AN EVALUATION OF THE BIOSPHERE 2 CENTER AS A NATIONAL SCIENTIFIC USER FACILITY

U.S. Department of Energy
Biological and Environmental Research
Advisory Committee

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EXECUTIVE SUMMARY

Biosphere 2 is a $150 million glass-enclosed environmental mesocosm that includes a number of synthetic terrestrial biomes as well as a tropical ocean biome. Since 1996, Columbia University has managed the facility for research and education purposes. Columbia University recently approached DOE about providing funds to operate the Biosphere 2 Center (B2C) as a national scientific user facility for experimental climate change science.

The Global Change Subcommittee of the Department of Energy (DOE) Biological and Environmental Research Advisory Committee was asked "…to provide its collective comments and perspective on the potential of B2C as a user facility…" A review team was formed that included five members of the Global Change Subcommittee and three additional individuals with expertise in disciplines relevant to the evaluation but not represented on the Subcommittee.

For its evaluation, the review team was asked to answer the following questions:

1. What are the potential values and uses of the Biosphere as a user facility for research relevant to the DOE mission, and what are its scientific and operational limitations as a user facility?
2. Would investing in the core maintenance and operation of B2C at the present time be timely and appropriate for DOE and the Biological and Environmental Research division (BER)? If not, is there a need for further, fully independent assessment of the potential uses, limitations, and strengths of B2C compared to other facilities, either in existence or that could be constructed?
3. How might BER seek independent input on the relevance, limitation, potential uses, and value of B2C from members of the scientific community conducting research in topical areas that would require a major facility such as B2C?
4. If DOE should consider providing core operating funds for B2C, what factors should DOE consider about timing, level, and sources of investment in operating funds for the B2C?

The review team conducted its evaluation by conducting a site visit and by evaluating documents provided to the team by officials of B2C.

In its response to the question #1, the review team identified both unique capabilities and important limitations of B2C. Perhaps the key advantage of B2C is the opportunity to study relatively large vegetation assemblages and an ocean biome under highly controlled conditions. No other facility provides the capability of controlling temperature, precipitation, and atmospheric composition in such large environmental chambers. This makes it possible to conduct long-term, multidisciplinary investigations of ecosystem responses to climate change. A crucial feature is the potential to determine all fluxes and pools (i.e., close the budgets) for carbon, nitrogen, and other nutrients, as well as other compounds of interest.

The facility also suffers from numerous limitations that result primarily from the fact that it was not originally constructed as a scientific research facility. The fundamental limitation of B2C is that the "natural" biomes exist as single units, meaning that treatments or replicates have to be performed sequentially in time rather than simultaneously in space. A second major limitation is the biomes are highly artificial, with assemblages of species that do not exist together naturally. Moreover, certain critical biotic components of ecosystems (e.g., soil, flora and fauna) are highly impoverished relative to natural systems. These features make it difficult to extrapolate results to the real world. A related concern is that the soils are highly artificial, and severe soil disturbance occurs whenever new soils are introduced. The large-stature synthetic ecosystems that constitute a key advantage of B2C also suffer from an inherent limitation for time series analyses in that the systems may still be responding to a prior treatment when a new experiment is initiated. Such lag effects may hopelessly confound treatment effects.

The responses of the review team to questions 2 through 4 are summarized in five recommendations:

RECOMMENDATON 1: BER should not fund the operation of B2C at this time.

RECOMMENDATION 2: BER should not conduct any further investigations or assessments of B2C at this time.

RECOMMENDATION 3: Any further consideration by DOE/BER of funding for B2C should be done through an open, competitive RFP process through which other proposals for ecosystem research facilities are solicited and the strengths and weakness of B2C can be compared with those of alternative types of facilities.

RECOMMENDATION 4: Any future funding for the operation and maintenance of B2C should not be taken from the current research budget at BER.

RECOMMENDATION 5: Any further consideration by DOE/BER (or a broader consortium of agencies) to provide support for the operational costs of B2C should be conditional on obtaining new funding specifically targeted for national user facilities for research on ecosystems and global change.

BACKGROUND

Biosphere 2 is a $150 million glass-enclosed environmental mesocosm that includes a number of synthetic terrestrial biomes as well as a tropical ocean biome. The total surface area enclosed is approximately 6200 m^2. Biosphere 2 was constructed in the late 1980s as a demonstration project to determine whether a small number of humans could sustain themselves in a sealed, energy-rich environment. In 1996 when the human sustainability demonstration project was terminated, Columbia University signed a management agreement with the owner of Biosphere 2 Center (B2C) to manage the facility for research and education purposes. Columbia University recently approached DOE about providing funds to operate B2C as a national scientific user facility for experimental climate change science.

