Final Report
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Columbia University
Biosphere 2 Center

EARTH SYSTEMS QUESTIONS IN EXPERIMENTAL CLIMATE CHANGE SCIENCE: PRESSING QUESTIONS AND NECESSARY FACILITIES

A workshop sponsored by the United States Department of Energy and Columbia University Earth Institute, Biosphere 2 Center 14-18 December 2001.

TABLE OF CONTENTS

Note on preparation of report.

The responsibility for preparation of this report lies with Barry Osmond (the PI funded to convene the event), who thanks Susan Delaney, Nancy Mager and Dr Norman Chonacky for assistance with the organization and recording of the workshop. The report is drawn from panel summaries, abstracts, plenary presentations, and taped records of discussions. It has been circulated to all participants and the comments and clarifications requested have been included, along with a minority opinion expressed by one participant.

EXECUTIVE SUMMARY

Sixty-four scientists from universities, national laboratories, and other research institutions worldwide met at Columbia University's Biosphere 2 Center in Arizona December 14-18, 2001 to evaluate the feasibility and potential of the Biosphere 2 Laboratory (B2L) as an inclusive multi-user scientific facility (i.e., a facility open to researchers from all institutions, according to agreed principles of access) for earth system studies and engineering research, education, and training relevant to the mission of United States Department of Energy (DOE) by addressing the following issues:

Is B2L appropriate for research supporting the DOE mission?

The mission of DOE was presented by Dr Jerry Elwood, Director, Environmental Sciences Division, Office of Biological and Environmental Research. Participants concluded that:

- There is an inadequate capacity to undertake large-scale experiments, with adequate control of environmental variables, needed to gain mechanistic understanding of the responses of ecosystem processes to global climate change, and the capacity of the biosphere to mitigate these changes.
- The unique facility of B2L is a focus for interdisciplinary research, guided by the twin drivers of curiosity and need that have been proven to advance the well being of humankind over the last century. As with a research vessel or accelerator, bringing together of expertise around a facility has the potential to strengthen the Nation's institutional and human resources in experimental climate change science.
- In this context, the controlled synthetic ecosystems of B2L (that mirror but do not duplicate natural ecosystems) are recognized as extraordinary tools for experimental research relevant to the DOE science mission and vital to sustaining the Nation's leadership in this field.
- The "apparatus" has been proven capable of delivering novel process level, mechanistic insights to ecosystem functions in the soil-plant-atmosphere continuum and in the benthos-ocean-atmosphere continuum. These insights are expanding the frontiers of natural sciences, providing empirical data that, for example, underpin computation and simulation as fundamental tools for discovery in scaling from the leaf to the landscape. Examples include B2L experiments showing that at atmospheric CO_2 concentrations expected to prevail mid 21st Century, the sink capacity of rainforests for sequestration of CO_2 may saturate, and coral calcification will be reduced by 40%. Such data reduce the uncertainty, and increase our confidence in predicting the consequences of impending global climate change.
- One of DOE's goals is to understand how energy technologies impact existing ecosystems and ecosystem services. It wasn't clear that by themselves the model systems in B2L were appropriate for this goal. However, it was clear that complementing existing natural ecosystem observational programs such as FACE and Ameriflux with experimental studies on the synthetic model ecosystems of B2L adds great strength to the mission of DOE.
- Further modifications to B2L are needed to realize the full potential of the facility, but the urgent first priority of the research community is to have assured long-term access to the apparatus beyond 2005, when the present contract for private support of the facility expires.
- The research community represented at the workshop identified a menu of 36 key science questions in several ecosystems and technologies that can best, and in many instances, only be addressed in B2L.
- There is a pressing need for DOE to leverage more than $250M private investment in B2L to sustain a unique and essential tool for experimental climate change science, thereby expanding the Nation's capability in cutting edge research.

If so, how can B2L be used best to support research addressing the DOE mission, and what are the underlying science questions? (Responses to two other requests i.e., the ecological and earth system science question(s) that would underlie any future DOE-supported research at B2L; the integration of modeling and experiments in ecology and earth system science at B2L, are included here.)

