Report

Biosphere 2: A Place for Integrative Studies in Chemical Research and Chemical Education in Defense of Planet Earth

by Debra Colodner, Leonard Fine, William Harris, and Bhawani Venkataraman

As soon as you open the airlock door, you are hit with the humid, musty air. Biosphere 2's tropical rainforest is clearly no ordinary laboratory. Trees tower around you, blocking the windows that define the edges of your experiment. Soil, about 1 meter deep, carpets the floor, and a concrete mountain complete with waterfall rises in the distance. Leaves bigger than dinner plates shimmer under loud blowers that circulate and cool the air. Ants run crazily on every visible surface and are not shy about scampering up your boot and then wherever they may go. Today is the tenth day without rain. The system is closed and CO_2 is being maintained at 400 ppm; relative humidity is holding at about 65%; temperature is stable at 25 °C; methane and nitrous oxide concentrations have begun their daily ascent and will climb until the biome is flushed with outside air at night. A team of students snakes past you along the wooden path. Not long after, you hear loud exclamations and laughter as one of them has slipped into the muddy bog. You note the time, as you will look for this event in the methane data.

Just another day at Columbia University's Biosphere 2 Center. Biosphere 2 is the largest enclosed ecological laboratory in the world. It sits on a 250-acre campus between Tucson and Phoenix, Arizona, that includes exhibits for visitors as well as student classrooms and dormitories. The Biosphere 2 apparatus covers about 3 acres of Arizona grassland with complex ecosystems: a tropical rainforest, a million-gallon coral reef tank, a savanna, a marsh, a desert, and a cottonwood forest. The university took over management of the site in 1996 and just signed a 10-year extension of its management agreement. It is far along in the process of refitting Biosphere 2 for tight atmospheric control and monitoring of ecosystem processes. Currently, there are research programs going on in the former agricultural area, now transformed into a forestry experiment, in the coral reef, and in the rainforest. These experiments are designed to take advantage of the unique scale of Biosphere 2. Its systems combine the environmental controls of a laboratory with some of the biological complexity of the "real" world. Here, scientists can test models that have been developed at the laboratory scale for applicability to larger, more complex systems.

Some History

The original goal of Biosphere 2 was not to help us learn more about life on Earth, but how to support humans on other planets. It was built in the late 1980s and early 1990s as a grand experiment in closed life-support systems. Eight people lived inside Biosphere 2 from 1991 to 1993 and ran the tremendously complex physical and biological plant. It wasn't long after they were sealed inside that they realized the system had some serious flaws. One of the most serious was a soil overly rich in organic matter, which left our intrepid "Biospherians" in a battle with soil microbes for oxygen. The microbes would have won the battle were it not for infusions of oxygen from external sources. Because of this and a number of other problems, the grand experiment had been reduced to a great failure. An increasingly skeptical public lost confidence in the scientific credibility of the investigators and their apparatus. But all that has since changed.

Around 1994, the owner of the site, Edward Bass, began searching for a university to help define the future of the facility. Columbia geochemist Wallace Broecker was brought in from the Lamont–Doherty Earth Observatory to consult on the oxygen problem. Carbon and oxygen budgeting had revealed a "missing" sink for CO_2 inside Biosphere 2. With the help of Jeff Severinghaus, then a graduate student, Broecker was able to prove that the missing carbon had gone into the expanses of concrete on which the Biosphere structure was built. At the same time, Broecker's visits to Biosphere 2 convinced him of the potential of the facility for ecosystem research, and initial research programs were outlined with the help of collaborating scientists from around the country. Today, partnerships in research are the benchmark of the experimental programs.

Current Research at Biosphere 2 Center

Most of the experiments in Biosphere 2 revolve around questions of the effects of increased atmospheric CO_2 on ecosystems. It is known from laboratory and field studies that leaf-level photosynthetic rates increase with increasing atmospheric CO_2 concentrations, at least over short time scales of up to a few years and with moderate increases in CO_2 concentration (*1*, *2*). As the basis of these results, it has been proposed that enhanced productivity stimulated by anthropogenic CO_2 may have turned the world's forests into a net sink for CO_2 (*3*, *4*). This would represent a significant debit in the global atmospheric carbon budget, because normally these systems are believed to be balanced with respect to CO_2 uptake and release. This "CO_2 fertilization effect" may be a large part of the "missing sink" for CO_2 in Biosphere 1, the real world. However, measuring this effect in the real world is difficult because it depends upon small differences between large photosynthetic and respiratory CO_2 fluxes over large spatial and temporal scales.

