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INSIDE

The Biosphere and Me

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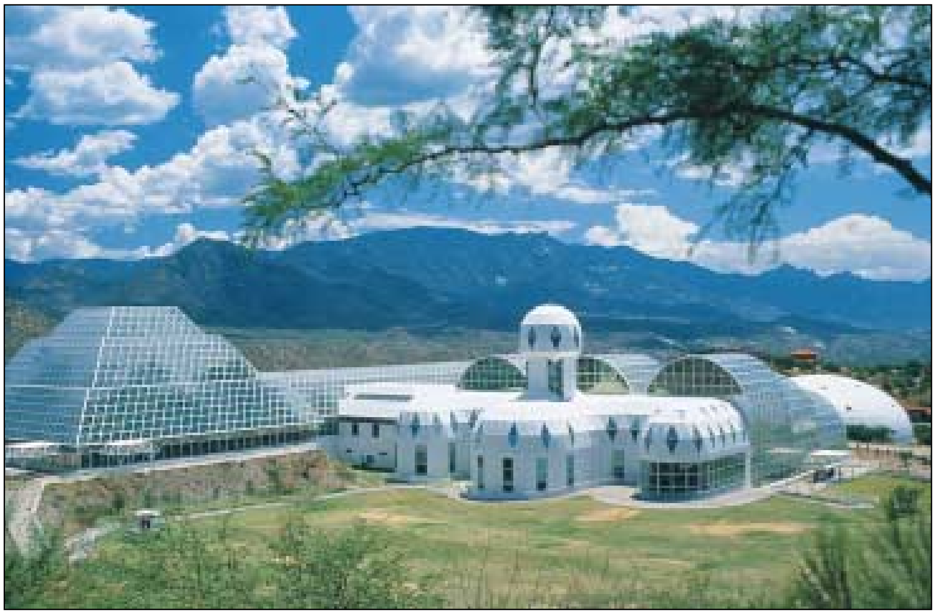

Biosphere 2, near Oracle, Arizona. *Photo by Karen Silva. Copyright 1996 Biosphere 2 Center, Inc.*

ABSTRACT

Biosphere 2 was originally constructed for the purpose of determining whether a materially closed ecological system could be maintained in equilibrium and sustain human beings for long time periods. But after a change in management, this initial goal was set aside, and it was decided to use this wonderful facility for research and education on various aspects of biogeochemistry, plant biology, and ecosystems studies. To this end, Columbia University was commissioned to manage the activities at this site, located just north of Tucson, Arizona.

SERENDIPITY

One visit to Biosphere 2 and I was hooked. Now, four years later, I'm locked in an alliance with Bruno Marino in an attempt to create a world-class research center on this site. People ask me, "Wally, how on earth did you ever get so involved in this thing?" I give a somewhat different answer each time I'm asked. The reason is that I am of many minds on this subject. No doubt part of my obsession stems from the sheer magnificence of the site in the Arizona desert and of the Biosphere itself, which fits comfortably with the surrounding beauty. On another level, I realize that the Biosphere is unique. Because the cost approached $150 million, no chance exists that this wonderfully engineered visionary garden will ever be duplicated. I considered it a tragedy that this incredible facility was being used to accomplish what I viewed to be a frivolous goal. Maintaining eight people in a matter-sealed environment for a period of two years was a clever stunt, but then what? Biosphere 2 also grabbed my geochemical antenna. Biosphere 1 (Earth) is a closed system, but this is a concept not so easily grasped. Could we use what goes on in the closed environment of Biosphere 2 to alert our fellow earthlings to the possible consequences of industrialization? Perhaps experiments could be conducted in Biosphere 2 which would help us to prepare for the impacts of the experiment mankind is conducting in Biosphere 1 through the addition of fossil fuel CO_2 to the atmosphere.

As is often the case for important events in one's life, the opportunity to influence the course of Biosphere 2's use came about through serendipity. Just eight months after the group of eight Biospherians was sealed up in this glass house, Jack Corliss, then a part-time consultant to the group that built and operated the Biosphere, asked me if I would be willing to discuss with John Allen, the group's leader, the possible causes for the ongoing drop in their O_2 reserve. Like almost everyone else on the planet, I had by this time read newspaper stories (largely critical) about this venture, but I was very short on details. I had just enough information that my curiosity would not allow me to turn down Jack's invitation. So, I crossed the

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IN THIS ISSUE

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Hudson to a Manhattan restaurant for a dinner with John Allen—and quite a dinner it turned out to be. Allen reminded me of an aging Indiana Jones. He flashed a somewhat crumpled graph showing the trend followed by the O_2 content of Biosphere 2's air over the period following closure. I say "flashed" because John clearly did not want any of the journalistic critics who might be lurking at the surrounding tables to get a glimpse of this evidence that all was not going well in his house of glass. My first thought (which ultimately proved to be correct) was the obvious one. I said, "John, I bet you put too much organic matter in Biosphere 2's soils." We argued the pros and cons of this idea at great length. We agreed on only two points. First, I would tell no one about the mysterious decrease of Biosphere 2's O_2, and second, I would visit the Biosphere after a meeting on soil radiocarbon which by chance was to be held in Tucson in a week's time.