The Global Change Subcommittee of the Department of Energy's (DOE) Biological and Environmental Research Advisory Committee was charged with assessing the potential of B2C as a user facility. The review team that prepared this evaluation included five members of the BERAC Global Change Subcommittee, as well as three additional individuals with expertise in areas pertinent to the review but not well represented on the Global Change Subcommittee (see Appendix A for list of review team members). Six members of the review team visited B2C on January 7, 2003. Those six plus two additional members met at the National Center for Atmospheric Research in Boulder on January 8 and 9 to discuss the site visit and draft this report.

In addition to conducting a site visit at B2C, the review team was asked to utilize a report of a workshop held at B2C in late 2001 as a source of information on the potential value and limitations of the facility. The workshop was funded by DOE/BER and had a goal of evaluating the feasibility and potential of B2C as a national user facility for earth system research relevant to the mission of DOE.

The review team was asked "…to provide its collective comments and perspective on the potential of Biosphere 2 Center as a user facility…" Specifically, the review team was asked to address the following questions:

1. What are the potential values and uses of the Biosphere as a user facility for research relevant to the DOE mission, and what are its scientific and operational limitations?
2. Would investing in the core maintenance and operation of B2C at the present time be timely and appropriate for DOE/BER? If not, is there a need for further, fully independent assessment of the potential uses, limitations, and strengths of B2C compared to other facilities, either in existence or that could be constructed?
3. How might BER seek independent input on the relevance, limitation, potential uses, and value of B2C from members of the scientific community conducting research in topical areas that would require a major facility such as B2C?
4. If DOE should consider providing core operating funds for B2C, what factors should DOE consider about timing, level, and sources of investment in operating funds for the B2C?

A BRIEF HISTORY OF THE BIOSPHERE 2 SITE

Biosphere 2 Center is located in high-desert country in a rural region of southern Pinal County, 20 miles north of the city limits of Tucson, Arizona. The developed campus covers 250 acres at an elevation of 3,900 feet in the foothills of the Santa Catalina Mountains. Prior to the construction of Biosphere 2, the property was operated as a ranch. In 1969 it was purchased by the Motorola Corporation and used as a management training institute. Motorola constructed the guest suites (now the Biosphere 2 Hotel), meeting rooms and dining rooms. After ten years Motorola donated the property to the University of Arizona Foundation, which used the property for corporate and education retreats until the Foundation sold the property to the founders of Biosphere 2, Space Biosphere Ventures, Inc., in 1984.

The next ten years were devoted to the design, construction and initial experimental phases of the Biosphere 2 project. The early goals of the project were to design an enclosed facility that could be used by humans to live on other planets, and to demonstrate the inter-connectedness of humans and the environment (Allen 1991). Construction of the main apparatus began in January 1987 and was concluded in September 1991. Total construction costs were on the order of $150 million. The enormous greenhouse enclosed a number of synthetic “wilderness” biomes including a tropical rainforest, desert, and ocean, complete with coral reef. It also included a large agricultural biome where food was raised, as well as living quarters for the “Biospherians”.

Walford (2002) has recently reviewed the first mission (September 1991 to September 1993) in which four men and four women lived inside the totally sealed, but energy rich environment of Biosphere 2 growing all their food and recycling all their air, water and wastes. The experiment was a success in engineering terms but a failure as a sustainable planetary ecosystem analog.

The tightly closed structure (which has a leak rate of less than 10 percent per year) was furnished with an extremely rich organic soil. The soil supported rapid growth of the synthetic ecosystems and crops in Biosphere 2 with rice yields as good as the world’s best. However, the rich soil was the major factor in causing the experiment to become unsustainable. Soil respiration was so high, and soil reserves of carbon were so great, that the atmospheric composition changed rapidly. Oxygen was absorbed from the air by soil microbes, and these released huge amounts of CO_2 from the soil back to the air. The buildup of CO_2 exceeded the photosynthetic capacity of plants to assimilate it and to regenerate O_2. While some of the excess CO_2 was absorbed by the fresh, unsealed concrete of the structure, forming limestone, the CO_2 concentration remained elevated above desired levels. More importantly, O_2 levels continued to decline rapidly, and additional O_2 had to be added to enable the eight human occupants to survive. A second shorter experiment with humans was conducted in 1993-94.

Following these experiments, in April 1994 the project owner, Edward P. Bass, brought in a new management team to restructure the organization and refocus the mission towards research. He invited scientists at Columbia University for advice on what might be done. This advisory role led to an acceptance by Columbia of full responsibility for the conduct of research, education, and public outreach activities on the site. On January 1, 1996, Columbia University joined

Biosphere 2 to expand and guide its programs, and the facility became the Biosphere 2 Center (B2C). Under the aegis of the Columbia Earth Institute, new educational, research and visitor programs were established. The initial 5-year management contract with Columbia was renewed in 2001 and now extends through 2010. In 2005, Bass's obligation to share in the costs of operating B2C will end, and the cost to Columbia presumably will increase accordingly.