An experimental system such as Biosphere 2 allows one to account for the carbon with much greater accuracy. Current experiments in the rainforest mesocosm are designed to measure the net exchange of CO_2 by the ecosystem under different atmospheric CO_2 concentrations. The experiments test whether the carbon balance shifts to net ecosystem uptake under rising CO_2 conditions, and whether and where

Figure 1. Undergraduate students measuring water quality parameters in the Biosphere 2 tropical rainforest mesocosm. Current research here focuses on ecosystem-level exchange of CO_2 and other trace gases under changing environmental conditions, such as during drought or under higher atmospheric CO_2 levels (*5*).

this effect saturates with respect to CO_2. Additional experiments are underway to study net ecosystem exchange of carbon under varying moisture conditions. Atmospheric closure also allows one to study the response of other important greenhouse gases, such as N_2O (nitrous oxide) or CH_4 (methane), to changing environmental conditions (Fig. 1). The Biosphere rainforest mesocosm acts essentially like a very large flux chamber in which ecosystem-scale processes can be studied. Because there is only one rainforest in Biosphere 2, experimental perturbations are performed in time-series fashion.

The former agricultural area of Biosphere 2 now houses a cottonwood forest. Cottonwoods have proved useful in testing the suitability of the apparatus and the soils within for growing a temperate forest. Interestingly, the same soils that nearly did in the Biospherians are the probable culprit in producing trees that appear to be overdosed on nitrogen. Within a year's time, the soils are likely to be replaced—a necessary but daunting task in the face of 2000 m^3 of the stuff, all of which will need to be sterilized—and new trees will be planted. Unlike the rainforest, the agroforestry mesocosm lends itself to easy sectioning into three areas. These will be run at three CO_2 concentrations, ambient (360 ppm), twice ambient (720 ppm), and four times ambient (1440 ppm), to look at effects on ecosystem functions such as CO_2 and water exchange, trace gas production, and nutrient cycling. These processes will be studied at the cellular, leaf, branch, and ecosystem scales. In addition, temperature changes will be imposed on the three experimental bays using time-series techniques, to look at the coupled effects of CO_2 and temperature.

Along with the rainforest and temperate forest studies, a third mesocosm under active investigation is the coral reef (Fig. 2). This is a synthetic ocean contained in a tank larger than an Olympic swimming pool, complete with its own wave machine and beach area. Fish, echinoids, crustaceans, living coral, sponges, and macroalgae, the last dominating the bottom-dwellers, cohabit. The essential question scientists studying the reef mesocosm are trying to answer also focuses on the response of the system to increased CO_2. Scientists now believe that about half of the CO_2 humans add to the atmosphere each year ends up in the ocean, shifting the carbonate balance in seawater as carbonate ions react with dissolved CO_2 and the pH falls. The net chemical reaction is

$$H_2O + CO_2(aq) + CO_3^{2-} \rightarrow 2HCO_3^-$$

If atmospheric CO_2 rises from its current level of about 360 ppm to 900 ppm, as it is predicted to do in the next (22nd) century, the pH of surface ocean waters can be expected to fall from its present value of about 8.1 to 7.9. That is significant! Such a change in pH will decrease the carbonate saturation state of the oceans and is likely to adversely affect the ability of corals and other calcifying organisms to precipitate their calcium carbonate skeletons. The carbonate saturation state is defined as

$$\Omega = \frac{\left[Ca^{2+}\right]\left[CO_3^{2-}\right]}{K_{sp}}$$

Where K_{sp} is the solubility product for a particular form of calcium carbonate (calcite or aragonite).

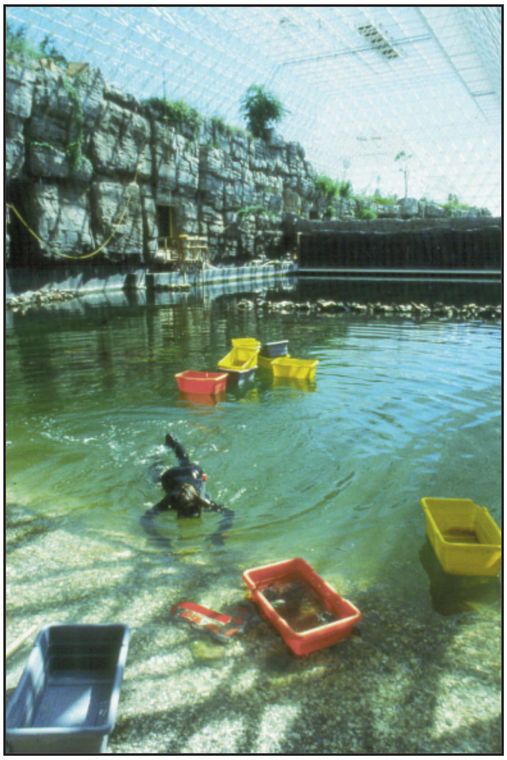

Figure 2. The coral reef mesocosm at Biosphere 2. Current research here focuses on the effects of higher pCO_2 on calcification rates, diversity of benthic invertebrates, and nutrient exchange in reef environments.