Participants posed 36 specific science questions, grouped in the following 9 core experimental areas relevant to DOE's mission, that should guide the use of B2L for experimental climate change science:

- Measurements of pools, fluxes and residence times of carbon and other elements (N, P) as rate limiting mechanisms in marine and terrestrial ecosystems that will permit application of control analysis, for example, to understanding responses of ecosystems to changing climate and their impacts on predictions of atmospheric CO_2 concentrations
- Experiments that will complement and extend observational ecosystem level research done in FACE, flux tower and LTER programs
- Experiments that will exploit the greater sensitivity and more rapid response time of changes in the natural abundance isotopic composition of ecosystem components and gases in B2L to understand processes and mechanisms controlling biogeochemical cycles in natural ecosystems
- Experiments to calibrate remotely sensed optical signals against whole ecosystem carbon fluxes in B2L for application in natural ecosystems
- Research that will advance and validate modeling methods through the control of environmental variables and capacity for replication in time in B2L
- Experiments that will manipulate biocomplexity (biodiversity) to determine its role in robustness of ecosystem responses to changing climate
- Research that will expand our experience in the operation of a collaborative environment to support an inclusive multi-user facility as an open ecological observatory for experimental climate change science, and
- Research that will create an intellectual center for experimental climate change science and become a nucleus for development of new theories and methods for field research in the natural ecosystems of Biosphere 1

What advantages and disadvantages (financially, operationally, and scientifically) does B2L present with respect to ecological and earth system science research?

In posing this question Program Manager Dr Jeff Amthor pointed out that accurate cost comparisons are very difficult to make. However, the cost of research in B2L ($3.1M p.a. for engineering and maintenance staff, utilities and capital items 1999-2001) is of the same order as that of major natural ecosystem FACE and AmeriFlux projects supporting a similar number of projects and researchers. Only the ocean mesocosm in B2L is yet near to fully engaged (with 20 researchers); when fully staffed the cost per researcher in B2L is predicted to be comparable with that of the other climate change science projects.

Operationally and scientifically, participants identified the advantages of B2L as:

- precise control of environmental variables, including temperature, precipitation and CO_2 in B2L that are simply not available elsewhere at this scale.
- synthetic but sufficiently complex model systems that mimic many important aspects of real world ecosystems, yet are simple enough to be comprehensively understood through controlled experiments. The model synthetic, but complex ecosystems of B2L are structurally and

floristically good analogs of natural systems, and serve as excellent tools for large-scale experimental research.

- replication in time with precise control of environment analogous to the familiar approach of laboratory science that, until now, has not been available at the scale of ecosystem research.
- replication in time, with stable ecosystem composition, that accelerates the acquisition of process and mechanistic data at the system level that cannot be obtained otherwise. Acute and chronic perturbation procedures can be applied and stochastic phenomena can be investigated with precision.
- system composition and properties that change little in the course of experiments facilitates study of short-term response function that complement FACE experiments in which memory effects persist (accumulate) as "acclimation," itself an important but potentially confusing process.
- tight containment and high ratios of biota to volume that permit mass balance measurements, and ensure that signal-to-noise ratios are much higher in B2L than in unconfined field experiments. This facilitates instantaneous rate studies of processes as a function of diurnal and seasonal variables.
- control of environment that permits systematic evaluation of interacting variables with the increased precision afforded by replication in time, without the variations in composition that require extensive replication in space in the field.
- convenient but controlled access to canopies as tall as 20m that otherwise requires cranes or towers.
- opportunities for replacement of ecosystem components (soils, biota, etc.) at well supported sites as required.

Nevertheless, the artificial nature of the B2L ecosystems was a concern for several of the participants. For example, Paul Hanson (Oak Ridge National Laboratory) emphasized "the limited radiation levels, artificial soils and non-native species mixtures are not representative of existing natural ecosystems. This is a common concern for many experimental systems in addition to B2L (small pots, growth chambers, etc.), but newer research in FACE systems or around Ameriflux towers has been conducted to measure ecosystems or their components in as natural a setting as possible. On the other hand, B2L as a closed system does appear to have utility for testing models of the artificial systems contained within it. Ecosystem models might very well be improved by this interaction. Improved models could subsequently be tested against real world data from naturally occurring ecosystems."

