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EARTH APPLICATIONS OF CLOSED ECOLOGICAL SYSTEMS: RELEVANCE TO THE DEVELOPMENT OF SUSTAINABILITY IN OUR GLOBAL BIOSPHERE

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ABSTRACT

The parallels between the challenges facing bioregenerative life support in artificial closed ecological systems and those in our global biosphere are striking. At the scale of the current global technosphere and expanding human population, it is increasingly obvious that the biosphere can no longer safely buffer and absorb technogenic and anthropogenic pollutants. The loss of biodiversity, reliance on non-renewable natural resources, and conversion of once wild ecosystems for human use with attendant desertification/soil erosion, has led to a shift of consciousness and the widespread call for sustainability of human activities. For researchers working on bioregenerative life support in closed systems, the small volumes and faster cycling times than in the Earth's biosphere make it starkly clear that systems must be designed to ensure renewal of water and atmosphere, nutrient recycling, production of healthy food, and safe environmental methods of maintaining technical systems. The development of technical systems that can be fully integrated and supportive of living systems is a harbinger of new perspectives as well as technologies in the global environment. In addition, closed system bioregenerative life support offers opportunities for public education and consciousness changing of how to live with our global biosphere. © 2003 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The conversion of natural ecosystems to agricultural areas, the loss of biodiversity and the depletion of resources worldwide have raised questions concerning the increasing loss of life support capability for the biosphere as a whole and total loss of many ecosystems and species. With around half the world's natural resources and primary productivity being affected by, and directed to, humans, our species is starting to appreciate that its survival and quality of life depends on regulating its activities, and insuring that crucial biogeochemical cycles continue to function. The increased awareness of the ecological challenges facing humanity has led to a dramatically changed perspective of how we should regard our global biosphere. These perspectives and the focusing on sustainable ways of living on the Earth have direct parallels with the challenges of developing bioregenerative life support for space applications. The potential applicability of some of the technologies being developed for small, partially or fully materially closed ecosystems can help shift from the destructive mindset of "unlimited resources" to that of conserving, recycling and sustainably operating.

In recent decades, the changed perception of our planet has been reflected in a series of developments, which might be sequenced as follows:

- Starting with the work of R. Buckminster Fuller and others, the Earth was seen as a kin to a space vessel in the metaphor of "Spaceship Earth," with need for the "regenerative landscape" (Fuller, 1963)

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- The assumption of never-ending growth of industry and resource consumption as a definition of progress was challenged, most notably in the 1970s by the Club of Rome who commissioned research, using the new approaches of systems models and computer modeling, published as "The Limits to Growth" (Meadows et al, 1972)
- There has been a surge of concern about the continued viability of how humans live on this planet, with new keywords such as "comprehensive" and "sustainability" which implies recycling of industrial byproducts and end products, and away from exponential increase in the use of resources.
- The discipline of "ecological economics" emerged which in contrast to earlier economics that regarded Earth resources as a free good, and which also did not account for hidden environmental costs, such as the discharge of pollutants or spent materials into the Earth's air, water and soil "buffers". New forms of environmental accounting were developed such as emergy analysis, which measures both the human economy, and the environmental "services" provided by nature, and puts both types of inputs into common units permitting comprehensive evaluation (H.T. Odum, 1996).
- Many thinkers have come to the recognition that in contrast to virtually all other species on the planet, humans are not limited in their population or activities by local ecosystems, but are dependent on the entire biosphere, which contributes to our life support (Eldredge, 1998; Diamond, 1992).
- The growing crisis in air quality, both locally in cities and industrial areas, and worldwide through our buildup of greenhouse gases, have made it clear that even this once most taken for granted and abundant of resources is under stress by the size and increasing industrialization of the world's human populations.
- NASA and other space agencies have reflected these concerns with Earth research programs such as "Global Habitability" to link space-based sensors and monitoring of the Earth to bear on the questions of environmental damage and to inventory natural resources.

In this context, the development of closed ecological systems and bioregenerative life support technologies while originally motivated solely by the need for space life support, may offer valuable lessons, insights and potential applications for sustaining Earth life support.