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Figure 3. Students in the Earth Semester program on a field trip in Northern Arizona. The undergraduate programs generally take advantage of their proximity to sites such as the Grand Canyon, Meteor Crater, mining operations, and the Gulf of California for fieldwork opportunities.

Figure 4. Undergraduate students using surveying equipment to map the Biosphere 2 desert mesocosm.

Recent Biosphere 2 laboratory experiments provide evidence of this effect (*6*). If this is the case in the real world, and should it continue, there will be an added stress for corals that are already struggling to cope with other environmental changes in coastal regions of the world, such as increased nutrient and sediment loading.

Education at Biosphere 2 Center

The Biosphere 2 Center is also a laboratory for educational research, reform, and remediation. Could there be a better place to make the case for education in context and integrative studies? Easy access to field sites, clear night skies, a new 24-inch telescope, and ongoing research "under the glass" all provide learning opportunities for undergraduates who come to live on campus for four to 16 weeks. The flagship program is the Earth Semester, a 16-week immersion in environmental science and policy. Many of the 100 students currently enrolled each semester come from about 25 partner institutions around the country, but college students from other U.S. and international institutions are also welcome. Students take courses in Earth Systems Science, Ecology, and Environmental Policy, unified by an interdisciplinary seminar. The individual courses in the Earth Semester support thematic modules designed to teach basic science and management of ecosystems, from local to global scales. Undergraduates representing the range of traditional academic disciplines are mixed together in the same classroom to teach each other and learn to solve problems together. The Earth Semester classrooms extend to field sites on campus and around the southwestern U.S. (Fig. 3) where students can fully experience the context of their science.

Opportunities for students are expanding rapidly and will continue to grow over the next few years. A new astronomy program, the Universe Semester, started in Fall 1999 with 25 students, and summer field courses in ecosystems science, biodiversity, and astronomy are also now available. A new undergraduate Technology Semester program for chemistry and engineering students is being planned around an "instrumentation-intensive" laboratory course in environmental chemistry and an energy course. Both of these draw on results from research areas in chemical ecology and molecular diversity, carbon budgeting and management, and remote-sensor applications in complex ecosystems.

An experiment in graduate education and training has brought first-year students beginning their Ph.D. studies in chemistry from Columbia University in New York City to the desert of Arizona. The objectives of the program are ambitious and multifaceted:

- to learn methods of conducting basic and applied research
- to understand the complexities inherent in scaling laboratory experiments and models to larger systems
- to participate in environmental chemistry, an area of primary local, regional, and national research interest
- to teach the interdisciplinary nature of environmental research
- to create an environment that encourages students to collaborate with and learn from each other
- to establish a useful model for reforming graduate education that can serve other than SME&T departments and universities beyond Columbia

The education programs make use of the Biosphere 2 apparatus in different ways. All Earth Semester students do independent research projects, and about half of them do theirs inside Biosphere 2 (Fig. 4). The scale of the system is not only advantageous for research, it serves as a teaching metaphor for human interactions with our planet. On Earth, human influence on the chemistry of the atmosphere is an abstract notion for many students. Within the glass-enclosed Biosphere 2, however, the effects of human actions are immediately apparent. For example, the Biospherians nearly ran out of oxygen because they naively designed a soil that was too rich. One of the meta-lessons of Biosphere 2 is that people do not yet know enough to design and manage a system that can support life for long periods of time. It teaches a new level of respect for the global life-support system we were given, and recognition of the extent to which people have already influenced this system.

