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Guest Editorial

Biosphere 2: Introduction and research progress

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1. Introduction

This special issue of *Ecological Engineering* presents 21 papers describing some of the scientific research of the Biosphere 2 Project and key aspects of the facility. The goal of the special issue is to provide, in simplest terms, a guide to the biological and mechanical elements of the facility and the evolving science that they enabled. This special issue is dedicated to all those who took part in the project since its inception. The time periods covered by papers in this special issue are shown in Fig. 1 with summaries for some of the key environmental conditions that prevailed.

The Biosphere 2 enclosure as a whole can be called a mesocosm. It is comprised of individual model ecosystems with differing climates and management strategies, also referred to as biomes or individual mesocosms, including the desert, rainforest, savanna, thornscrub (ecotone), mangrove–marsh and the coral reef–ocean biomes. Humans were dominant in the intensive agricultural biome (IAB) and the human habitat (Fig. 2). The challenge for the builders and designers of Biosphere 2 lay in creating a biosphere with similarities to our earth (Biosphere 1) that could be controlled and operated by humans. Biosphere 2 can also be used to study earth system processes and aspects of earth stewardship which require that biological and chemical processes operating in Biosphere 2 reflect those of the natural world. Much has been learned since the facility was constructed and issues revolving around the use and operation of the facility have over time changed as illustrated by the papers in this special issue.

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Biosphere 2 has no precedent due to its large scale features and internal mechanical and biological complexity—it is a unique combination of apparatus, ecology and biogeochemistry. The world within Biosphere 2 is large enough to allow studies of large scale whole-system behavior and of the micro-scale realm where microbes and molecules meet. Moreover, it has served as a 'human-rated' test facility in which two groups demonstrated that, within the constraints of operation at the time, they could live within the apparatus in unison with the mechanical and biological systems.

Typically, new phenomena must be first described before being formally studied. The publications herein have concentrated on gathering facts, thus laying a

