiments performed in this facility can specifically help investigate effects of importance to future climate change and agriculture, under settings that resemble field conditions better than any other existing growth-chamber (Marino, et al, 1999).

Research in sustainable, high-yield, non-toxic agriculture was discontinued in 1995 by Columbia University, who dismantled the agricultural system created at Biosphere 2. They currently use that area for experiments on the response of monocultures of trees to elevated carbon dioxide.

MEDICAL RESEARCH AND HUMAN HEALTH

The medical and physiological research conducted during the closure experiments of Biosphere 2 demonstrate the value of new systems where factors previously inseparable could be studied. Thus, the decline in atmospheric oxygen, which permitted sophisticated biogeochemical research using isotopic fractionation to discover the sources and sinks of oxygen in Biosphere 2 (e.g. Severinghaus, 1994), also allowed investigation of the importance of atmospheric pressure changes or oxygen decline in the triggering of human metabolic response mechanisms during the first 2-year closure these two factors were de-coupled inside Biosphere 2 (Walford et al, 1996; Paglia and Walford, in press). Other innovative research included the first studies of human response to high nutrient/restricted caloric diets (Walford et al, 1992), and the metabolism and energetics of humans in hypoxic and low-calorie conditions (Walford et al, 2002, Weyer et al, 2000; Verdery and Walford, 1999). The overall health of the biospherians crews inside Biosphere 2 confirm that the original design of the Biosphere 2 technosphere systems did avoid a buildup of toxics, and the bioregenerative technologies and life systems inside Biosphere 2 maintained a healthy environment.

EDUCATION AND MODELS FOR A SUSTAINABLE FUTURE

Perhaps the most important legacy that Biosphere 2 bequeaths is the worldwide interest in biospherics that it aroused through the impact it had on millions of people around the world. "The emergence of eight healthy humans

proves that artificial biospheres which are based on a high diversity of species and biomes in a high-tech system can work. These eight individuals had emerged from a world which they had not polluted, with clear, pure water, which had grown plant biomass some 50% greater than when they entered...each developing with quite distinct ecosystem characteristics. In addition, each biospherian reported an intense heightening of awareness of their connection to their world...The successful 2-year closure was an initial, but important step in combining needs of life, imperatives of technology, information processing, diversity, microbial evolution and recycling towards realization of Vernadsky's noosphere" (Allen and Nelson, p. 21)

Many of the original team that created Biosphere 2 continue to work on closed ecological systems, bioregenerative technologies and the science of biospherics. Planetary Coral Reef Foundation has applied the observation that the coral reef biome was the indicator of the health of Biosphere 2 to the study of our planetary coral reefs. Working with MIT and Dr. Phil Dustan of the College of Charleston, a pioneering project is underway to map and monitor living coral reefs from space, thereby enabling a managerial and scientific stewardship approach to our own biosphere (Dustan et al, 2000). As well, the constructed wetland wastewater treatment research inside Biosphere 2 (Nelson et al, 1999) has inspired the development of new, high diversity wetland approach, called Wastewater Gardens™, being applied in a number of developing countries (Nelson, 1998; Nelson et al, 2001).

The creative team that designed, built and operated Biosphere 2 from 1984 to April 1994, and its Test Module from 1986-89, designed and are operating their third closed system, the Laboratory Biosphere (Dempster et al, in press) and are now engaged in designing a Mars On Earth™ biosphere to advance the bioregenerative closed ecological systems needed for maintaining a crew of four in a Mars surface habitat (Allen and Alling, in press). International scientific interest helped generate a new scientific journal devoted to the field of Biospherics and total life systems, the Journal of Life Support and Biosphere Science, helped inspire the new Japanese closed ecological system, and helped create a worldwide interest in large scale ecological and life projects, such as the Eden Project in Cornwall, UK.

The small size and dramatically rapid cycling inside Biosphere 2 made it both a wonderful "cyclotron of the life sciences" but also a striking exemplar of the new thinking required to move towards a sustainable future. "The achievements of the biospherians go beyond the application of state-of-the-art methods of sustainable agriculture. Biosphere 2 recreates in miniature the flows and balances that occur on Earth--but it moves through these cycles on 'fast- forward'. Carbon dioxide turnover on Earth takes about three years: in Biosphere 2 it takes about three days. On Earth it takes years or decades to see how changes in the rainforest affect the growth of sorghum or sweet potatoes in another part of the world; in Biosphere 2, the impact may be seen in a matter of weeks. In Biosphere 2, agricultural materials such as crop nutrients and animal wastes recycle through the water and air systems in days, as opposed to weeks or years on Earth. It is, in this sense, an ecological laboratory of incalculable value - the world's largest test-tube. The greatest lesson of Biosphere 2, that there is no 'away', is equally important to Biosphere 1. This must be realized soon by all of Biosphere 1's 'crew' because unlike Biosphere 2, Earth cannot be replaced" (Richard Harwood, 1993).

CONCLUSION

Biosphere 2 has helped change the paradigm with which we see the future of life here on Earth and in space. It has raised awareness that although we may take small steps in the direction of sustainability of our global biosphere, the goal will be to fully harmonize human activities and technosphere with what is now becoming to be seen as our planetary life support system. In space, though our first bioregenerative life support systems will be constrained by the severe weight and volume constraints of space transport, the eventual goal is to create robust biospheric systems both for ecological health and the psychological well being of its inhabitants. Though the precise form and content of these future space biospheres may be unknown, Biosphere 2 has forged the vision and underscored the reality that we humans are a part of and will always be dependent on biospheric systems. The future depends on our ability to better understand, create and live in biospheres, natural and man-made.

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