Moving towards sustainability implies at least elements of the following:

1. Increased reliance on renewable natural resources and energy sources,
2. Minimizing or eliminating draw down of non-renewable resources,
3. Eliminating or reducing quantity and toxicity of "byproducts",
4. Developing "ecosystem networks" which can re-use the byproducts of one process, thus keeping elements in productive circulation,
5. Maintaining or increasing rather than decreasing biodiversity as a result of human activities,
6. Developing understanding of how our global biosphere operates so that we can better harmonize human activities and economy within this life-support system,
7. Providing feedback loops so that people can see more clearly the consequences of their actions on their local ecosystems and the global biospheric system, and
8. Providing exemplars and role-models of proper biospheric responsibility as a source of inspiration and hope

With these goals in mind, it is instructive to look at some of the milestones in the history of closed ecological systems and the lessons/technologies and insights they provide.

MICROCOSMS/MESOCOSMS AS ECOSYSTEM LABORATORIES

The development of miniaturized ecosystems, loosely called microcosms or mesocosms depending on size, was motivated at first as a way of bringing ecosystem dynamics into the classroom. Later it was discovered to be an effective tool for research since many of the attributes of ecosystems when made in miniature, are easier to carefully study.

These systems have included both aquatic and terrestrial ecosystems, and have been closed to varying degrees to material inputs (water, nutrients) while requiring energetic inputs from sunlight or artificial light. Processes of self-organization have been studied in such systems, and other phenomena such as ecological succession, competition for resources and shifts in bioenergetics as systems mature. In general, such ecological micro/mesocosms are built using the large biodiversity found in the original natural system, though single species or limited species systems have been used for particular research needs. This work has established the usefulness of living models drawn from nature to study some of the complex behavior and patterning found in natural ecosystems (E.P. Odum, 1971; Beyers and Odum, 1993).

WORLDS IN BOTTLES

A parallel development was that of the totally materially closed ecosystem contained in laboratory flasks typically ranging from 100 ml to 5 litres in volume. Pioneered by Clair Folsome in 1967 at the University of Hawaii, similar work was then undertaken by Joe Hansen at Jet Propulsion Lab, Cal Tech, Bassett Maguire at the University of Texas and Frieda Taub at the University of Washington. It was discovered that diverse aquatic assemblages of microbes and algae could persist apparently indefinitely (some systems have now been functioning for over three decades since closure) as long as they were provided with adequate light input. This was not true of mono-specific or more limited assemblages of species which lacked the metabolic capability of completing all the biogeochemical cycles needed to sustain life in their miniature world. Thus the crucial role of microorganisms in completing the biogeochemical systems, which are crucial for persistence and sustainability of life support, was clearly shown in these first completely materially closed ecosystems (Folsome, 1985; Folsome and Hanson, 1986).

SIMPLE ALGAL/HUMAN ECOSYSTEMS

The earliest American and Russian research for space life support using bioregenerative technologies focused on systems using monocultures of algae and humans. These systems proved that algae could successfully purify and recycle water and provide oxygen for the human, but could not prevent the buildup of trace gases over time in the sealed chambers (Shepelev, 1972; Cooke, 1971). Some of the byproducts of Chlorella, a favorite algal species of early space life support work, proved toxic to higher plant crops (Terskov et al, 1979).

NASA CELSS RESEARCH AND TESTBEDS

The NASA CELSS (Controlled Environmental Life Support System) research program has led to advances in understanding crop dynamics and maximization of yields through manipulation of environmental parameters such as light, temperature, humidity and through selection of crop cultivars for ability to produce high yield ratios. Similar research in Russia and European space efforts have also looked at ways of raising yields by suppressing phyto-respiration with lowered oxygen levels (Andre et al, 1989); and sought effective ways to maximize use of limited space and volume (e.g. Salisbury et al, 1987; Wheeler et al, 1996).

This research has almost exclusively used hydroponic methods of growing, and so a direct application to the feeding of vast populations, especially in poor, developing countries, may be problematical. But there is clearly important knowledge that has been gained of fundamental dynamics of crop physiology and the importance of environmental parameters, which have potential applications to increase the yield-effectiveness of agriculture (Salisbury et al, in press).

More recent NASA work in integrating testbeds for bioregenerative life support have included work on ways of recycling human and plant wastes (e.g. Wignarajah and Bubenheim, 1997), control/information systems which have potential for application to monitoring similar vectors in the Earth's environment, and in dealing with issues of trace gas buildup relevant to global pollution problems (e.g. Tibbits, 1996, Batten et al, 1996).