The limitations the B2L physical infrastructure might impose on future research (e.g., what is the expected life of the HVAC system, how does the transmittance of solar radiation through the structure affect ecological processes, et cetera?

All precisely engineered systems face a limited working life. Biosphere 2 was designed optimistically to last 100 years. The first decade of operation of the $150M facility has been remarkably trouble free, with a replacement cost (1996-2001) of engineering components of $322K p.a. The original design focus of B2L was not experimental climate change science and as a consequence, well recognized limitations of the apparatus include:

- the composition of the artificially constructed soils. There was no consensus as to what comprises an appropriate soil but Phil Dougherty (Forest Research Westvaco) asserted that the soil used in the forestry biome was nutritionally similar to that in which commercial forests are planted in the SE-US. In spite of the lack of consensus, the very active soils of B2L have highlighted how little we understand the role of soil metabolism in ecosystem carbon budgets.

- By many standards, research using the soils in B2L is a vast improvement over research on plants grown in small containers of vermiculite or commercial potting mix (data from such studies is currently used to parameterize large-scale models). In any event, soil replacement, like replanting of other synthetic ecosystems in B2L, remains a viable long-term option in future research planning.
- The extensive white enamel space-frame needed to support the tightly sealed glass enclosure diffuses and absorbs about 50% of the incoming solar radiation. However, given the latitude and desert location of the facility, daily maximum, and annual PFD inside B2L is greater than other naturally lit plant growth facilities around the world.
- The absence of UV radiation is common to all glass and most transparent synthetic structures used for plant growth. It is widely agreed that UV radiation is a second or third order environmental problem for low altitude ecosystems, and most attempts to artificially supply UV radiation introduce more problems than they solve.
- The absence of UV-dependent photochemical processes also alters the chemistry and lifetimes of trace gases inside B2L, but in predictable ways. With UV-transparent glass now more readily available, replacement to enhance experimental features for plant-atmosphere interactions, is possible, and the absence of UV radiation facilitates investigations of UV effects through comparisons with plants grown outdoors.
- The absence of pollinators and of significant numbers of herbivores at present constrains the use of B2L for research involving higher trophic levels and reproductive processes. Such studies may be undertaken in future, after the menu of research questions dealing with autotrophy-only has been fully addressed. In the meantime, netted enclosures will allow studies of insect responses to CO_2 and plant volatiles under controlled conditions.

What advantages and disadvantages does B2L present for ecological and earth system science research compared to other facilities, either in existence or that could be constructed?

In addition to the points made above, it is clear that B2L is already a valuable experimental facility and should be considered as a prototype that is stimulating thinking about other large-scale controlled environmental facilities, including those envisaged under the Terrestrial Ecosystem Research Facilities (TERF) recently explored within DOE.

- It provides a decade or more time advantage over any newly conceived facility elsewhere in the world at present.
- Workshop participants frequently expressed the view that B2L and any similar structures currently envisaged, are likely to be complementary to, and cannot substitute for, other purpose built facilities such as FACE or Long Term Ecological Reserves (LTER).

Although other observational and experimental facilities such as FACE, open-top chamber facilities, and eddy-covariance systems have identified some key questions, they too have limitations that can be overcome through the control afforded in B2L. These include:

- The influence of episodic events that are extremely important in shaping the structure and function of most major ecosystems, on ecosystem responses to global change.
- The inability to control intact functioning soils in growth chambers and greenhouses.
- The interaction of elevated CO_2 with other global change factors in intact ecosystem experiments (or mesocosms).

- The role of time delays in plant and ecosystem responses to global change. There are few experimental data that examine how cyclic environmental behavior (wet-dry cycles, multi-year droughts, etc.) impact ecosystems in a global change context.

New facilities can be built to meet specific needs and should take advantage of the lessons we have learned over the last decade or so. Two examples in which the B2L experience is currently stimulating new developments are:

- "Boreosphere" designs (University of Umeå, Sweden) in which areas of boreal forest may be trenched, fitted with soil monitoring and temperature control systems, and enclosed with a controlled climate and atmospheric system. This minimum disturbance to an established natural ecosystem is an attractive compromise, but is not inexpensive.
- Biosphere 3 designs (Osaka University) perhaps targeting designer plants for changed future climates in which genetically modified crop plants and trees can be safely evaluated under realistically simulated environments.