It was with great anticipation that I drove across the desert to Biosphere 2 that May day in 1992. After a brief meeting with John Allen during which he regaled me with concepts put forth by his hero, the Russian geochemist Vernadsky, I was placed in the able hands of Biosphere 2's chief engineer, Bill Dempster. He toured me around (but, of course, not into) the fabulous Biosphere—its power plant, its cooling towers, and its "lungs." Then Bill and I sat down in his office to discuss the O_2 problem. It was Bill who unfolded the mystery by showing me that my theory based on excess respiration in Biosphere 2's soils could not be the whole story. The problem was that the CO_2 content of Biosphere 2 air had not risen anywhere near as far as would be expected from the disappearance of O_2. For each mole of O_2 consumed by the bacteria living in the soil, roughly one mole of CO_2 would have been produced. Had this CO_2 accumulated in the closed air space, the content should have risen to several percent. Yet, at that time, it was only about 0.1%. Here was the kind of puzzle designed to capture the attention of any alert geochemist. I went back to Lamont with visions of oxidation-reduction reactions dancing in my head.

SECOND THOUGHTS AND FINALLY SUCCESS

I sought out Jeff Severinghaus who had begun his graduate work at Lamont at the beginning of the spring term. Jeff was interested in the global carbon cycle and was particularly impressed by the approach being taken by Ralph Keeling, then a postdoctoral fellow at the National Center for Atmospheric Research. Ralph had succeeded in developing the capability to measure the rate of decline in Earth's O_2 resulting from the burning of fossil fuels. Jeff was on the lookout for a research problem related to this approach. So, I said, "Jeff, if you can't find one involving Biosphere 1, why not settle for Biosphere 2?" Jeff bit, and we immediately began what turned out to be a long series of investigations of possible solutions to the seeming enigma. As Biosphere 2 initially contained 1.2 million moles of O_2 (40 tons), we figured that it shouldn't be hard to track down the fate of the missing 10 or so tons. Could the Biospherians have removed the matching excess CO_2 into their sodium hydroxide scrubber? Could there be another sink for O_2—the oxidation of fixed nitrogen, of reduced sulfur, of divalent iron in the soils? Rust? Clearly, in order to answer these questions, one of us would have to spend some time at the Biosphere. Jeff offered. Dempster and Allen agreed. So, during the summer of 1992, Lamont's involvement in Biosphere 2 research began. Jeff, with considerable help from Bill Dempster, rather quickly eliminated the CO_2 scrubber and N and S oxidation from contention. Although the Biospherians had indeed run their NaOH stripper during winter months, the amount of CO_2 removed accounted for only one-fifth of that necessary to balance its carbon budget. Any N and S oxidized would have appeared in the recirculating water supply as NO_3^- and $SO_4^=$. Analyses of the water showed that the amounts of these substances were far too small. The required 50 or so tons of rust were clearly nowhere to be seen. The acid soils of Biosphere 2 were hardly likely to host massive $CaCO_3$ accumulation. This left iron in the soils as the only remaining item on our list of suspects. Jeff, again with help from Bill Dempster, constructed a set of sealed soil chambers with the intent of measuring the ratio of O_2 consumption to CO_2 production. Although preliminary experiments with these chambers did indeed indicate that O_2 was going down faster than CO_2 went up, this result proved to be an artifact of CO_2 uptake by the soil moisture. Bafflement!

During this period, Jeff began to get cold feet about work at Biosphere 2. The press mercilessly hammered away at what they perceived to be evidence of cheating by the Biospherians. Did they import hamburgers or have secret nights on the town? Jeff and I both knew these suspicions were unfounded. One only had to look at the Biospherians to see that they were on the verge of starvation. One had only to speak with them to know that they took their mission very seriously. Further, Bill Dempster proved to be a superb colleague, intelligent, knowledgeable, dedicated, resourceful, and totally honest. But around us swirled the aura of public relations gimmicks and what we felt was a charade of great science as portrayed by John Allen and his top aides. John once told me, “Wally, we are out to uncover the great principles of ecology.” I replied, “John, I’m not sure whether such principles exist. If they do, this is surely not the setting in which they will be discovered.” When Jeff suggested that he cut his connection with the Biosphere for fear that he would inherit a reputation for Barnum and Bailey science, I tried to dissuade him by pointing out that geologists who worked in Cuba were not making a statement of admiration for Castro. As we took no money for consulting fees, research expenditures, or even airfares, I reminded him that we were clean!