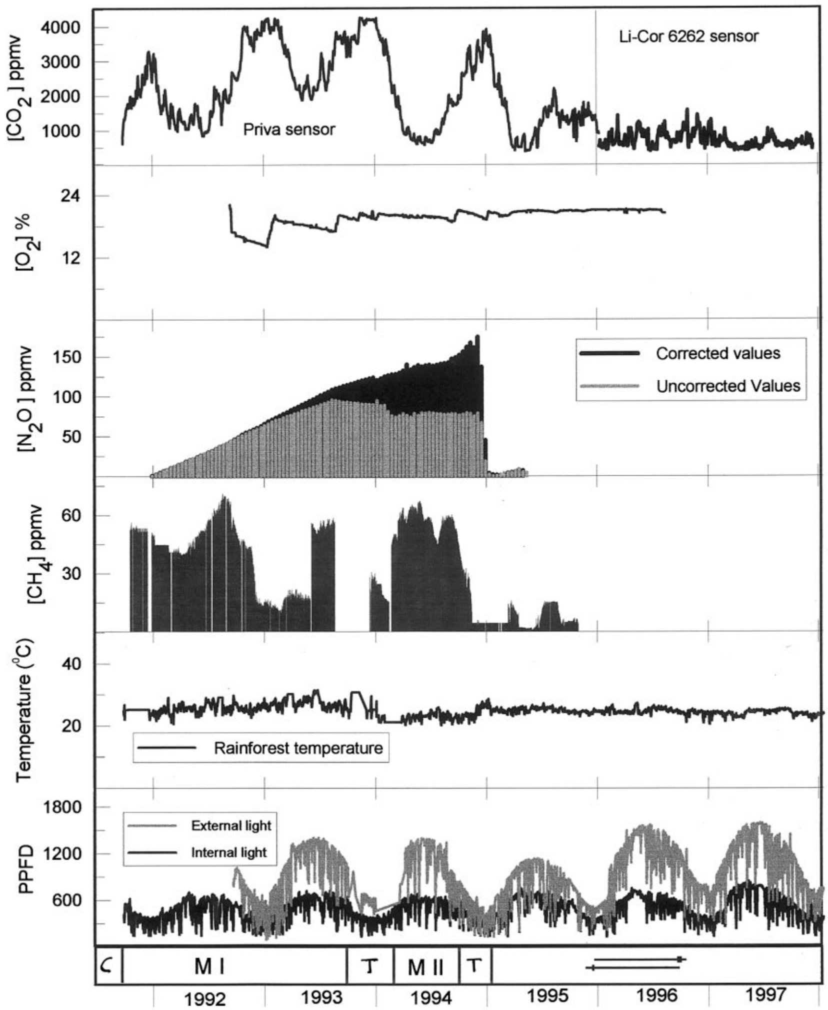

Fig. 1. (*Continued*)

foundation for more critical and synthetic thinking in the future. In this introduction we first discuss the periods of closure for Missions 1 and 2 (1991–1994) followed by a description of modifications and new developments (1995–1998) that enabled independent use of parts of Biosphere 2 (e.g. separation of the agricultural biome from the wilderness biomes and use of isolated biomes) for a variety of studies in the earth sciences.

2. Closure: 1991–1994

2.1. Mission 1 and Mission 2

There were two periods of closure: Mission 1 for 2 years, and Mission 2 for 6 months. Concepts which inspired the design and construction of Biosphere 2, adapted from the writings of the Russian geochemist V.I. Vernadsky, are summarized with notes related to Mission 1 by Allen and Nelson (1999). The 'air-tight-matter-closed' capability of the facility marked the defining structural feature of Biosphere 2. Dempster (1999), the designer of the lung systems that lay at the mechanistic heart of the Biosphere 2 closure approach, reports data for a leak rate of about 10%/year. Zabel et al. (1999) describe details of construction that made closure possible for the sealed missions. In contrast, leak rates of about 1.5%/day are reported for the wilderness area, when sealed off, for a newly configured Biosphere 2 facility (Zabel et al., 1999) in which air flow for the agricultural area and the wilderness areas were isolated from each other (Fig. 2).

Fig. 1. Environmental variables within Biosphere 2 as a function of time. The time scale: construction (C) Mission 1 (M1, Sept. 26, 1991–Sept. 26, 1993), transition 1 (T), Mission 2 (M2, March 6, 1994–Sept. 17, 1994), transition 2 (T), operation as an open or semi-closed system using ventilation fans (double arrows). The data, from top to bottom, are: (1) CO_2 concentration given in ppmv for original industrial sensors (PRIVA) and for high precision LI-COR analyzers. Note the decrease in overall CO_2 concentrations after the system was operated in an open or semi-closed mode using ventilation fans. (2) O_2 concentration given in % showing the decrease to about 14% during Mission 1 and replenishment with external O_2. O_2 gas was analyzed with a commercial gas analyzer. (3) N_2O concentration given in ppmv analyzed by gas chromatography (C. Rasmussen, personal communication). The N_2O data have been corrected for leakage using the SF6 concentration (C. Rasmussen, personal communication) and rose to nearly 300 times that of the ambient atmosphere (approximately 310 ppb in 1997). (4) CH_4 concentration given in ppmv analyzed by commercial continuous flow analyzers. The record is incomplete and subject to calibration errors. (5) Average daily temperature, given in °C, for the rainforest biome. (6) Internal (light shading) and external light (dark shading) given in photon flux density (me m^{-2} s^{-1}). Note the nearly 50% reduction of internal light due to absorption by the glass and shading by the spaceframe structure. During the first period of closure there were eight people in the Biospherian crew living inside: Taber MacCallum, Jane Poynter, Roy Walford, Linda Leigh, Sally Silverstone, Mark Van Thillo, Abigail Alling, and Mark Nelson. During the second period of closure, seven people were in the crew living inside: John Druitt, Charlotte Godfrey-Romo, Tilak Mahato, Rodrigo Romo, Pascal Maslin, Matt Smith (replaced Matt Finn), and Bernd Zabel (replaced Norberto Alvarez-Romo).