THE BIOS 3 RESEARCH IN SIBERIA

The line of research which produced the Bios 3 experimental facilities for bioregenerative life support included many milestones such as being the first to include higher plant crops, supporting human occupancy for 4-6 months and achieving near total regeneration of air and water, along with significant portions of the diet required by their crews of 2-3 people (Terskov et al, 1979)

Perhaps equally important is the fact that the Russian work included much technology into the system, such as food harvesting and processing equipment, which required both careful selection and screening, and ultimately the integration of such elements as out gassing from materials, and how to deal with other byproducts of technology in a small volume. Humans were not merely a component part of the food chain, as in earlier experiments, but active decision-makers managing their life support system.

The Russian work underscored the possibility of creating complex technological life support ecosystems, with strong material closure, and successfully integrating people. Their lack of soil and microbial components required them to oxidize trace elements to prevent buildup of trace gases, and they frequently cited the problem of completing biogeochemical elemental cycles to prevent "deadlock" elements as a challenge for future work.

BIOSPHERE 2 RESEARCH – BIOSPHERIC SCIENCE LABORATORIES AND TEST-BEDS

The goals of the Biosphere 2 facility – to create a long-term laboratory for studying global ecology and for advancing bioregenerative technologies and systems for long-term space life support systems – led to the inclusion for the first time of many elements previously left out of space life support testbeds. Thus, major biomes of the tropical belt of the global biosphere (e.g. rainforest, savannah, desert, wetland and ocean) were included, thus re-uniting the work of the ecological microcosm school with that of closed ecological system/space life support research (Allen, 1991; Nelson et al, 1993, Allen and Nelson, 1999). To attempt to close the loop completely on water, all human wastewater was treated within the system using constructed wetland technology (Nelson et al, 1999), soil-based agriculture was used to increase relevance for agricultural application and to enhance microbial diversity and facilitate recycling of animal and crop waste products (Silverstone and Nelson, 1996; Nelson et al, 1994). In addition, a very sophisticated computer network system provided real-time monitoring and display of thousands of sensors, enabling the crew and outside support staff and scientists to effectively manage the system.

The development of the world's first "biospheric laboratory", in that it incorporated a range of biomes rather than only human habitat/agricultural system laboratories as in previous space life support research, may perhaps be the enduring achievement of Biosphere 2. It is perhaps for this reason that the project was able to touch the popular imagination of large numbers of people around the world with its striking metaphor and reality of people challenged to work and live with their biosphere in close harmony during the initial two year closure experiment.

It is also for this reason that the crew of Biosphere 2 experienced with such cogency their metabolic connection with their mini-world (see Alling et al, 2002; Alling and Nelson, 1991). It is the same connection that people have with our global biosphere, but the effects of scale make it harder for people to experience this truth. Inside Biosphere 2, with cycles accelerated many hundreds of times from their Earth biosphere rate, it was much more evident to the resident "biospherians" crew that every human action had consequences, and hence, it become much more feasible to experience every moment, our interconnection with our biosphere. It became evident the "the health of our biosphere and our health" were intimately connected.

BIOREGENERATIVE TECHNOLOGIES

Some of the technologies emerging from space life support and closed ecological systems research have great potential application. These include the constructed wetlands approach for wastewater recycle and purification, and soil bed reactors for air purification in Biosphere 2. Soil bed reactors utilize the wide metabolic variety of microorganisms as a means of reducing trace gases – and like most natural mechanisms, the microbes respond and will increase efficiency of removal after initial exposure to particular contaminants. Biosphere 2 was the first facility to demonstrate that soil bed reactor function could be combined with normal plant or crop production ((Frye and Hodges, 1990; Nelson et al, 1994). The greening of houses, communities and cities might eventually be coupled with such a technology to improve air quality, indoor and outdoors.

The work on intensive cultivation of important crops may have application for extreme environments, and the need for toxin-free plant production may lead to breakthroughs in plant resistance, poison-free cropping methods and plant protection, and a better understanding of crop physiology and environmental response may lead to better methods in open field agriculture of these crops (Eckart, 1996).

The study of "biospheric laboratories" such as was pioneered by Biosphere 2, may give an unprecedented opportunity to de-couple phenomena, such as lowered oxygen and atmospheric pressure, which will give researchers new perspectives. The creation of such systems "biomic areas" modeled on natural systems should give useful data for restoration ecologists, just as laboratory mesocosms proved productive. The educational and inspiration/role model aspects of closed ecological systems relate to giving people a means of visualizing their own relationship with the global biosphere and its life support functions.