Then, at last, the breakthrough came. Jeff’s father, a high-altitude physiologist, pointed out something we had never considered; concrete takes up CO_2. Portland cement initially contains about 15% $Ca(OH)_2$, which upon exposure to carbon dioxide is converted to $CaCO_3$. CO_2 in–H_2O out. With the help of Taber McCallum, one of the eight resident Biospherians, Jeff obtained cores of concrete exposed on the inside of the Biosphere. He compared the thickness of the $CaCO_3$-saturated rind in these cores with that for cores he obtained from concrete on the outside of the structure. Those from the inside had a 2-cm-thick rind compared to only 0.2 cm for the outside. This was to be expected because the CO_2 content of the air inside the Biosphere averaged about eight times that outside. Although humidity dependent, the rate of CO_2 uptake by concrete should be roughly proportional to the CO_2 content of the air in contact with the concrete. Jeff multiplied the amount of $CaCO_3$ per unit area by the area of exposed concrete and, lo and behold, found that it accounted for the missing CO_2!

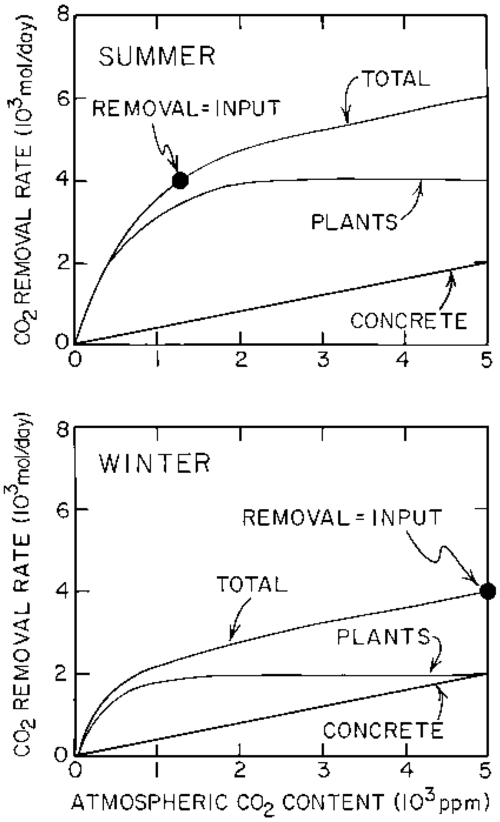

Figure 1. Hypothetical dependence of uptake of CO_2 by Biosphere 2 plants and concrete on the CO_2 content of its air. The former increases and then plateaus at CO_2 contents above 1500 ppm; the latter rises linearly with CO_2 content of the air. During summer months, when light is high, the plateau rate of uptake of CO_2 by plants is assumed to be twice that for winter months, when light is low. As the uptake of CO_2 by concrete is independent of light level, its trend with atmospheric CO_2 content should show no seasonality. Assuming that the rate of respiration is the same in summer and winter, (i.e., 4000 moles/day), the steady-state CO_2 content during winter months would have to be more than four times that in the summer in order for removal to match respiration input. In this hypothetical case, during summer months, 87% of the daily CO_2 goes to plant growth and 13% to the concrete carbonation. During the winter, the split is close to 50:50. If during winter months the Biospherians removed, through scrubbing, 600 moles of CO_2 per day, then the amount to be removed by the plants and concrete would have dropped to 3400 moles per day. This could be accomplished at a CO_2 content of 3500 ppm.

IT COULD HAVE BEEN VENUS

Although this finding solved the original mystery, it served to whet my appetite to understand exactly how Biosphere 2’s carbon cycle was regulated. On the basis of the magnitude of the soil-respiration–driven night-time rise of CO_2 content, it was clear that the CO_2 in Biosphere 2’s atmosphere was being replaced on the time scale of just a few days. Yet, over periods of weeks, its CO_2 content oscillated about nearly the same daily mean, suggesting that some mechanism allowed Biosphere 2’s CO_2 content to reach a steady state. In other words, a feedback loop must have been operative which tended to drive the CO_2 content of Biosphere 2’s atmosphere toward that level at which the combined removal by plant growth and by concrete carbonation matched the input from respiration. As shown diagrammatically in Figure 1, the rates of both uptake processes are dependent upon CO_2 concentration. In the case of concrete carbonation, the rate presumably rises linearly with CO_2 content of the air. The rate of photosynthesis also rises with CO_2 content, but it asymptotically approaches an upper limit. The magnitude of this limit depends on the light level. As the environmental conditions in Biosphere 2 (temperature, rainfall, humidity) were held nearly the same around the year, light was the only seasonally variable factor. Indeed, during times of peak summer insolation, the amount of sunshine received in Arizona is slightly more than twice that received in winter months. While the curves shown in Figure 1 are based on my guesses, they are at least qualitatively correct. They clearly show why the CO_2 content of Biosphere 2’s air underwent such strong seasonal cycles. Night-time CO_2 rise rates suggest that soil respiration was more or less the same in summer and winter. It averaged about 4000 moles/day. During summer months, higher photosynthesis rates permitted most, but not all, of this CO_2 to be removed through plant growth. By contrast, under winter conditions, we estimate that only about half the CO_2 generated by respiration could be removed by plant growth, and, hence, no plant-growth feedback control could exist. The rest of the CO_2 had to go into the concrete. For this to happen, a CO_2 content of roughly 5000 ppm was required. Because the Biospherians worried that the winter CO_2 content