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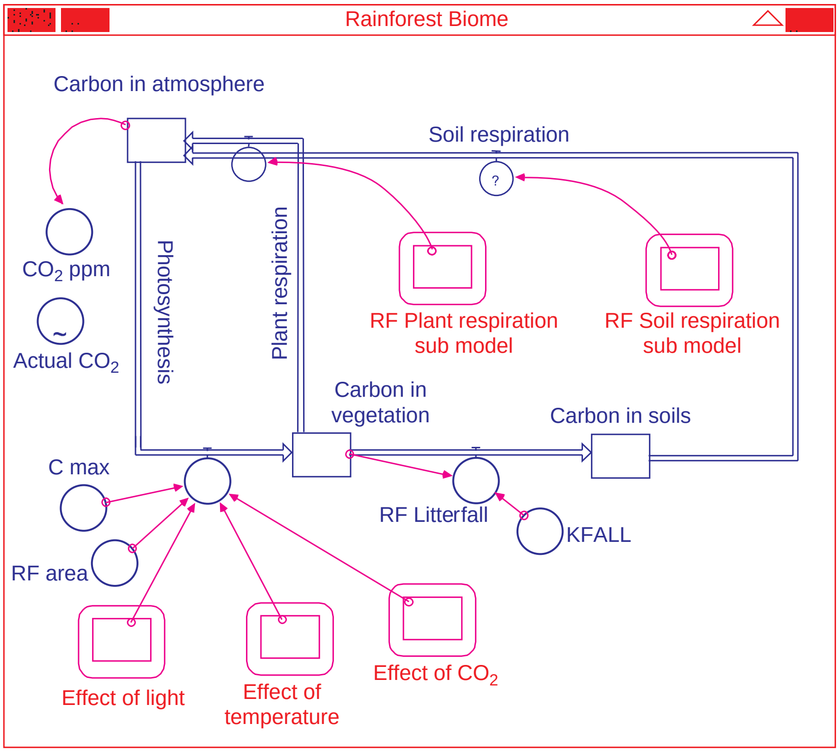
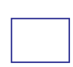


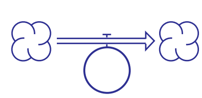
Figure 5. STELLA (High Performance Systems) model of the carbon cycle in the Biosphere 2 tropical rainforest mesocosm. STELLA is an iconographic flow-reservoir modeling program with which students can construct their own system models. The symbols shown here are explained in the box below.

Symbols Used in STELLA

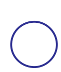
In this model, there are three reservoirs: atmosphere, soils, and plants. Each is indicated as a rectangle.



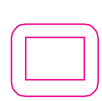
Likewise, there are three flows of carbon: photosynthesis, plant respiration, and soil respiration.



The converters, indicated by circles, hold constants or formulas that modify the flows or reservoirs.



Submodels are used to organize a complex model, and in this case, contain functions to modify the carbon flows.



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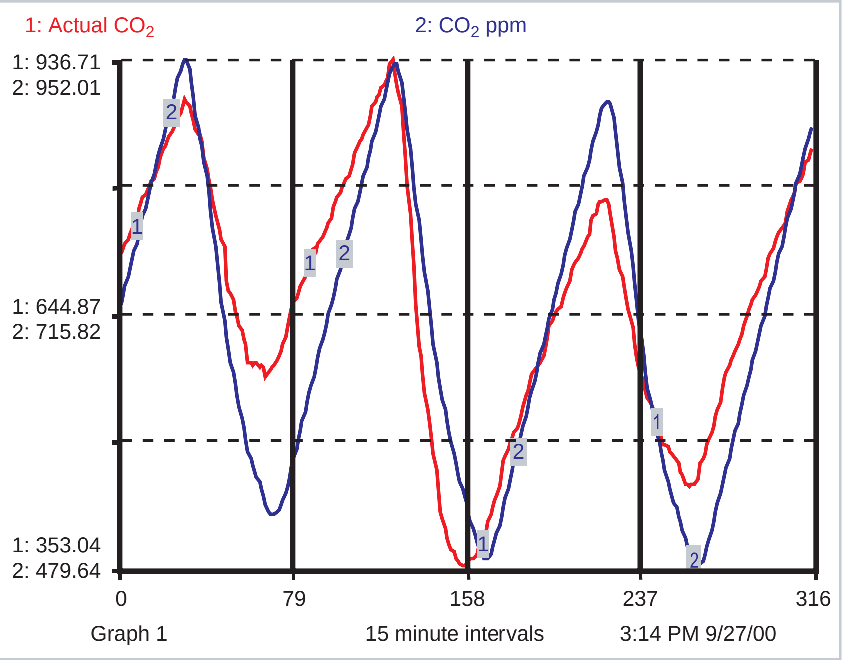

Figure 6. Comparison of (2, blue) model-calculated and (1, red) actual CO_2 data for the atmosphere of the tropical rainforest mesocosm under closed conditions.

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Faculty and students who are not at Biosphere 2 can use Biosphere 2 to teach and learn about basic concepts in environmental chemistry such as chemical cycles. A carbon-cycle model of Biosphere 2 is available in STELLA (High Performance Systems) on the Biosphere 2 Web site (*http://www.bio2.edu/education/edu_entry.htm*). Because of the small scale of the atmosphere, the plants and soils drive large diurnal changes in CO_2. Many kinetic concepts are embedded in the model, and students can explore the effects of light, temperature, or CO_2 concentrations on rates of photosynthesis or respiration (Figs. 5 and 6).

Biosphere 2 is a new kind of facility for scientific research and education operating across interdisciplinary boundaries in defense of Biosphere 1. Its unique scale, somewhere between the laboratory and Biosphere 1, is stimulating new modes of research and teaching.

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