WHAT IS EXPERIMENTAL CLIMATE CHANGE SCIENCE?

Experimental climate change science strives to inform scaling and modeling issues through measurements obtained through manipulative experiments. So much of climate change science is based on simple models of complex systems. In contrast to observational climate change science, it uses controlled experiments to test hypotheses leading to mechanistic understanding of biospheric processes. It strives to expand the scale and range of controlled experiments with complex natural systems, such as forests and coral reefs. Experimental climate change science thus provides unique insight into processes that determine sustainability of Earth systems.

May (1999) observed that "*many of the most intellectually challenging and practically important problems of contemporary ecological science are on much longer time-scales and much larger spatial scales*" than are currently being undertaken. He noted surveys in 1989 showing only 25% of manipulative field studies exceeded 10m in size, and 40% lasted less than a year, with only 7% exceeding 5 years. Numerous experimental manipulations of soil temperature and CO_2 of natural ecosystems using Free Atmosphere CO_2 Enrichment (FACE) have been initiated since this assessment, but the truth of this assessment endures.

Experimental climate change science requires facilities that are capable of precise control of environmental parameters and careful monitoring of a wide range of ecosystem responses. The necessary facilities must be able to operate over prolonged periods of time. The National Assessment Synthesis Team recently identified the need to *"[develop] the capability to perform large-scale (over an acre) whole-ecosystem experiments that vary both CO_2 and climate"* (NAST Synthesis on Climate Impacts, Nov 2001). *"As a facility, or as a prototype for an experimental ecology facility of the future, the time for large scale experimental systems such as Biosphere 2 has come"* (Marino and Odum 1999).

Why do we need experimental climate change science?

There is now absolutely no reasonable doubt that increasing concentrations of CO_2 and other greenhouse gases are the principal drivers of the multi-faceted process known as global climate change. As May (1999) noted *"As one leading example, our lack of detailed understanding of the changing balance of CO_2 on land, in the atmosphere and in the sea undercuts predictions about the* *effects of climate change, and could impede the clear implementation of the Kyoto proposals for reduction of emissions".* According to one participant (abstract from Monson, U Colorado Boulder), one of the primary constraints facing our ability to predict ecosystem carbon sequestration in a future world of increased CO_2 and warmer climate is the availability of truly mechanistic models; i.e., models that are based on the first-principles of biophysical and biochemical relationships.

This first-principles approach seems in contrast with the overview of Goldenfield and Kadanoff (1999) that *"apparently there are no general laws for complexity. Instead, one must reach for 'lessons' that might, with insight and understanding, be learned in one system and applied in another".* While some believe that *"The mechanistic bases for the observed biotic responses to climate change have been well established through experimental and observational studies on the behaviour, ecology and physiology of wild species"* (Walther et al 2002), they concede that *"the complexity of ecological interactions renders it difficult to extrapolate from studies of individuals and populations to the community or ecosystem level. We do not, for example, have a clear understanding of the roles of short-term versus long-term environmental stochasticity..."* These apparently contrasting views of how to move forward to obtain general, predictive ecosystem models are at the heart of a dichotomy in ecosystem science. A large-scale controlled ecosystem facility is surely a key asset to bridge these contrasting approaches. Biosphere 2, although not originally designed as a scientific tool, has been transformed as a prototype apparatus, indispensable to the new discipline.

Why study plants in a highly engineered closed system?

The mini-ecosystems of B2L are synthetic but representative models in an apparatus that permits manipulative experiments at an appropriately large scale, to guide the scaling of knowledge from the leaf and organism to the ecosystem. *"Biosphere 2 will continue to stimulate the minds of those who have the vision to think beyond the veil of tradition. As much as anything else this technology, or a conglomerate of them, may play a vital role in the emergence of new sciences due simply to the fact that this tool enables experimental work at a scale that has rarely been possible"* (Marino and Odum 1999).