Biosphere *continued on p. 4*

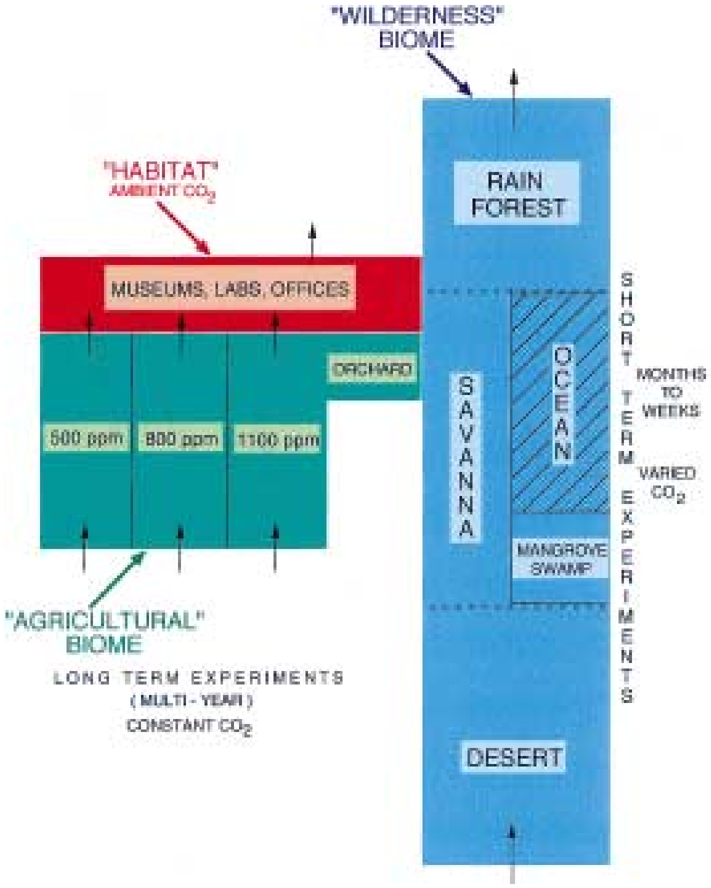

Figure 2. Diagram showing the compartmentalization planned for Biosphere 2. Colors indicate the threefold subdivision. Dashed lines show the positions of the roll-up curtains for temporary isolation of the rain forest and desert. The black arrows indicate the direction of the air flow associated with CO_2 control.

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of their air might skyrocket to unreasonable levels, they operated a scrubbing device capable of removing 500 moles of CO_2 per day. This dropped the net input from 4000 to 3500 moles per day and hence required removal by the concrete of 2000 to 1500 moles per day. Therefore, the winter CO_2 levels stabilized at about 3750 ppm instead of at 5000 ppm (see Fig. 1).

Unbeknownst to the builders of Biosphere 2, by incorporating immense amounts of concrete into their glass house, they prevented a Venus-like runaway CO_2 buildup. Without concrete, even with the scrubber running full tilt, during winter months, production of CO_2 by respiration would have exceeded removal by about 1500 moles per day. This excess would have accumulated in the air. Each winter day, the CO_2 content of Biosphere 2's atmosphere would have risen by about 250 ppm. Over the 90-day winter period, it would have climbed to a staggering 22,000 ppm.

Was no consideration given to this problem by Biosphere 2's designers? I think not. They were organic gardeners intent on maximizing the Biospherian's food supply. Consequently, they put too much organic matter into their soils (artificially created by mixing peat moss and bog mud with site excavation alluvial silt and clay). In the agricultural area, they made the additional mistake of extending the organic-rich material to a depth of nearly 1 m (in most of Biosphere 1's agricultural plots, the organic-rich A-horizon extends to about one fifth this depth). One has only to take another look at Figure 1 to realize that had its creators installed one-half the amount of organic matter, then even during the winter periods Biosphere 2 would have achieved steady state on the rising part of the curve of growth rate vs. atmospheric CO_2 content. The mean daily CO_2 content would have stabilized at perhaps 650 ppm during low-light periods and close to the outside ambient conditions during summer months.