In order to make the facility more suitable for scientific research, Columbia supported a 3-year, $3 million retrofit. Polyvinyl-chloride curtains now isolate the rainforest, ocean, and desert biomes, allowing scientists to control environmental conditions and monitor gas and water fluxes for each unit. Similar curtains were installed in the agricultural biome so that it now is divided into three separate large chambers, which are now being used to evaluate the responses of cottonwoods to elevated CO_2 (400, 800, and 1200 ppm CO_2). New environmental control and monitoring equipment was installed to support this type of experimentation. There have been several recent reports of the new mission of B2C in the scientific press (Bunk 2001; Parasi 2001, Cohn 2002).

Figure 1. Polyvinyl-chloride curtain separating two biomes.

During the site visit, the review team learned of recent developments at B2C that were germane to the team's charge. Officials of Columbia University, which is under contract to manage the site until at least 2005, have re-evaluated their commitment to B2C. While the full implication of this decision is not yet clear, the level of commitment has been reduced substantially. In particular, plans have been cancelled to hire six new senior faculty members to be located at B2C. These recent developments did not influence the deliberations of the review team except insofar as how they could potentially affect the ability of the B2C scientific team to prepare a compelling vision and proposal for the future use of Biosphere 2 as a national user facility.

ANALYSIS AND RECOMMENDATIONS

Before visiting B2C the review team requested from the President of B2C written information on major scientific achievements, research priorities for the next five years, and details of operating costs, as well as lists of past and current research grants, and of publications resulting from work at B2C. The table below is taken from that document and provides information on the projected costs for operating and maintaining the research facility at B2C over the next 15 years. Costs that are included in the table are those that the B2C officials believe are legitimate operating costs. For instance, they believe that the budget should include funds for on-site teams of junior-level researchers who oversee ongoing research for off-site investigators. Columbia and B2C are seeking assistance from DOE/BER in covering all or part of the operating costs.

Table 1. Projected costs (in thousands of dollars) of operating and maintaining the research facility at B2C (figures provided by B2C).

Costs for operating, maintenance, and renovation **	**2003**	**2004**	**2005**	**2006**	**2007**	***2012****	***2017****
Operations, facilities, engineering and instrumentation***	1,845	2,048	2,301	2,595	2,835	*3,139*	*3,638*
Utilities	1,058	1,071	1,083	1,175	1,197	*1,391*	*1,605*
Capital maintenance	511	368	339	580	602	*408*	*464*
Renovations****	711	607	1,909	210	212	*259*	*309*
Total facility operations	4,125	4,094	5,632	4,560	4,844	*5,197*	*6,016*
Research, technical, administration*****	1,032	1,175	1,262	1,437	1,677	*1,873*	*2,130*
Total B2C operating costs	**$5,157**	**$5,269**	**$6,894**	**$5,997**	**$6,521**	*$7,070*	*$8,146*

* Simple extrapolations of 2007 using an annual escalator.

** Includes all operating costs associated with maintaining the glass-enclosed research facility as an engineering system; not included are costs associated with the education program, hotel, grounds, etc..

*** A crew of 30 is required to keep the facility operating and maintained 24/7/365. The crew operates the energy center and maintains all the engineering systems associated with the operations of the facility.

**** Includes once-only renovations planned 2002-5, with renovation contingency 2006-

***** Includes technical and instrumental support for research programs in B2C as a whole, plus biological teams in each of the ocean, rainforest and plantation forestry biomes (usually one PhD and two technicians) to supervise and conduct research programs for off-site scientists. Because of the complexity of the facility and the instrumentation, and because multiple simultaneously conducted experiments must be coordinated with minimum human impact, this type of support cannot be brought to the facility by each independent research team.

In preparing its report, the review team relied primarily on the aforementioned documentation provided by B2C, as well as the presentations and discussions at the site visit. The review team did not make use of the 2001 B2C workshop report because the information in that report was deemed too general. In addition, on checking the review team found that several individuals who attended the workshop felt that the report did not accurately reflect the discussions at the workshop, especially on the issue of limitations of the facility.

Question #1. What are the potential value and uses of Biosphere 2 as a user facility for research relevant to DOE's mission and what are its scientific and operational limitations?