2.2. Ecosystems and biogeochemistry

The establishment of and biotic changes in the rainforest biome are given by Leigh et al. (1999) showing considerable diversity for the 60% of surviving species originally introduced. The approach to establishing the rainforest biome was to

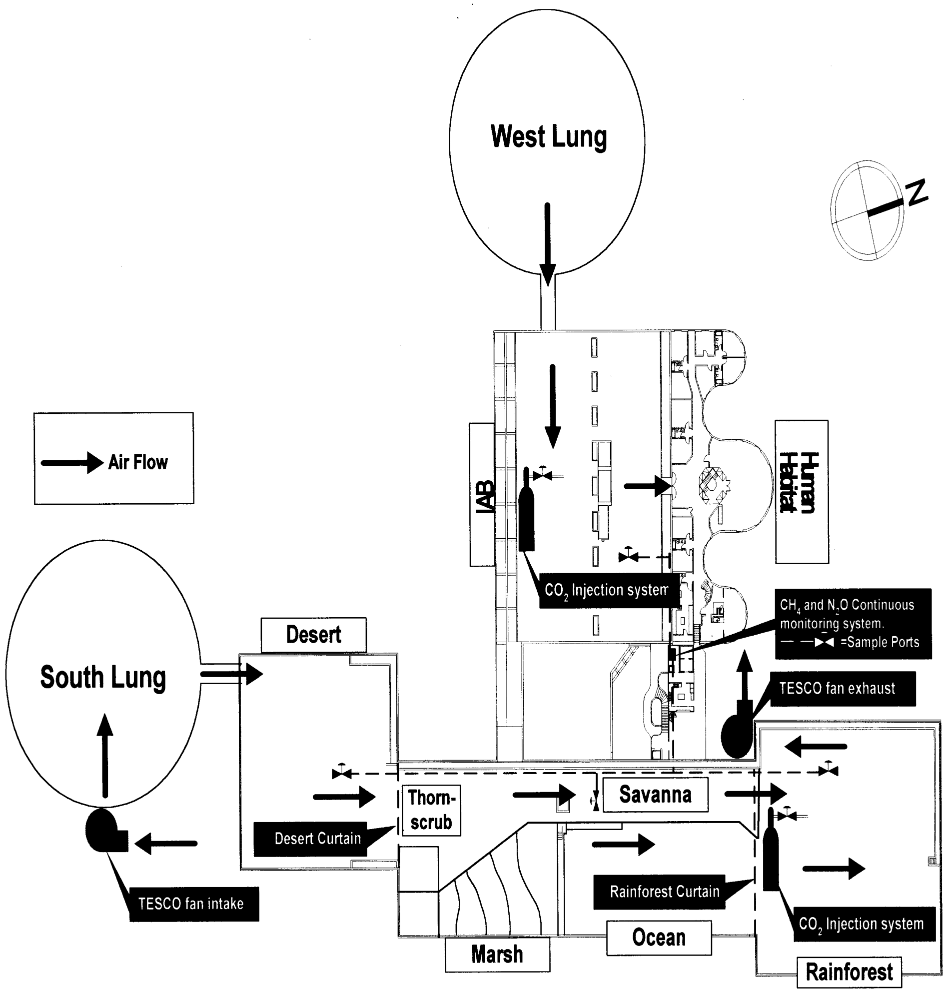

Fig. 2. Plan view of the Biosphere 2 facility. Note the placement of ventilation fans (TESCO) and air flow for control of CO_2 and N_2O concentrations in the wilderness area (desert, thornscrub, marsh, ocean, savanna, rainforest). CO_2 injection is now possible using tank CO_2 to dampen the typically large diel swing in CO_2 of up to 400 ppmv. Operation of the south lung is still routinely required for the wilderness area during periods of brief closure. The west lung operation would be required for closure of the agricultural area. The plastic curtains referred to in the papers in this special issue are located as indicated at the desert and rainforest interfaces with the savanna. In 1998, the Human Habitat and the Orchard were open to the outside atmosphere and the public.