Let us return to the situation with regard to O_2. For each mole of CO_2 generated by respiration, roughly 1 mole of O_2 is consumed. To the extent that this respiration CO_2 is consumed by plants, the lost O_2 is replenished. But if, instead, the CO_2 goes into the concrete, then replenishment doesn't occur. Hence, CO_2 uptake by Biosphere 2's concrete and O_2 decline went hand in hand. When initially closed, Biosphere 2 contained about 1.2 million moles of O_2. Averaged over the entire year, the excess of soil respiration over plant growth was about 1000 moles per day. Hence, during the course of one year about 0.4 million moles of O_2 (or one-third of the total) was lost. So great was this loss that eventually the management had to back off from their self-imposed ban against any transfer of matter into Biosphere 2 by bringing in tank trucks loaded with liquid O_2. By February 1993, 1.4 years after closure, the O_2 content had fallen from its initial 21% to about 14%. The Biospherians, living at 3800 feet elevation, were experiencing oxygen availability equivalent to that at an elevation of 17,500 feet! Again, it is easy to see from Figure 1 that if respiration had been 2000 rather than 4000 moles per day, a much smaller amount of CO_2 would have gone into the concrete (about 200 moles per day). In this case the O_2 content would have declined at the rate of only 10% per year, and the Biospherians would not have run short during their two-year stay.

One interesting observation was that just prior to replenishment of O_2, the eight Biospherians were dragging around, hardly capable of climbing stairs. When the first injection of O_2 was made into one of the two external lungs, the Biospherians waited behind a sealed hatch in the connecting tunnel. Their air contained 14% O_2. Upon completion of the first O_2 injection, the lung air contained 27% O_2. When the hatch was opened and the Biospherians stepped into the O_2-rich environment, their rejuvenation was instantaneous. They ran and jumped for joy and even did somersaults!

MEANWHILE, OUTSIDE

As my interest in the Biosphere rose, so also did my discontent regarding its management and direction. First, the advisory committee constituted by scientists of great prominence—Keith Runcorn, Jim Arnold, Tom Lovejoy—resigned in protest over the lack of information. Then, in a surprise move made without consultation with any of us, Jack Corliss was appointed director of research. Finally, a new crew of seven Biospherians was installed for a second mission whose objectives were no clearer than those surrounding the first. In my estimation, this very expensive facility was going nowhere. In frustration, I wrote a long letter to Ed Bass, the patron of the operation, bewailing this state of affairs and suggesting how the Biosphere might be put to better use. Much to my surprise and to that of many other Biosphere watchers, on April 1, 1994, Bass's financial advisors moved in and assumed management. As it turned out, this move had been in the offing well before my letter was written.

At the time of the takeover, John Allen and two of his faithful, Abigail Ailing and Mark Van Thillo, were in Japan. Ailing and Van Thillo flew back to Arizona and in the pre-dawn hours of April 3 came across the desert and broke the seal on one of Biosphere 2's hatches. Abigail went inside and ordered the resident Biospherians to leave. They refused, and the Biosphere was resealed (but not until 15% of its air had been exchanged). This triggered arrests of Ailing and Van Thillo and generated lawsuits that have yet to be settled. Ailing claimed that she was trying to prevent something akin to the Challenger disaster. The new management said that had problems arisen, the Biospherians could simply have opened any of several hatches and walked out. Further, no one can point to any aspect of Biosphere 2's operation which might have placed it or its occupants in sudden jeopardy.

Upon the departure of the Allen group, the management of Biosphere 2 was placed in the hands of Bannon and Associates, a company specializing in the reorganization of troubled business enterprises. Their charge was twofold. First, stem the financial bleeding, and second, place the long-term operation of the Biosphere campus in the hands of a university or group of universities. Steve Bannon, the CEO of Bannon Associates, took personal charge of this exercise. He immediately took up residence on the Biosphere 2 campus and remained there for 21 months until these tasks were completed. On January 1, 1996, Columbia University assumed management of the Biosphere.

The 1-meter-deep ocean with beach and coral reef. *Copyright A9 Biosphere 2.*

Steve Bannon turned to me, as the only external scientist actively involved at Biosphere 2 but not receiving funding from the Allen group, for advice regarding how a legitimate scientific program might be set up. My advice was to seek a hands-on scientist as director of research. "Any candidates in mind?" he asked. "Lots, but if you ask who might be good at it and also likely to accept the job, then I can think of only one, Bruno Marino at Harvard. He's a leader in the field of isotope biogeochemistry and is looking for this kind of job." A second piece of advice to Steve was that until a more permanent arrangement could be made, Biosphere 2 science should be planned jointly by scientists at Lamont and Biosphere 2. In this way, not only would the newly created research group on the Oracle campus be buttressed, but also the Lamont connection would provide the credibility necessary to entrain scientists from other places. With some reassurance from Columbia's Vice Provost, Michael Crow, the cooperative effort was launched. Bruno Marino accepted the job and arrived on site in September 1994.

But the millennium had not arrived. Seven Biospherians still resided in the sealed glass house. The new management had never dealt with science or scientists. The mission-to-Mars mentality hung like a shroud over the whole enterprise. The outside world still rolled its eyes whenever Biosphere 2 was mentioned. Simply put, Bruno and I faced an uphill battle.