CONCLUSION: CLOSED ECOLOGICAL SYSTEMS AND THE NOOSPHERE

The Russian pioneer of the science of the biosphere, V.I. Vernadsky, saw that the challenge of our time was the harmonization of what he termed the "technosphere" with the biosphere. He foresaw the emergence of the "noosphere", a sphere of intelligence, which humanity must develop since our impacts on the global biosphere are so powerful

H.T. Odum is considered the father of "Ecological Engineering", a new discipline, which seeks a symbiotic mix of man-made and ecological self-design that maximizes productive work of the entire system (including the human economy and the larger-scale environmental system) (H.T. Odum, 1994). By minimizing human manipulation and the use of machinery, ecological engineering solutions aim to increase material recycling, enhance efficiency, reduce costs and maximize the contributions of ecological processes in the total system. An important application of ecological engineering is the design of interface ecosystems, such as constructed wetland sewage treatment systems (as were developed by Wolverton for NASA's life support systems, and further developed for Biosphere 2), to handle byproducts of the human economy and to maximize the performance of both the human economy and natural ecosystems (Mitsch and Jorgensen, 1991, Wolverton, 1989).

H.T. Odum and E.P. Odum, the founders of Systems Ecology, tried in vain during the early days of space life support development in the 1960s to get a model of complex, high diversity species systems able to self-organize, accepted as a viable path of development. Instead the prevailing mode has been extremely highly engineered systems minimizing such ecological diversity and robustness. It is perhaps time to heal this historical division within the field of space life support systems, recognizing the strengths that both approaches represent.

The opportunity and challenge for those working on bioregenerative technologies and closed ecological systems for space life support is starkly underscored by their necessity to achieve successful recycling and stability of their systems in volumes far smaller than those of Earth's natural ecosystems, and with vastly accelerated cycling times. Table 1 presents some estimates of the buffers in Earth's biosphere compared to Biosphere 2 and the Laboratory Biosphere (Dempster et al, 2002) and Table 2 contrasts carbon ratios and cycling times.

Table 1. Buffer sizes, carbon ratios and cycling times in Earth's environment compared to Biosphere 2 and the Laboratory Biosphere (data from Eckart, 1996; Nelson et al, 1993; Dempster et al, *2002*). The Earth's atmosphere was calculated at an equivalent standard air pressure: Biosphere 2 and the Laboratory Biosphere atmospheric volumes vary depending on position of the variable volume chamber, and an average air volume was used for the calculations.

For each m2 of soil (terrestrial or agricultural soil), there is the following:

	Earth Land area: 1.5×10^{14} m^2 Atmospheric volume: 4.3×10^{18} m^3 (Equivalent at standard pressure)	Biosphere 2 Land (soil) area: 6300 m^2 Atmospheric volume average 180,000 m^3	Laboratory Biosphere Land area: 5.37 m^2 Atmospheric volume: Averages 40 m^3
Water surface	2.4 m^2	0.2 m^2	0.1 – 0.6 m^2
Water volume	8300 m^3 (given ocean average depth of 3400 m)	0.9 m^3	0.07 m^3
Atmosphere	29,000 m^3 (equivalent at standard pressure)	29 m^3	6.8 m^3

Table 2. Estimates of carbon ratios in biomass, soil and atmosphere in the Earth's biosphere, Biosphere 2 and the Laboratory Biosphere facility and an estimate of carbon cycling time as a consequence (data from Schlesinger, 1991; Nelson et al, 1993; Bolin and Cook, 1983; Dempster et al, *in press*).

	Earth	Biosphere 2	Laboratory Biosphere
Ratio of biomass C: atmospheric C	1:1 (at 350 ppm CO2)	100:1 (at 1500 ppm CO2)	240-700:1 (mature crop to atmosphere at 1500 ppm CO2)
Ratio of soil C: atmospheric C	2:1	5000:1	1500:1 (atmosphere at 1500 ppm CO2)
Estimated carbon cycling time (residence in atmosphere)	3 years	1-4 days	0.5-2 days

These considerations suggest that there is enormous necessity for intelligent design to make small closed ecological systems function properly. In the coming decades, the opportunity exists for this work to become ever more relevant to the parallel efforts to understand the Earth's biosphere and to transform the human endeavor to a sustainable basis. We live in a virtually materially closed ecological system currently on Earth – and to live long-term in space we will need to create new closed ecological systems. Learning to sustain, recycle and harmoniously live within our world(s) is the overriding challenge we face both on Earth and if we are to live in space, whether in space stations or on lunar and planetary surfaces. We must learn from both efforts if we are to survive and evolve.

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