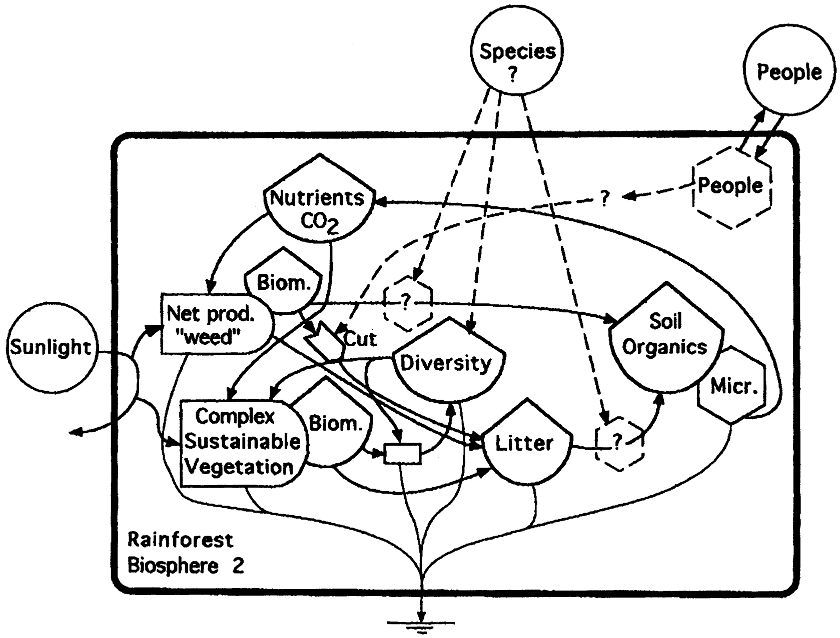

Fig. 3. Aggregated systems diagram of the rainforest in Biosphere 2 using energy systems symbols (after Odum, 1993). Lines are energy and material flows. Degraded energy leaving Biosphere 2, primarily by infra-red radiation, is depicted at the bottom as 'used energy'. Storage reservoirs are represented by pointed-round-bottom symbols, external sources by circles, photosynthetic producers by bullet-shaped symbols and consumers by hexagons. The pointed and indented block represents an interaction of two factors that generate a product. The rectangular box (miscellaneous symbol) represents functions by which biomass and diversity sustain species. Question marks and dashed lines represent uncertainty in the biogeochemical cycling of biomass due to varying management practices of the crews during closure. Biom., biomass; micr., microorganisms; net prod., net production; cut, cutting of biomass by people.

over-pack it initially and allow it to 'self-organize' into an adapted and stable system. A companion paper on the development of soils in the rainforest by Scott (1999) reports incipient development of a soil profile similar to that of some natural rainforests even though the initial soils were of local origin and were homogeneous. During the closures, rapidly growing vines developed in bright light next to the glass walls and roof resulting in loss of rainforest biota. Much human effort was directed into pruning vines and other weeds and proved to be a challenging management issue with ecological and biogeochemical consequences. Fig. 3 shows a systems overview (after Odum, 1993) of the main features of the rainforest area of Biosphere 2 showing the complex nature of the interactions between plants, biogeochemistry and humans. Competition between weedy plants and mature forest species is represented as well as the influence of biogeochemical cycles by human management of the biota (cutting of successional weedy plants) which affected the amount of litter deposited on the forest floor and subsequent decomposition. CO_2 released by soil respiration and release of nutrients are shown in a recycling pathway. Decomposition pathways where flows were apparently limited by low density of appropriate species and that could be introduced into Biosphere 2 are indicated by question marks. The human influence on carbon cycling within Biosphere 2 is explicitly modeled in Engel and Odum (1999). Nelson (1999) provides estimates for litterfall and decomposition rates for the rainforest, desert, thornscrub and savanna biomes.