Potential Value and Uses

A number of features of the facility are unusual or unique in terms of its potential for conducting research on the responses of ecosystems to global change. These include:

Long-term experiments on large stature vegetation. A key feature of B2C is the opportunity to study relatively large vegetation assemblages (or ecosystems) under highly controlled conditions. The vegetation can be larger and older than in other mesocosms, avoiding artificial root crowding and similar artifacts that plague studies in greenhouses and other controlled environment facilities. The size of the B2C mesocosms is sufficient to allow studies of longer-term processes, an especially valuable attribute for examining carbon cycle issues. In B2C, it would be possible, in principle, to design studies that covering various time scales, including decomposition and growth dynamics normally out of reach for mesocosm studies. In order to take advantage of this essential feature of B2C, long-term experiments would have to be planned that, in general, exclude shorter-term and replicated-in-time (e.g., pulse-response) manipulations.

Addressing broad questions with interdisciplinary research teams. B2C has the potential to draw researchers from a wide range of disciplines in earth science. To date, researchers representing such fields as physics, ecophysiology, remote sensing, natural products chemistry, and behavioral ecology are involved in B2C projects, ranging from major personnel and facility commitments to relatively minor, more "opportunistic-type" projects (see below). While current projects do not comprise an integrated whole (i.e., address a single overarching question), there exists untapped potential in B2C to form such a multi-investigator, multidisciplinary project.

Scale-related measurements and modeling. Few ecological projects are designed to simultaneously measure, at different scales over long periods of time, key parameters and processes related to a single question. The most important and unique feature of B2C is the capacity to study relatively large, enclosed synthetic ecosystems or biomes. B2C is the only facility in which it is possible to control atmospheric CO_2, temperature, and precipitation simultaneously for large-stature vegetation. In addition, because the biomes enclose relatively large assemblages of plants, including trees, it is possible to explore scale-related relationships from the leaf to the canopy. These two features are crucial in allowing investigators to develop bottom-up or mechanistic models and test them against top-down measurements. Studies of the combined effects of changes in temperature and CO_2 on agroecosystems are possible in B2C, although with only three chambers, the number of treatments that can be imposed simultaneously is limited.

Figure 2. Cottonwood trees growing in one of the three chambers of the agricultural biome.

Replication of other types of treatments, such as nitrogen fertilization, is possible within individual biomes. While replication of CO_2 or temperature treatments is not possible, the sizes of the enclosed biomes still make it possible to undertake truly unique and important investigations of interactions of multiple factors at the ecosystem level.

Closing the mass budget. One of the principal advantages of any mesocosm is the capability to close the mass budgets for compounds or elements exchanged between the atmosphere, vegetation, and soils. The unique feature of B2C is the large size of the mesocosms, presenting opportunities to close the mass budget for large-stature vegetation. The facility is suitable for investigations of:

- Budgets of carbon, nitrogen and other nutrients
- Isotope budgets
- Budgets of trace gases
- Budgets of contaminants

Recent work at B2C has examined all of these issues. For example, studies of reactive trace gases emitted from trees have provided data on chemical species that are too labile to be studied effectively in the field. This work was facilitated by another feature of B2C, the exclusion of ultraviolet radiation (UV), which allows reactive compounds to survive much longer than they would in the field. There was some discussion during the review about the possibility of closing the nitrogen budget in a real sense. Specifically, it may be possible to measure N_2 loss via denitrification in such a facility using ^{15}N tracers. This has been done in the past using very small microcosms and also with chambers on the soil in a field setting. Each of these techniques has problems: the microcosm is too small to be realistic and the field flux chambers invariably introduce artifacts (e.g., changes in moisture, temperature, windspeed) into the measurement of gas flux from the soil. While as yet untested, the B2C facility offers an intermediate scale of measurement, which may be the most realistic approach for closing the N budget. Measurement of such fluxes on the scale of the biomes at B2C would likely introduce few artifacts.

Figure 3. Ocean biome with coral reef.

Coral reef ecology. The coral reef biome provides capabilities similar to those of the terrestrial biomes in terms of controlling environmental drivers and closing budgets. In this biome scientists have investigated the effects of chemical additions that change the calcium carbonate saturation state of seawater on the calcification of particular reef biota. Such experiments may well provide insights into the possible influence of climatic and/or atmospheric changes (e.g., increasing CO_2 concentration) on important marine organisms, such as corals. It is possible in this artificial system to control carbon chemistry, temperature, and light available to the reef organisms and evaluate associated levels of calcification, production, and growth.

Although experiments cannot be simultaneously replicated, it has been possible to periodically impose a change in water chemistry and observe whether the same effect is repeated. Publications resulting from this work illustrate that these experiments have been logically planned and carried out, and have been corroborated by corresponding laboratory and field observations. There is clearly potential for furthering the understanding of the influence of calcium carbonate saturation state in seawater on reef organisms, as well as possibly addressing the exchange of carbon between the atmospheric and water phases.