It should not be forgotten that B2L has been made available by its owner because the first very complex experiment revealed just how little we know about the response of ecosystems to imposed climates. It was a combination of superb engineering and tight enclosure in B2L that, with incomplete knowledge of the cycling of carbon and oxygen that lead to the highly publicized failure to sustain a habitable environment during closure. High soil metabolic activity (principally in the agricultural mesocosm), and the artificial sink for CO_2 in uncured structural concrete, was responsible for the puzzling O_2 draw-down (to below 15%) without accumulation of CO_2 in the initial experiment. This led to termination of the "human experiment" (Allen 1991) and the subsequent scientific investigations of (Broecker 1996) that made the facility available for experimental climate change science.

FORMAT OF THE WORKSHOP

The mission of the Columbia Earth Institute (CEI) is to advance our understanding of Earth to enhance sustainability, so participants were asked to focus on the full sweep of science needed to understand how Earth's biosphere will respond to climate change (e.g., the carbon cycle and climate feedbacks), and how this change will affect key issues of concern to society. Recognizing also the importance of experimental climate change science to the mission of DOE, and that B2L may have a unique contribution to make, DOE and CEI collaborated to host the workshop reported here.

Following introductory comments from the owner of Biosphere 2 (Edward P Bass), the Executive Director of the Biosphere 2 Center (Barry Osmond) and the Executive Vice-Provost of Columbia University (Michael Crow), the cognizant DOE Division Director (Jerry Elwood) and Program Manager (Jeff Amthor) outlined the agency's missions and purposes at the workshop. The program (Appendix 1) was designed around 5 keynote presentations and 6 sessions embracing the ecosystems and technologies relevant to the B2L.

Each session heard brief presentations from panelists, most of whom had provided abstracts listing up to 5 key points, and a short research presentation relevant to the session from a B2L researcher, before breaking into sub groups for detailed discussion. Overview reports of these discussions were prepared by the session chairs, and presented to the participants prior to commencement of the next session. About 60% of the formal program was spent in discussion, and virtually all participants made panel presentations. The following report is drawn from panel summaries, abstracts, plenary presentations, and taped records of discussions. Abbreviated abstracts are attached (Appendix 2), and PowerPoint presentations are available from Biosphere 2 Center, on request.

BIOSPHERE 2 LABORATORY AS AN EXPERIMENTAL CLIMATE CHANGE SCIENCE FACILITY

Background

Biosphere 2 was privately constructed in the late 1980s (Allen 1991) to discover whether 8 humans could sustain themselves in a sealed, energy-rich environment comprised of synthetic ecosystems, including a 35,000 m^3 rainforest, a 37,000 m^3 agricultural area and a 2,500 m^3 ocean. Columbia University's first involvement with the project was the provision of assistance in solving a puzzle related to the declining oxygen levels inside the laboratory (Broecker 1996). The University assumed full responsibility for the conduct of research, education, and public outreach activities on the site in 1996 under a management agreement that extends through 2010.

The Biosphere 2 Center (B2C) is now a non-profit education and research center, one of eight centers in the CEI, situated in the Sonoran desert 40 km north of Tucson, Arizona. It is being developed as a small western campus of Columbia, with responsibility for the world's largest contained and controlled environment facility for plant growth and integrated studies of Earth system science. The B2C has a broad mission to:

- serve as a focus for research, teaching (1,100 graduates thus far), and learning about Earth and its systems,
- catalyze interdisciplinary thinking and understanding about Earth and its future,
- be a key center for Earth education and for outreach to industry, government and the general public and
- focus public attention (200,000 visitors annually) on the issues related to Earth systems policy, planning and management.

Researchers and modifications funded by Columbia University have transformed Biosphere 2 into a unique large-scale, controlled-environment facility for manipulative, experimental climate change research, the B2L. The operating costs of the facility continue to be met by the owner, Mr.

Edward P Bass, through 2005. Columbia University continues to invest in the facility, notably through the ongoing appointments of research leadership faculty.