Data for the coral reef biome during closure are given by Atkinson et al. (1999) showing that the coral reef biome, while not akin to large well-established natural reefs, is similar to reefs that have suffered damage due to anthropogenic activity. Details of the mangrove marsh system and the IAB, including food production during the first closure, have been published elsewhere (Finn, 1996; Silverstone and Nelson, 1996). Finn et al. (1999) use the data collected during closure to test ecological hypotheses of understory vegetation within mangrove forests. Data for species composition and biodiversity through time during closure and thereafter are briefly addressed in the biome papers. Biota of Biosphere 2 grew under very high CO_2 concentrations for the periods of closure (see Fig. 1), making it a long term elevated CO_2 experiment with concentrations of CO_2 approaching 4000 parts per million by volume (ppmv) (Fig. 1). Results for the desert and savanna biomes are in preparation.

The biogeochemistry of the Biosphere 2 system during periods of closure is known from data for environmental variables including temperature, humidity and atmospheric concentrations of CO_2, O_2, CH_4 and N_2O (see Fig. 1). The dynamic range and evolution of atmospheric species were monitored with a large number and variety of sensors for operational and safety purposes. While these data are incomplete, a model study conducted by Engel and Odum (1999) provides key insights into the biogeochemical metabolism and gaseous balance of the system. The studies revealed that the agricultural biome was the greatest contributor of CO_2, due to carbon rich soil, to the atmosphere and the greatest consumer of atmospheric O_2, which was then locked up primarily in the massive concrete structural elements of the facility. This one way flow of O_2 bound by CO_2 into the concrete as carbonates and the low leak rates, resulted in a potentially life-threatening circumstance for the Biospherians that ultimately required the injection of O_2 (Severinghaus et al., 1994). Silverstone et al. (1999) report data for soil organic matter confirming the high carbon content of the IAB soils based on archival pre-closure soil samples taken in 1990 and samples exported in 1993. Based on data reported by Silverstone et al. (1999), soil organic matter trended downward from initial values of about 6–8% in 1990 to 4–6% in March of 1993. Additional soil data for the IAB are summarized in Marino et al. (1999a). The Engel and Odum (1999) study offers an overview for the period of closure for the whole system and of sub-models built for each of the biomes. The model studies of the closure period tell us that the Biosphere 2 facility was, in some respects, self-compensating for levels of CO_2 due to plant growth and uptake by concrete, but initial conditions created a system that was unbalanced with respect to atmospheric O_2 concentration. This circumstance, in our view, does not detract from the overall success of the design, construction and functionality of the facility. A high capacity and efficient CO_2 control system would have greatly mitigated this problem.

2.3. Life during closure

How was life during closure? Allen and Nelson (1999) summarize the crew's work requirements and time demands (see also Walford et al., 1996). Aspects of food production and nutritional status have been addressed elsewhere (Silverstone and Nelson, 1996). The 2-year enclosure witnessed negligible sickness but substantial weight loss due to a low-calorie, nutrient-dense diet (Walford et al., 1992, 1995). According to standard psychological tests, the Biospherians appeared less prone to depression and were more sociable compared to profiles of astronauts; however, interpersonal and individual problems were reported and were most severe towards the end of their stay (Walford et al., 1996). The wastewater treatment system used during the closed missions described by Nelson et al. (1999) was one of several biologically based recycling systems. Others included the soil bed reactor of the agricultural area, the algal scrubbers used in the ocean, and the aquaculture lagoons used in the basement of the agricultural area. These were designed for the treatment of water or air and were ultimately the basis for life support. Some of these systems are evaluated by Marino et al. (1999a). The initial 2 year closure was to be one of many such experiments with human inhabitants lasting up to 100 years.