Serendipitous opportunities for research. Because of its large size, diversity of biomes, and highly controlled environmental conditions, B2C does provide some unforeseen and unusual opportunities to researchers from an array of disciplines. Several examples were described to the review team during the site visit. For instance, the arrangement of air ducts results in some parts of the biomes experiencing constant directional "winds". One group of researchers has taken advantage of these conditions to understand the flight responses of moths to chemical cues produced by plants and their role in location of specific plant types by moths.

Inherent Scientific and Operational Limitations

Biosphere 2 was not constructed to be a facility for experimental research on ecosystems. Consequently, and not surprisingly, it has a significant number of limitations when used for such a purpose. The following list highlights the more important limitations.

Sample size of one. A fundamental limitation of B2C is that the "natural" biomes exist as single units, meaning that treatments or replicates have to be performed sequentially in time rather than simultaneously. The agricultural biome is divided into three chambers, but these are not identical in terms of light regimes and edge effects and also do not allow replication. These aspects of B2C make it impossible to take full advantage of the size and environmental control features of the facility, because they limit the statistical power of any experiments and confound treatment effects with other causes of variation. While this is a serious limitation, it should be noted that an analogy can be drawn to watershed studies, which also suffer from minimal or no replication. Long-term studies from watersheds such as Hubbard Brook, Coweeta, Walker Branch, and H.J. Andrews have unquestionably shown the value of such studies despite the lack of traditional statistical replication, and time-series analyses from these sites are readily accepted by the scientific community. AmeriFlux and FACE facilities also suffer from limitations on replication and the number of treatments.

Figure 4. Rainforest biome.

Artificiality of B2C biomes: The B2C team expressed a vision of using the facility as an experimental tool to study ecosystem processes in response to climate change. Although the facility clearly has potential for further studies of material budgets and for scaling from leaf to canopy, the artificiality of the biomes places limitations on B2C's use as an experimental ecosystem tool. For example, the plant species composition and diversity of the tropical biome is not representative of any naturally occurring tropical forest, making it difficult to explicitly extrapolate ecosystem scale results to any natural system. Additionally, the biomes have relatively extreme artificiality with respect to their consumer communities. The artificiality ranges from absence of any semblance of a complete food web due to the lack of a complement of natural consumers (insects, mammals, earthworms, etc.) to the presence of unnatural numbers of particular species of consumers that have flourished in the greenhouse environments. Some specific examples include: (1) Leaf cutting ants are known to be critical in the energy flow and material cycling in tropical forests, but are absent in that biome; (2) spider mite populations are orders of magnitude larger in the Agricultural biome than they would be in a natural cottonwood community, while other consumers of cottonwood, such as leaf beetles are largely absent; (3) ants and other soil fauna are known to play a critical role in nutrient cycling, but all the terrestrial biomes are dominated by one exotic ant species that was able to survive while almost 20 other ant species originally placed in the biomes did not persist; (4) the absences of mammalian consumers will make it difficult to test ecosystem level models of food webs, biodiversity, nutrient cycling, and energy flow in several biomes, e.g., kangaroo rats are known to be keystone species controlling species composition, energy flow and nutrient cycling in Southwestern US desert ecosystems.

Any mesocosm facility will have similar problems because of the need to assemble artificial suites of organisms, but the large scale of Biosphere 2 makes some of these problems more difficult to control or to quantify than would be the case in smaller facilities. While there is no question that tests of specific hypotheses regarding some ecosystem processes (particularly net ecosystem production) are very well suited for B2C, it nonetheless is important to recognize the constraints imposed by the artificiality of the biomes. The review team also recognized that herein lies a paradox: it is the very complexity of the natural world, where most conditions are outside the control of the experimenter, which makes model systems such as B2C so attractive. Controlled environment facilities provide a model or analog of the real world, both biological and abiotic, which can help fill the gap between complex field ecosystems and the simplicity of laboratory or greenhouse experiments. It is important to acknowledge that facilities like B2C are not intended to mimic the full complexity of nature; rather, they provide analogue models of ecological communities by including many but not all of the biological processes and interactions that occur in the field.