One problem was quickly resolved. When Bruno found that the N_2O content of the then three-year-old air in Biosphere 2 had risen to 79 ppm he said, "N_2O at this level is no laughing matter. It impedes vitamin B-12 synthesis in humans. Lack of vitamin B-12 can produce brain damage." So out they came, ending once and for all the use of Biosphere 2 as a human habitat.

TOWARD A NEW MISSION

This evacuation forced to the front the question of how exactly Biosphere 2 might be used as a science facility. Clearly, the fact that it was sealed offered the opportunity to do budgeting for carbon and water (and their isotopes). Also, the fact that it had been running at elevated CO_2 levels suggested that we might conduct experiments designed to explore the impacts of the ongoing buildup of anthropogenic CO_2 on the growth rate, water use, and product quality of plants. But this vision faced obvious problems. As the 500 or so species of plants in Biosphere 2 had been transplanted into a new regime of light, nutrients, temperature, and water, no true control or natural analogs existed. Further, all the biomes shared one air mass. Even the pH of the ocean tracked the ever-changing CO_2 content of Biosphere 2 air. Ranging up to 4000 ppm in the winter and down to 1000 ppm during the summer, the O_2 in Biosphere 2 also underwent 400 ppm diurnal cycles.

Realizing that the transformation of Biosphere 2 into a meaningful scientific apparatus raised complicated issues, Bruno and I decided to solicit white papers from

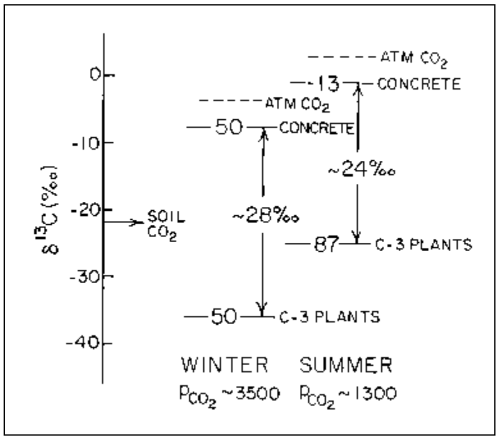

Figure 3. Cycle of carbon isotopes in sealed Biosphere 2. Since the CO_2 produced in Biosphere 2 resides in its atmosphere for only a few days before being removed by the plants or concrete, the ^{13}C budget must also be balanced on this time scale. As shown, the much greater importance of the concrete route during winter than during summer months gives rise to a large seasonal cycle in the $\delta^{13}C$ for the Biosphere's atmospheric CO_2 and hence also its plant matter.

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prominent scientists knowledgeable about aspects of problems that might be explored at the Biosphere. The writers convened at the Biosphere in mid-December 1994. While I found this get-together inspiring, I was disappointed that we didn't come away with any crisp plan. Rather, somewhat by default it was agreed that we spend the following year trying to understand more about how the Biosphere operated and carefully documenting its biota and soils. It was not that we didn't receive good suggestions, but that those we did receive did not provide a clear route by which we could overcome the limitations imposed on us by the design of the Biosphere.

So we entered 1995 without a clear mission. Fortunately, a man with a mission soon emerged. I first became aware of Guanghui Lin at the working sessions of the December white-paper meeting. Bruno had hired Guanghui to work on problems in plant physiology. I didn't realize what a gem he was until during a phone conversation he pointed out that an idea I had for altering the night-time temperature in Biosphere 2 would interfere with his proposed experiment. I heard him through, but I went away a bit miffed. I soon realized, however, that Guanghui had indeed come up with a sound and interesting strategy for the use of Biosphere 2.

Guanghui's original idea eventually became known as the spring experiment. It began in late February 1995 and continued through May 1995. The idea was to use analyzers manufactured by LiCor to measure the rates of CO_2 uptake and H_2O loss from leaves of selected species of C3 and C4 plants from each of Biosphere 2's biomes. By creative use of the lungs and a blow-through fan system, the research team was able to drop the CO_2 content of Biosphere 2's air in progressive steps from its February closed-system value of 1800 ppm to 400 ppm. During each week-long step, Guanghui and his team carefully measured CO_2 fixation and H_2O transpiration rates for leaves of his selected plants. He also archived leaf tissue and sugar samples for subsequent stable isotope analyses. Guanghui had launched us on what we hope will prove to be a very successful line of research. As outlined below, a second and more extensive winter experiment was subsequently completed.