Based on results from Mission 1, and after a 5.5 month period for system maintenance and upgrades and introduction of species to the biomes, especially to the desert and agricultural areas, Mission 2 commenced in March 1994 and was terminated after about 6 months. Results for food production of Mission 2, showing increased crop yields (including comparisons with Mission 1), are described in Marino et al. (1999a). Weight loss was less during Mission 2 due to increased food consumption. The food production of Biosphere 2, overall, was adequate to maintain both crews; however, it is likely that the full capacity of the 0.5 ha IAB was not yet fully realized (Marino et al., 1999a). Aspects of operation during this period are given by Zabel et al. (1999).

Fig. 4 summarizes the overall metabolism of Biosphere 2 in 1994. Net daytime photosynthetic production was generally similar to nighttime net respiration indicating a nearly balanced system. The small difference between the upper and lower curves represents the net CO_2 sequestered in organic matter and carbonates. Values of gross photosynthesis shown in Fig. 4 were high compared with those reported for the Luquillo Rainforest in Puerto Rico (Odum, 1970). The absorption of CO_2 by the concrete was probably reduced for the period of Mission 2 due to the application of sealer to the concrete walls and floor of Biosphere 2.

3. The Biosphere 2 open system: 1994–1998

During this period, research emphasis was placed on studying the processes within the biomes. Since Biosphere 2 was originally built for whole-system studies, considerable support infrastructure was added after the agricultural and wilderness areas were separated as described above and illustrated in Fig. 2. One change representing a significant departure from previous operation was the design and installation of a ventilation system for Biosphere 2. Zabel et al. (1999) describe the modifications to the wilderness area that allowed for flow of air from the outside to the inside (flow-through mode), providing reasonable control for the mean CO_2 content, and reduction of N_2O concentrations (see Fig. 1). This modification allowed a series of first order experiments to investigate the effects of high CO_2 on plants and ecosystem function (Lin et al., 1998). The concentration of CO_2 to levels that are relevant to global change studies (from about 700 to 1200 ppmv) were maintained fairly well, although with a daily amplitude of nearly 400 ppmv.

Thus, Biosphere 2 was reset for studies of responses of plants and ecosystems to possible future global environmental change. This endeavor was greatly aided by the installation of high precision CO_2 monitors to replace the industrial grade sensors that were used previously. Plastic curtains were used to isolate the desert and rainforest biomes for up to several days (Marino, 1994), and, in conjunction with the high precision CO_2 monitors and the flow-through system, biome or 'whole ecosystem' experiments were possible. This meant that ecosystem level function could be studied in relation to changes in temperature, water status, CO_2 concentration, nutrients and other factors (e.g. Lin et al., 1998; Rosenthal, 1998) at an unprecedented scale. Likewise, whole system-level studies carried out in the

