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Science; Nov 15, 1996; 274, 5290; ProQuest
pg. 1150

ECOLOGY

Biosphere 2 and Biodiversity: The Lessons So Far

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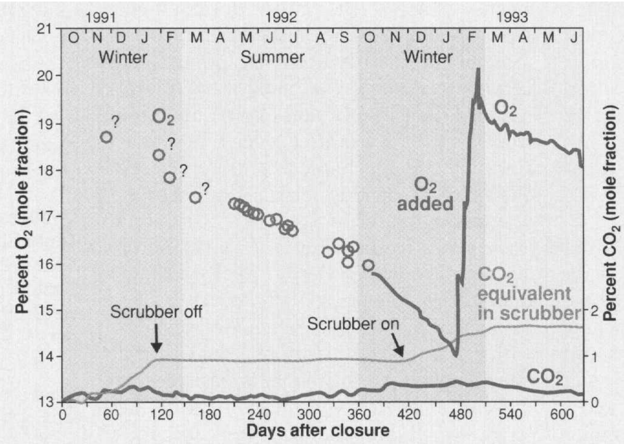
On 1 January 1996 (*1*), Columbia University took over scientific management of Biosphere 2, a 3.15-acre closed ecosystem in Oracle, Arizona, containing soil, air, water, plants, and animals. Since then, the facility has been seeking suggestions for its future research mission from a broad range of scientists. In September, Columbia's Wallace Broecker, Biosphere 2's new chief scientist, convened a committee of ecologists, plant physiologists, and population geneticists to propose possible biodiversity experiments at Biosphere 2 (*2*). These have yet to be evaluated, in part because the new director of Biosphere 2, William C. Harris, has just moved to Columbia from the National Science Foundation. Nevertheless, the committee on biodiversity experiments was struck by some fundamental lessons already learned from Biosphere 2.



Oxygen and carbon dioxide in Biosphere 2. The drop in O_2 concentration in 1992 is much greater than the increase in CO_2, suggesting an unexpected sink for O_2 or CO_2. This sink ultimately proved to be $CaCO_3$ in the concrete walls of Biosphere 2. (The scrubber removed CO_2 from the atmosphere.)

No existing closed-environment facilities for ecological research approaches the size and sophistication of Biosphere 2: the original airtight footprint covered 13,000 m^2 and enclosed 204,000 m^3. Despite the enormous resources invested in the original design and construction (estimated at roughly \$200 million from 1984 to 1991) and despite a multimillion-dollar operating budget, it proved impossible to create a materially closed system that could support eight human beings with adequate food, water, and air for 2 years. The management of Biosphere 2 encountered numerous unexpected problems and surprises, even though almost unlimited energy and technology were available to support Biosphere 2 from the outside. Isolating small pieces of large biomes and juxtaposing them in an artificial enclosure changed their functioning and interactions rather than creating a small working Earth, as originally intended.

The staff of Biosphere 2, and several reports (*3–5*), revealed to the committee numerous examples of surprises that had been encountered since the facility began its first "mission," the widely publicized enclosure of eight Biospherians from 1991 to 1993. By January 1993, 1.4 years after material closure of Biosphere 2, the oxygen concentration in the closed atmosphere fell from 21% to about 14% (see figure). This oxygen level, ordinarily found at an elevation of 17,500 feet, was barely sufficient to keep the Biospherians functioning. Carbon dioxide levels skyrocketed, with large daily and seasonal oscillations. Subsequent analyses discovered that microbial degradation of carbon in the highly fertile soils (needed for food production) consumed the atmospheric oxygen, producing carbon dioxide. Although no one knew it at the time, some of the carbon dioxide combined with the calcium in the concrete used to construct Biosphere 2 to produce calcium carbonate (*4*). The original atmospheric oxygen, in effect, became locked up in the walls of the structure. In early 1993, before the end of the first 24-month "mission," oxygen was added to Biosphere 2's atmosphere from outside. Another atmospheric problem was also unanticipated. The N_2O concentration of the air rose to 79 parts per million after 3 years of closure. At that level, N_2O may reduce vitamin B_{12} synthesis to a level that can impair or damage the brain. These and other such unforeseen problems made the biogeochemical regulation of a closed atmosphere a delicate problem.

Vines originally introduced as a carbon dioxide sink (such as morning glory, *Ipomoea* aff. *hederacea*) proved to be exceptionally aggressive. The vines required a great deal of hand weeding, which was not entirely successful, to prevent them from overrunning other plants, including food plants. The trunks and branches of large trees became brittle and prone to catastrophic and dangerous collapses. Although some species were expected to go extinct, particularly among the plants, the extremely high fraction of species extinctions (for example, 19 of 25 vertebrate species) was unanticipated (*3*). All pollinators went extinct. Consequently, the majority of the plant species, which depend on insect or vertebrate pollinators for reproduction, had no future beyond the lifetime of the individuals already present. The majority of the introduced insects went extinct, leaving crazy ants (*Paratrechina longicornus*) running everywhere, together with scattered cockroaches and katydids. Despite the relatively small size of the Biosphere 2 ocean compared to the land areas, extinction rates in the ocean appeared to be lower than those on land. Air temperatures in the upper reaches of the glass structure were far higher than anticipated, while light levels were significantly lower. Areas designed to be deserts initially became chaparral or grasslands because of a failure to adjust the rainfall to reduced evaporative demand. Water systems became loaded with nutrients, polluting aquatic habitats. Nutrients had to be removed from the water by passage over plates on which algal mats grew. The algal mats were then harvested manually, dried, and stored within the enclosure. Water chemistry management made it necessary to separate a planned brackish estuary from the ocean.

These surprises left the committee with the impression that Biospherians, despite annual energy inputs costing about \$1 million (*5*), had to make enormous, often heroic, personal efforts to maintain ecosystem services that most people take for granted in natural ecosystems. Even these efforts did not suffice to keep the closed system safe for humans or viable for many nonhuman spe-

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