Soil Disturbance. One of the biggest limitations of the Biosphere 2 facility is the presence of highly artificial soils. Furthermore, the impact of disturbance whenever new soils are introduced results in large changes in physical structure of the soil (aggregation, peds, natural pores and cracks, horizon formation, fragipans and duripans) that develop over thousands of years in nature and simply cannot be reconstituted. Such changes in soil structure cause very large effects on soil hydrologic processes, including infiltration rates, water-holding capacity, and the relative importance of macro- and micro-pore flow (saturated and unsaturated flow). Perhaps more important, it is also well-known that such disturbances cause large increases in soil organic matter decomposition, which can cause a pulse of CO_2 and nitrogen release for up to several years. This is essentially the plowing effect, wherein wildland soils converted to agriculture typically lose 40 percent of their organic matter and nitrogen over time. This was the major reason that the first "human experiment" failed in B2C. Although the release of CO_2 and nitrogen attenuates with time, this phenomenon still causes concern in experiments conducted over the sorts of time periods for which B2C is most appropriate. For example, if a "control" period occurs during the peak of CO_2 and nitrogen release and the subsequent treatment period occurs after this peak has attenuated, then the treatment effects on parameters such as net ecosystem carbon accumulation will be hopelessly confounded with the counteracting effects of CO_2 and N release from soils. In other words, the carbon balance would initially be artificially negative, resulting in N release. This in turn could have a fertilization effect on plants and then result in the carbon balance becoming artificially positive. In smaller scale pot or mesocosm studies, these problems are overcome with the use of intact soil monoliths or with replication and the existence of untreated controls, or both. However, these approaches are not possible in Biosphere 2 at the scale of entire biomes. B2C is, in essence, a very large, complicated, uncontrolled, and un-replicated pot study from a soils point of view.

Spatial heterogeneity of biomes. Because all the biomes except the agricultural biome originally were designed to simulate natural ecosystems, they include substantial spatial heterogeneity. For example, the desert biome includes topographic variation (e.g., upland and lowland) and at least two distinct soil types. While this provides more realistic environmental conditions, it precludes easily subdividing the biomes to allow experimenters to impose different treatments simultaneously. Additional heterogeneity is imposed by the glass structure such that light conditions vary spatially. Finally, because the air ducts and other aspects of the engineering were not constructed in a manner that would enable the large biomes to be sub-divided into independently controllable units, it would be prohibitively expensive to re-engineer most parts of the facility in this way.

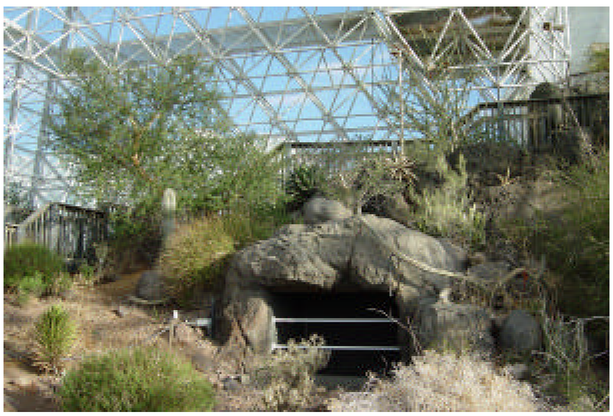

Figure 5. Desert biome showing some of the spatial heterogeneity.

Litter decomposition. The readily observable accumulation of litter on the forest floor of the tropical ecosystem clearly indicates that litter decomposition is impaired in some fashion. One likely cause is the lack of native organisms (such as macroinvertebrates) that play an important role in decomposition in native tropical forests. This unnatural litter accumulation poses obvious problems with any experiments dealing with ecosystem carbon accumulation and limits extrapolation of results to the real world.

The memory effect. As noted earlier, since biomes in B2C are not replicated, experimental treatments must be performed sequentially in time, one following the other. This may introduce serious lag or ‘memory’ effects. Effects of treatments on vegetation and soils, while sometimes subtle because of the large pool sizes and buffering power involved, are not readily reversed. It also may take long periods – longer than scientists can wait – for the systems to equilibrate after a new treatment is imposed. This poses a potential problem for time series analyses in that the systems may still be responding to a prior treatment when a new experiment is initiated. Such lag effects may hopelessly confound treatment effects.

Mass-balance studies. While a key advantage of B2C is the capacity to do mass balance studies and close element and energy budgets for relatively large artificial ecosystems, there are some limitations. The large size introduces exchange terms (the system is not truly closed) and mensuration errors into the mass balance analysis. The absence of UV makes it difficult to ascertain the actual chemistry of photo-stimulated gaseous emissions, since UV light can play a role in the biophysical and biochemical processes.

Limited access: A dilemma. There appears to be a need to limit access of students, the public, and even researchers to B2C. The facility is most appropriate for long-term studies. Consequently, it is essential to limit disturbance to the ecosystems by researchers, students, and visitors. This situation places B2C on the horns of an intractable dilemma. Given the expense to operate the facility it would be desirable to maximize the number of users, yet the long duration experiments for which the facility is most suited necessarily limit its availability to many users.

Long-term maintenance issues. Biosphere-2 is a very large-scale engineered facility with huge embodied costs. The potential to harness these investments for research is a major advantage of B2C but the risks of major failures are a downside. There are risks that transient failure of the mechanical systems could compromise years of work. Although B2C was engineered with redundant systems for long service, there remains a finite risk that long-term experiments could be compromised by catastrophic equipment failures, and quite large expenditures might be required to respond to such problems. An agency or consortium supporting B2C long term should be prepared to accept this risk, and a comprehensive evaluation of the actual risks should be undertaken before making any commitment.