Finding a creative use for Biosphere 2's ocean proved to be a more demanding task. Constructed as the analog of an east-facing Caribbean reef, this Olympic-swimming-pool–sized water body has some serious drawbacks. Despite the deployment of an algae scrubber through which its water is processed once each 3.2 days, the water clarity remains marginal. Interception by the overlying glass and space frame and the afternoon shadowing by the cliff along its western shore results in woefully low light levels, down to 15% of the incoming radiation. The pumps that recirculate the water through the algae scrubber efficiently grind up those plankton that manage to sprout. Nitrate, ammonia, and phosphate are not measurable in the water column. While this near absence of nutrients is normal for coral lagoons, it prevents us from assessing the nutrient status of a benthic community. Air injectors push 1000 CFM of air through its waters, creating such a high gas-exchange rate that its CO_2 content (and hence pH and $CO_3^=$) slavishly follows that for the overlying atmosphere. While many of the corals remain alive, they must by any measure be in a poor state of health. Rather, the red algae, *Amphiroa*, thrives with such rapid growth rates that divers must periodically harvest it in order to prevent a complete takeover.

Clearly our first task was to revamp this monster. The air-injection system has been replaced with a water-recirculation system. The algae scrubber will be turned off, and we hope that its cleansing action will be replaced by that of a healthy planktonic ecosystem. New corals will be transplanted into small areas where the light will be artificially enhanced. Thanks to the efforts of Lamont's Taro Takahashi and Chris Langdon, we have the capability to precisely monitor pCO_2 and pO_2 in the ocean. We also have access to Taro's lab for the measurement of ΣCO_2 (to ±1 μmol/kg) as well as to isotope dilution techniques for high-precision measurement of water-column Ca, Mg, Sr, and U. Taro, Chris, and their troops have already shown that diurnal changes in O_2, ΣCO_2, and alkalinity can be precisely determined.

At a planning meeting held at Lamont in the summer of 1995, it was decided that our goal would be studies of coral growth and chemistry as a function of $CO_3^=$ ion content. Through chemical additions in the absence of the air-injection system, we could decouple the ocean's pCO_2 from that in the air and thereby maintain the $CO_3^=$ concentration at any desired level. By mounting "tracer" corals on base plates, we can deploy benthic chambers to compare their carbon fixation and $CaCO_3$ deposition to that for the entire Biosphere ocean (as tracked by water-chemistry changes). We can also study how the Sr to Ca, U to Ca, ^{13}C to ^{12}C, ^{11}B to ^{10}B, etc. ratios change with the ocean's acidity and other environmental variables.

Before we proceed with any such program, however, we must assess the state of health of the resident corals. Fortunately, everything grown in Biosphere 2 carries a very strong carbon isotope signature. Upon closure of Biosphere 2, the $\delta^{13}C$ of its air was offset to a new value, which averaged 5‰ more negative than that for outside air. With the passage of seasons, it has swung back and forth through an annual cycle of about 5‰. Briefly, the cause of the offset and annual cycle (Fig. 2) has to do with the split of CO_2 removal between photosynthesis on one hand and concrete uptake on the other. The former, dominated by C3 plants, exhibits a 20‰ or so preference for isotopically light CO_2. The latter exhibits the 4‰ difference between the diffusion rates of $^{12}CO_2$ and $^{13}CO_2$. Hence, during summer when photosynthesis dominates, the $^{13}C/^{12}C$ ratio of the photosynthate is close to that in respiration CO_2 (i.e., – 22‰). During winter, when CO_2 removal by the two processes is closer to equal, the $\delta^{13}C$ for C3 plant matter is more negative. Because with the air-injection system operating the isotopic exchange time between ocean carbon and atmosphere carbon was on the order of two weeks, any $CaCO_3$ precipitated in the ocean must bear the ^{13}C signature of the overlying atmospheric CO_2.

Despite these strides toward harnessing both the terrestrial and ocean systems for research, the basic problem remained. Did these short-term experiments offer any insight into the consequences of the ongoing buildup of CO_2 in Earth's atmosphere? While sequenced changes in the CO_2 content of Biosphere 2 air provided a way to at least partially compensate for the absence of a true control, such experiments provide only information on how a given species responds to short-term changes in CO_2 content of the air in which it grows. Many plant physiologists and most ecologists would consider such experiments to yield a misleading guide to the long-term impacts of fossil fuel–induced rise in our atmosphere's CO_2 content. Realizing this, we decided early on that we must also find a way to conduct long-term experiments. I initially thought in terms of building a separate set of identical greenhouses on the Biosphere 2 site. Each would operate at a different CO_2 content. It didn't take long to realize that this was impractical, for it would blow the budget. During the December 1994 white paper meeting, Bruce Kimball of the U.S. Department of Agriculture suggested that the agricultural biome lent itself to separation into three separate sections that could be operated at different CO_2 levels. Although this was a very appealing idea, it was clear that Ed Bass, Biosphere 2's patron, did not look with favor on dividing up his glass house into many independent compartments; so our thinking was stalled for several months.