Characteristics of the Biosphere 2 Laboratory

The B2L now consists of 10 year-old, medium-scale synthetic communities of plants and soils (mesocosms) encased in a gas-tight glass, metal and concrete shell. Lightweight transparent curtains allow reversible closure of the rainforest and three intensive forestry sections. The intensive forestry sections are currently operated at three different CO_2 concentrations. In practice, each mesocosm is a large controlled environment chamber through which fluxes of water, carbon and other compounds can be monitored precisely. This allows whole-system mass-balance and response to changing CO_2 and/or other climate factors (e.g.. net ecosystem carbon exchange (NEE), transpiration, trace gas production and isotope balances) to be measured. Each isolated terrestrial mesocosm is equipped with CO_2 injection and extraction systems so that the CO_2 partial pressure can be controlled in the range of 400 ppm (close to present level) to 1200 ppm. Fans installed inside each mesocosm minimize temperature stratification, and the rainforest, desert and intensive forestry biomes have a single-pass water system.

The B2L is a unique research facility for investigation of "system-level" responses to climate change, yielding data that are needed to validate models that scale up from leaf to canopy to ecosystem (publications 1998-2001 in Appendix 3). Because of its size and control capabilities, the apparatus enables researchers to compress the time scale of inquiry in complex systems, and to obtain much greater sensitivity in the tightly closed space than can be obtained out doors. It complements other approaches to researching earth systems; teaches us how to operate and optimize such facilities, and is an indispensable apparatus for the emerging discipline of experimental climate change science. Participants repeatedly stressed the following distinctive advantages of B2L that underpin its importance as a venue for experimental climate change research:

- Biosphere 2 mesocosms are synthetic but sufficiently complex model systems that mimic many important aspects of real world ecosystems, yet are simple enough to be comprehensively understood through controlled experiments.
- Replication in time with precise control of environment is a traditional experimental approach in laboratory research that, until now, has not been available at the scale of ecosystem research. The absence of memory effects in B2L experiments (system composition and properties change little in the course of experiments) facilitates short-term response function studies that complement FACE experiments in which memory effects persist (accumulate) as "acclimation."
- Quick replication in time, without shifting composition, accelerates the acquisition of process and mechanistic data at the system level that cannot be obtained otherwise. Acute and chronic perturbation procedures can be applied and stochastic phenomena can be investigated with precision.
- Tight containment and high ratios of biota to volume permits mass balance measurements, and ensures that the signal-to-noise ratios are much higher in B2L than in unconfined field experiments. This facilitates instantaneous rate studies of processes as a function of diurnal and seasonal variables.
- Precise control of environmental variables, including temperature, precipitation and CO_2 in B2L are simply not available elsewhere at this scale.

- Control of environment permits systematic evaluation of interacting variables with the increased precision afforded by replication in time, without the variations in composition that require extensive replication in space in the field.
- Convenient but controlled access to canopies as tall as 20m in B2L is at least comparable to that in crane and tower systems.
- The synthetic but complex ecosystems of B2L are structurally, and floristically, good analogs of natural systems, and serve as excellent tools for large-scale experimental research. Just as mice, pigs and monkeys are not very faithful copies of humans, these animals nevertheless remain indispensable to the advance of medical research.
- Paul Hanson (Oak Ridge National Laboratory) emphasized that *"the artificial nature of the B2L constructed ecosystems was a great concern for many of the participants. The limited radiation levels, artificial soils and non-native species mixtures are not representative of existing natural ecosystems. This is a common concern for many experimental systems in addition to B2L (small pots, growth chambers, etc.), but newer research in FACE systems or around Ameriflux towers has been conducted to measure ecosystems or their components in as natural a setting as possible. On the other hand, B2L as a closed system does appear to have utility for testing models of the artificial systems contained within it. Ecosystem models might very well be improved by this interaction. Improved models could subsequently be tested against real world data from naturally occurring ecosystems."*

Although B2L is a unique facility with potential to contribute to our understanding of future climates, its original focus was not experimental climate change science. It was obvious at this workshop that those not familiar with the capabilities of B2C through engagement in research at the facility were highly critical of the initial conditions (soils, ecosystem compositions etc) established in B2L. There are clear philosophical differences between those ecologists who accept paradigms based on observation of natural systems and those who build paradigms on the basis of experimental manipulation. Similar philosophical polarization is found in most disciplines, and contributes towards reducing uncertainty and increasing confidence in our understanding of complex systems. Constructive assessment of the less-than-ideal residuals of the original design of B2L suggest the following:

- Although the composition of the artificially constructed soils used in B2L has been widely criticized, it is the most sophisticated large-scale, controlled-environment soil system available for research. Indeed, the very active soils of B2L have highlighted the fact that we do not understand the role of soil metabolism in carbon budgets.
- By many standards, research using the soils in B2L is a vast improvement over research on plants grown in small containers of vermiculite or commercial potting mix (data from such studies is currently used to parameterize large-scale models). In any event, soil replacement, like replanting of other synthetic ecosystems in B2L, remains a viable long-term option in future research planning.
- The extensive white enamel space-frame needed to support the tightly sealed glass enclosure diffuses and absorbs about 50% of the incoming solar radiation. However, given the latitude and desert location of the facility, daily maximum, and annual PFD inside B2L is greater than almost all other naturally lit plant growth facilities.
- The absence of UV radiation is a feature common to all glass and most transparent synthetic structures used for plant growth. However it is widely agreed that UV radiation is a second or

third order environmental problem for low altitude ecosystems, and most attempts to artificially supply UV radiation introduce more problems than they solve. The absence of UV-dependent photochemical processes also alters the chemistry and life-times of trace gases inside in predictable ways. With UV-transparent glass now more readily available, glass replacement to enhance experimental features for plant-atmosphere interactions, is conceivable. Nevertheless, the absence of UV radiation facilitates investigations of UV effects through comparisons with plants grown outdoors.

- The absence of pollinators and of significant numbers of herbivores at present constrains the use of B2L for research involving higher trophic levels and reproductive processes. Such studies may be undertaken in the future, after the menu of research questions dealing with autotrophy-only has been fully addressed. In the meantime, netted enclosures will allow studies of insect responses to CO_2 and plant volatiles under controlled conditions.

B2L in Relation to other Existing or Potential Facilities

It is clear that B2L is already a valuable experimental facility and should be considered as a prototype that is stimulating thinking about other large-scale controlled environmental facilities, including those envisaged under the Terrestrial Ecosystem Research Facilities (TERF) currently being discussed by DOE. It provides a decade or more time advantage over any newly conceived facility, or facility known to be contemplated elsewhere in the world at present.

Workshop participants frequently expressed the view that B2L and any similar structures currently envisaged will be complementary to, and cannot substitute for, other purpose built facilities such as FACE or Long Term Ecological Reserves (LTER). A workshop participant (Smith, UNLV) noted that current large-scale experimental systems often suffer from *"the inability to manipulate a broad range of variables...and an inability to completely account for all components of mass and energy balances."* FACE and open-top chamber facilities, and eddy-covariance systems, have identified some key questions that can only be overcome through the control afforded in B2L. These include:

- The influence of episodic events that are extremely important is shaping the structure and function of most major ecosystems, on ecosystem responses to global change.
- The inability to control intact functioning soils in growth chambers and greenhouses.
- The interaction of elevated CO_2 with other global change factors in intact ecosystem experiments (or mesocosms).
- The role of time delays in plant and ecosystem responses to global change. There are few experimental data that examine how cyclic environmental behavior (wet-dry cycles, multi-year droughts, etc.) impact ecosystems in a global change context.

B2L is a useful first step. Additional facilities are clearly needed. They should be built to meet specific needs and should take advantage of the lessons we have learned over the last decade or so. Two examples in which the B2L experience is currently stimulating new developments are:

- "Boreosphere" designs (University of Umeå, Sweden) in which areas of boreal forest may be trenched, fitted with soil monitoring and temperature control systems, and enclosed with a controlled climate and atmospheric system. This minimum disturbance to an established natural ecosystem is an attractive compromise, but is not inexpensive.

- Biosphere 3 designs (Osaka University) perhaps targeting designer plants for changed future climates in which genetically modified crop plants and trees can be safely evaluated under realistically simulated environments.