The motivation and requirements for manipulative ecosystem research at a large-scale facility. It is possible to advance compelling arguments for the importance of manipulative ecosystem research investigating the effects of climate change on ecosystem functioning at higher scales of complexity, and related issues. Many of the limitations of B2C derive from its development for other purposes, making it less than ideal for this kind of research. From the agency standpoint, it is a facility in search of questions, rather than a facility developed to address identified research needs.

Incomplete Baseline Information and Unexploited Opportunities

In addition to the inherent physical limitations of B2C, there are some important but surmountable shortcomings in terms of the lack of availability of critical data and information on the existing biomes. The absence of this information at the time of the review weakened the case made by the B2C staff for the value of the facility.

Soil data and information. Although verbal assurances were made that some soil analyses had been conducted and that soils were a strong consideration in the design and implementation of studies to date in the Biosphere 2 facility, there was no evidence of this in either the reports submitted to the committee or in the form of data sheets. Indeed, the verbal communications were conflicting; for example, the review team was told during the tour that soils in the cottonwood study (agricultural biome) had never been analyzed, whereas other investigators later mentioned that soils had been analyzed. While foliar analyses thus far show no nutritional problems, the lack of soil analyses combined with the fact that no fertilizer is added to these very rapidly growing plantations virtually insures that nutrient deficiencies will develop in an uncontrolled manner, be known only after the fact, and pose a threat to the integrity of these experiments.

It appeared that the soils in the desert biome had been severely compacted by the “bigfoot” effect (from investigators walking in the area), yet we were told that the desert soils have not been analyzed, nor have fundamental measurements such as bulk density been measured to compare with field data to see if the reconstructed soils bear any resemblance to those in the field. In sum, it appeared to the review team that the soils in B2C have not been addressed by the investigators involved.

Biogeochemical cycling studies. The existence of biogeochemical cycling studies in the terrestrial biomes of B2C was mentioned both in the report prepared for the review team and during the review. However, these statements seem to refer primarily to gaseous phase studies of very specific elements (largely C), and traditional biogeochemical cycling studies appear to be absent from the current research program. In some cases, simple opportunities have been overlooked, such as combining biomass with nutrient analysis data for the cottonwood studies to give measurements of plant uptake. Since the major advantage of the facility is its potential for measuring ecosystem fluxes and closing ecosystem budgets for various elements, biogeochemical studies are essential.

Question #2: *Would investing in the core maintenance and operation of B2C at the present time be timely and appropriate for DOE/BER? If not, is there a need for further, fully independent assessments of the potential uses, limitations and strengths of B2C compared to other facilities, either in existence or that could be constructed?*

The review team’s opinion is that there is not currently a compelling rationale for the investment of DOE/BER in the maintenance and operation of B2C. Such a compelling case would require a more clearly articulated vision of how B2C will meet critical needs of the global change community for ecosystem research facilities and will contribute to the mission of DOE/BER. Specific elements would include:

(1) *A strong, senior leadership team with expertise covering those disciplines that a) must be represented to fully exploit the potential of B2C and b) are relevant to DOE/BER’s mission.* At present, the leadership team for B2C has exceptional expertise in ecophysiology, but other critical disciplines, such as biogeochemistry, soil and microbial ecology, atmospheric science, community ecology, and ecosystem modeling are under- or not represented. A multidisciplinary team needs to develop a vision based on a whole-system, ecosystem perspective. A distinction must be made between scientists who are committed to working as part of a multidisciplinary team to utilize B2C to address important issues in global change research, vs. those that are utilizing B2C to pursue their personal, often unrelated, research interests. There may be a place for the latter, but a team that brings committed intellectual leadership is absolutely essential to build an integrated, multidisciplinary program. Such a team might have been assembled had Columbia University moved forward to fill a half dozen senior faculty lines associated with B2C.

(2) *A thoughtful analysis of the scientific niche for B2C with respect to other DOE/BER supported facilities such as FACE and AmeriFlux, and controlled environment facilities (currently supported by other agencies, e.g., NSF) such as the Phytotron or EcoCELLs.*

This type of analysis was missing from the written documents and oral presentations prepared for the site visit.

(3) *A well thought out process for how B2C will function as a user-facility*. A more clearly articulated plan is needed for how scientists will be able to access the facility, give input into the experimental designs within B2C, and provide feedback into whether B2C is meeting their needs as a user facility, as well as the financial incentives and costs for using B2C.