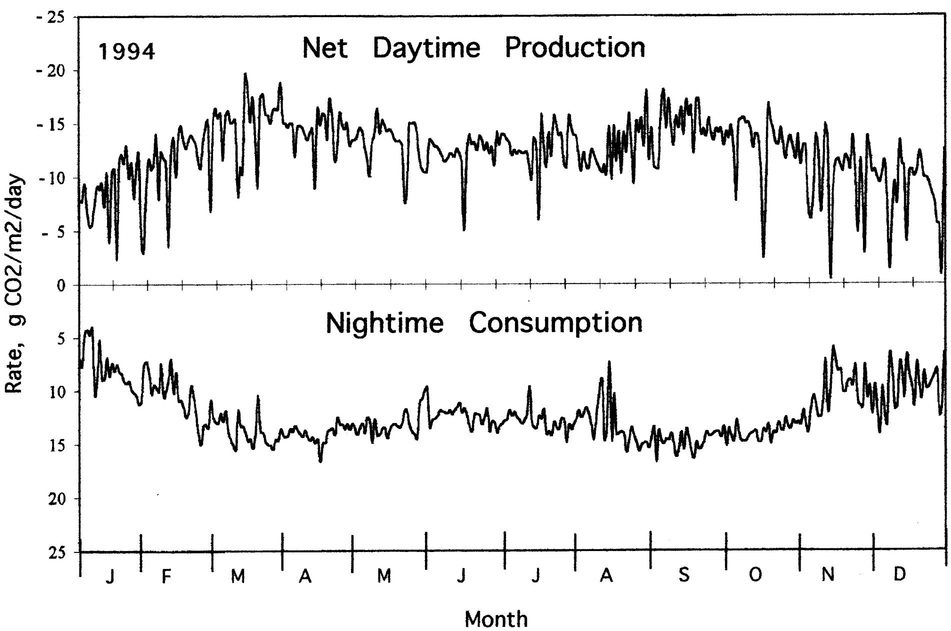

Fig. 4. Summary record of CO_2 metabolism of Biosphere 2 for the period 1994 including the second period of closure (March to September, 1994) (S. Pitts, personal communication; Kang and Engel, 1996). Net daytime decrease in CO_2 due to photosynthesis and carbonate absorption is shown in the upper panel. The net nighttime increase in CO_2 minus absorption by concrete, ocean, and soil is shown in the lower panel. Data are given in g CO_2 m^{-2} day^{-1}. An approximate measure of gross photosynthesis is given by the difference between the two curves.

Biosphere 2 ocean focused on nutrient cycling (Atkinson et al., 1999) and short term studies of the carbon cycle (Sweeney, 1999).

Rosenthal et al. (1999) describes the details of the CO_2 monitoring system and the approach for estimating CO_2 fluxes in the isolated rainforest biome. A similar approach was used for the desert and is described by Tubiello et al. (1999c). In both cases, enhancement of the carbon uptake was observed at the higher levels of CO_2 (850–900 ppmv) compared with lower levels ($\sim$400 pmmv), consistent with observations of natural systems. Studies of wheat growth in the agricultural biome, which complement analyses of Mission 1 and Mission 2 data (Silverstone and Nelson, 1996; Marino et al., 1999a) are given by Tubiello et al. (1999c). A computer model for wheat growth used to simulate observed wheat growth in Biosphere 2 indicated that photosynthetic efficiencies were intermediate between those observed under optimal field conditions and in typical growth chambers of controlled ecological life support systems (CELSS) used in NASA research. Enhanced yields of wheat in Biosphere 2 during the sealed missions were related to elevated CO_2 concentrations under which they grew, but this also consumed molecular oxygen, potentially causing an imbalance in the system.

The ability to monitor the changing reservoirs of water within the facility during experiments such as those described above is demonstrated by the work of Tubiello et al. (1999a) and was key to the study of water budgets in the various mesocosms. Kang (1999) demonstrated that the hydrogen and oxygen stable isotopic composition of water inside Biosphere 2 could be modeled, suggesting a variety of uses in plant physiological and isotopic plant proxy calibration studies.

In addition, infrastructure to support research included a canopy access system reported by Grushka et al. (1999). The canopy access system allowed intensive leaf level monitoring of the canopy. Large differences in gas exchange were found between leaves of the upper and lower canopies and the understory, significantly influencing the results of plant physiological models for this mesocosm (Grushka et al., 1999). A useful management and research tool in the context of providing baseline data for vegetation growth and structure is suggested by Marino et al. (1999b) based on remote sensing within the Biosphere 2 structure. Baseline monitoring of vegetation defined the state of Biosphere 2 for long-term monitoring and before perturbations and experiments were conducted. The use of remotely sensed data within Biosphere 2 could be extended to studies of plant physiological performance and be linked with leaf level measurements of gas exchange. On a global scale, a unique perspective on the heat budget of the facility by Nebot et al. (1999) linked heat supply and demand at various times of the year.