About the time our spring experiment was completed, rumors began to spread that Columbia's Mike Crow and Biosphere's Steve Bannon had been working behind the scenes to create an arrangement under which Columbia would assume management of the Biosphere campus. By July 1995, it became clear that such an arrangement was likely to come about. It was also clear that under the auspices of this arrangement Columbia would be allowed to make reversible structural changes to the Biosphere, so we decided to use Kimball's idea. In fact, an even more sweeping plan was put into place. The Biosphere would be divided into three quite separate parts. The wilderness (including the ocean) would be completely isolated from the agricultural area. The former would be used for time-sequenced experiments, and the latter, following the Kimball plan, would be used for long-term experiments at three different CO_2 levels. Finally, the habitat section of the Biosphere would be isolated from both the agricultural biome and the wilderness sections. It would be converted in part to a museum and in part to research space and run at ambient conditions. These "reversible" renovations are now in progress. A big question remains, however: What plants shall we grow in the tripartite agricultural area?

BIOSPHERE 2 AS A SCIENTIFIC LABORATORY

As I was writing this article (February 1996), a plan for use of the Biosphere as a research facility had begun to crystallize. The agricultural section would be used for long-term experiments carried out at controlled CO_2 levels. Each of its three newly isolated compartments would be ventilated during hours of darkness with outside air, and during daytime, they would be ventilated with enriched CO_2 air maintained in the Biosphere's south lung (stocked with CO_2-generating peat), so as to maintain the desired average CO_2 level and to minimize the diurnal swings. The wilderness area would be run in a time-sequenced fashion, varying both air temperature and CO_2 content. Through chemical additions, the ocean would be programmed through its own sequence of CO_2 (and hence also $CO_3^=$ concentrations).

So far, surprisingly enough, I've mentioned the word isotope only in a couple of paragraphs. As both Bruno and I are isotope geochemists, this might appear a bit odd. But be assured that, indeed, isotopic measurements will play a big role in the research program at Biosphere 2. In Bruno's research lab reside two isotope ratio machines, giving him the capability to measure the isotope ratios of carbon, nitrogen, oxygen, and hydrogen. As already mentioned, the carbon isotope ratio in Biosphere 2 air changes with season. It also undergoes a large diurnal cycle (~6‰). Five hundred or so plants draw their carbon from this isotopically variable supply, each one fractionating in accord with its own rules. The original $^{13}C/^{12}C$ ratio in the carbon of Biosphere 2 soils (~ – 22‰) sets the mean. Concrete and C4 plants fractionate by only a few per mil, while C3 plants produce a much larger separation which depends on CO_2 content of the air and probably a host of other environmental parameters whose values we can set. Clearly, Biosphere 2 is an ideal place to try to learn the rules governing these fractionations. We plan to exploit this potential.

The isotopes of water are also of interest. Currently, water is recycled within the Biosphere. In order to simplify isotopic bookkeeping, we have plans to convert the Biosphere to a one-pass system where all the rain and mist are supplied from a single reservoir of well water (desalted by reverse osmosis). We collect, sample, and then discharge to the outside the condensate created by the humidity control system (and by periodic condensation on the glass walls). We also collect, sample, and then discharge to the outside the water that drains through the soils. The difference between the isotopic composition of these two sinks will provide an index of the importance of evaporation from the soil surface (fractionating) and transpiration through the plants (nonfractionating). Of course, we can also explore the factors influencing the isotopic composition of the hydrogen and oxygen bound into organic matter.

Bruno plans to explore the cycles of N_2O and other trace gases. Because no UV light penetrates the glass ceiling, no photodissociation occurs in its atmosphere. Hence, the environment in Biosphere 2 offers insights into the production and destruction mechanisms in soil for these gases and, in the case of N_2O, also a means to explore what influences the isotopic composition of both the N and O in this gas.

The list of interesting isotopic studies is long. How much respiration CO_2 leaving the soil comes from the original soil organic ($\delta^{13}C = -22$‰) and how much from the C3 vegetation grown on that particular plot? What controls the $\delta^{18}O$ in Biosphere 2's CO_2?

Our small research group at the Biosphere can't possibly exploit this vast array of possibilities. Rather, we are reaching out to scientists at other institutions to join in our effort. So far, we have courted plant physiologist Joe Berry, Carnegie Institution; coral specialist Marlin Atkinson, University of Hawaii; and agriculturist Bruce Kimball, U.S. Department of Agriculture. We hope that still others will seek us out. Only if we can build cooperative efforts involving high-profile people at leading institutions (and also their students and postdocs) is there a chance that we can reach our goal of establishing the Biosphere 2 campus as a world-recognized center for biotic research.

Running parallel with our research program will be efforts to create a first-class educational program. It will range from on-site courses for students and teachers to a first-rate visitors center portraying issues related to our planet's future, and to an educational outreach program taking full advantage of the rapidly burgeoning global computer network.

Finally, a few words about our patron, Ed Bass. I find him to be a remarkable man, totally dedicated to the preservation of our planet's wildlife. During a period when competition for government support is more intense than at any time since World War II, Ed has taken it upon himself to bankroll the launch of this effort. I personally feel an enormous sense of obligation to make good on my promise to him to do everything possible to make a success of this remarkable opportunity.

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