(4) *A demonstrated commitment to using any DOE/BER support as a mechanism to leverage other funds towards making B2C as self-sustainable as possible*. The B2C management must be more entrepreneurial in its effort to seek funds for operating the facility. The vision for B2C should include a plan, with specific milestones, for the proportion of operating costs that should be covered by F&A funds (overhead on research grants) and user fees, and plans for developing competitive research proposals to a broad array of funding sources interested in global change research.

(5) *A demonstrated commitment of B2C to seek outside funding in competitions aimed at large-scale interdisciplinary research.* There is no record at B2C of proposals being funded by, or even submitted to, several recent and current competitions (such as NSF's Biocomplexity, IRCEB, FIBR programs) that focus specifically on interdisciplinary studies of biological and ecological complexity. These programs are viewed by the review team as excellent examples of the types of research that B2C should be pursuing. Such a record of funding (or at least proposals) would have provided a more compelling case that the leadership team of B2C is truly committed to having the facility function as an interdisciplinary tool for understanding the complex biological responses to global change.

Several members of the review team were pessimistic that a compelling case for the support of B2C could ever be made. Other members felt that articulating a compelling rationale is a feasible, albeit challenging and difficult possibility.

The review team's response to Question #1 identified both potential strengths and a large array of limitations of B2C, many of which have been previously identified. The review team believes that it is not fruitful now to conduct further independent investigations or assessments of B2C, or of B2C's relationship to other facilities that exist or could be built. Any further investigation is unlikely to uncover new information that would result in substantively different conclusions or recommendations. Moreover, it should not be the responsibility of DOE to seek a justification for funding B2C. Rather, the staff of B2C needs to make a more compelling case that addresses the five elements identified above.

RECOMMENDATON 1: BER should not fund the operation of B2C at this time.

RECOMMENDATION 2: BER should not conduct any further investigations or assessments of B2C at this time.

Question #3: How might BER seek independent input on the relevance, limitations, potential uses and value of B2C from members of the scientific community conducting research in topical areas that would require a major facility such as B2C?

The review team believes that the best way to maximize and optimize input from the scientific community into decisions by DOE/BER on whether to support the operating costs (and construction, if necessary) of an ecosystem research facility such as B2C – if funding was available – would be through an open competition for any available funding. This presumably would involve issuing an RFP that articulates a need for a specific type of facility for global change research on ecosystems in the context of BER's needs or those of a broader consortium of federal agencies. All proposals would undergo rigorous peer review.

In this model, B2C certainly would have an advantage given that it already exists and has had several years to develop a mission and vision for the facility with respect to the needs of DOE/BER. Nonetheless, it is highly likely that DOE/BER would receive other innovative and potentially exciting ideas for how to integrate a mesocosm facility into DOE/BER's mission. This process would guarantee strong input from the scientific community through both the proposals and the peer review process. It also would ensure that DOE/BER could evaluate B2C with respect to other potential ideas that are generated within the scientific community. Finally, it would force B2C to produce a compelling case in a proposal for operational support of the facility.

RECOMMENDATION 3: Any further consideration by DOE/BER of funding for B2C should be done through an open, competitive RFP process through which other proposals for ecosystem research facilities are solicited and the strengths and weakness of B2C can be compared with those of alternative types of facilities.

Question #4. If DOE should consider providing core-operating funds for B2C, what factors should DOE consider about timing, level, and sources of investment in operating funds for the B2C?

The current DOE/BER environmental research program represents a suite of research and facilities that are essential contributors to the goals and objectives in climate and earth system science program of the U.S Hence, none of the existing funding for research programs should be diverted in order to support the core operations of B2C, or any other national user facility. There is no justification for phasing out any existing DOE research grant or program in order to support near-term core-operating infrastructure costs at the B2C.

New sources of funding for experimental facilities for climate, earth system, and ecosystem science research could accelerate our nation's goal of reducing uncertainties associated with the nature and potential impacts of climate system variability and change. DOE, either alone or in conjunction with other federal agencies, should initiate a discussion of options for funding additional experimental infrastructure for controlled ecosystem manipulations.

The emerging interagency climate change science program is based on the premise that the U.S. requires an accelerated research program to address key questions in the science, observations and decision support areas that will encourage a focus on the information needed to underpin public discussion of climate change issues. Experimental facilities for long-term controlled manipulation of complex ecological systems will be essential to this challenge. The DOE has the experience and expertise to be a major contributor to new national climate change research initiatives.

RECOMMENDATION 4: Any future funding for the operation and maintenance of B2C should not be taken from the current research budget at BER.

RECOMMENDATION 5: Any further consideration by DOE/BER (or a broader consortium of agencies) to provide support for the operational costs of B2C should be conditional on obtaining new funding specifically targeted for national user facilities for research on ecosystems and global change.

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APPENDIX A
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