4. Conclusions

The majority of the papers indicate that, while Biosphere 2 is not an exact analog to the earth, the biomes share some of the essential biological processes and interactions that occur in nature. The less biologically complex nature of the ecosystems in Biosphere 2 resemble degraded and stressed natural habitats (i.e. the coral reef and rainforest), similar to ecosystems disturbed by anthropogenic activity, making these biomes potentially unique in restoration studies (see Peterson et al., 1992).

Notwithstanding complicating issues intrinsic to experimental systems, the Biosphere 2 facility has much to offer a variety of disciplines. For those interested in the component processes of ecological systems, the attractiveness of the facility lies in the ability to control key variables such as temperature and rainfall according to daily and seasonal climate regimes typical of natural habitats. These environmental variables cannot be easily controled in the field, making Biosphere 2 particularly attractive for temperature and CO_2 interaction studies. Closure of the system and parts thereof for brief periods allowed mass balances of total and isotopic forms of carbon, water and other substances. Although the ability to replicate experiments is currently limited, repetition of experiments is possible and has been performed to assess the system variability (e.g. Lin et al., 1998; Rosenthal, 1998; Rosenthal et al., 1999; Tubiello et al., 1999b).

For those interested in the overall balance of global processes, Biosphere 2 provided insights on the behavior of planet earth. The high soil organic matter at the start of the project caused excess CO_2 similar to that from fossil fuels causing global change in Biosphere 1. The increased CO_2 had direct effects on the vegetation, particularly for crop yields and for the rapid growth of vines and weed species in the rainforest as well as lowering the pH of the ocean which affected the health of the coral reef. These consequences of elevated CO_2 for the biota of Biosphere 2 are analogous to those that have occurred or might occur in Biosphere 1.

In other ways Biosphere 2 was an experiment on what might develop in ecosystems with major components missing. Because most of the normal insects and birds were missing from the rainforest, the observations provide rare insight into a biosphere without the most numerous animal types of Biosphere 1. Pollinators are largely missing and plant reproduction is asexual. By default, many insect niches are occupied by dense populations of a species of cockroach and a species of small ant. The belowground soil biology is largely unknown at present but completely captive in Biosphere 2, providing special opportunity for studies of soil microbiology, nematodes and trace gas composition. The lack of ultraviolet radiation in Biosphere 2 due to glass essentially eliminates typical tropospheric photochemistry. Without a source of UV, simulated stratospheric destruction of N_2O does not occur (see Fig. 1). The evolving composition of the Biosphere 2 atmosphere (e.g. N_2O, CH_4) under closure provides an integrated signal of plant/soil processes.

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. The idea that 'closure' itself can be expanded into a scientific discipline needs more attention and, in this endeavor, a wider sense of the uniqueness and potential rewards of using Biosphere 2 will be realized. Biosphere 2 is an example of the uniquely living biota that can persist despite stress and sometimes unfavorable conditions. The emergence of other large-scale closed or semi-closed (although not of the scale of Biosphere 2) experiments such as CLIMEX (Dise and Jenkins, 1995), the Ecotron (Lawton, 1996) and NASA's human-rated test facility (Henninger et al., 1996) suggest a growing awareness and acceptance of this approach.

The experiment thus far has shown the difficulty in recreating the viability of our planet, Biosphere 1. Scale and an over-packed inventory of the familiar plants and animals that we know, may not be enough or may require a longer time to more resemble planet earth. Biosphere 2 might offer a glimpse of biotic outcomes that we have not thought of or could not have predicted using models under simulated future climate change. It can suggest which experiments might be most profitably performed in the field. As a facility, or as a prototype for an experimental ecological facility of the future, the time for large-scale experimental systems such as Biosphere 2 has come. Clearly, institutional leadership must continue to support and catalyze agendas addressing the interests and needs of the scientific community; that will bring into focus the unique and rigorous science that can be carried out. Because the complexity and costs of such a large scale facility are enormous, perhaps Biosphere 2 could become a national laboratory, operated for all those studying sciences of the earth.

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