In the meantime, there is an urgent need to expand and assure access of the research community to B2L. As pointed out by a participant (Chonacky, CU) experience of DOE in building information technology infrastructure for collaborative research, such as its DOE 2000 project within the MICS office (http://www.sc.doe.gov/ascr/mics/index.html) provides an excellent guide and affords tools to build effective access of researchers to their colleagues and their data in B2L experiments that may extend over considerable periods of time.

Participants suggested that, given the physical and technological infrastructure already in place, it makes sense to co-locate some new facilities at B2C. These new facilities need to be designed to take advantage of technical developments (such as UV transparent plastics), and designed to overcome some of the limitations discovered in B2L (such as the shading of adjacent structures). Building on the boreosphere concept, and taking advantage of experience at the DRI Reno facility, one could ensure better instrumentation and control of soil processes, while taking advantage of the site, light and engineering available at B2C. Mike Miller (Argonne National Laboratory) explained that his research programs could not be transferred to B2L because *"biogeochemically the soils are very different from those found in the real world. The feedbacks one would want between soils and their nutrient cycles with roots and mycorrhizas are most likely not very realistic. Why? because of how the soils were developed. Hence, the mechanisms of interest to me, i.e., how soil processes especially linked with the mycorrhizal symbiosis, influence plant biomass allocation would be difficult to elucidate."*

Nevertheless, B2C represents a unique opportunity for DOE to leverage its support of experimental climate change science with the continuing investments made by Mr. Bass and Columbia in the existing experimental apparatus and its support. Furthermore, B2C is capable of hosting additional new facilities on its capacious site, which, if placed elsewhere, would require very costly duplication of physical infrastructure, housing, support services and human capital, all already in place in Oracle. One might compare this opportunity to the growth of programs and facilities into contiguous areas that has taken place over time in DOE National Laboratories such as Brookhaven.

Cost Comparisons: B2L, FACE and Eddy Flux Towers

It has proved difficult to extract meaningful data on the comparative costs of research in other observational/experimental systems such as natural ecosystem FACE and AmeriFlux projects operated with support from DOE and other agencies. The component costs of FACE vary greatly depending on when they were established, the level of sophistication and size and complexity of the plant system studied. Crops such as cotton and soybeans are inexpensive in FACE compared to a mature loblolly pine forest. The main annual cost in natural ecosystem FACE experiments is CO_2 supply ($250-750K p.a., Nevada Desert and Duke Forest sites respectively; Stan Smith and George Hendrey, personal communications) whereas in the open flow but contained B2L, CO_2 enrichment costs only $15K p.a.

On the other hand, utilities to achieve climate control in B2L are expensive, costing $711K p.a. (1999-2001). At B2L the average (1999-2001) annual running cost (engineering and maintenance staff, utilities and capital items) was $3.1M ($4M with site infrastructure) and the facility currently serves 30 researchers. When comparisons are made it needs to be noted that only one of three programs in B2L (ocean mesocosm) is now near to fully engaged (20 researchers). The capacity of B2L is scheduled to rise to some 100 participating researchers in 2005, facilitated in part by the collaborative information technology operating within the extensive telecommunications infrastructure already in place. The cost per researcher is then expected to be comparable with that of the other two DOE supported experimental climate change science initiatives.

KEY SCIENCE QUESTIONS THAT ARE BEST ADDRESSED IN B2L

This workshop was convened because of the pressing need to improve our understanding of, and to reduce the huge uncertainties in the knowledge base for, the role of the biosphere in climate change science. We firmly believe that the nature of the policy debate will only be changed if models and predictions about climate change are based on experimental evidence. For example, it is already clear that previous statements that *"our lack of detailed understanding of the changing balance of CO_2 on land, in the atmosphere and in the sea, undercuts predictions about the effects of climate change and could impede the clear implementation of the Kyoto proposals for reduction of emissions"* (May 1999) have indeed come true.

As a frame of reference, participants were presented with examples of questions that are currently being studied by a small group of researchers led by a committee appointed and funded by Columbia University and its private partners. Clear programs of medium-term, manipulative experiments (mostly to do with autotrophic processes) were proposed that notionally might consume the next 20 years of research at B2L, with these to be followed by long-term evaluations of trophic interactions and evolutionary processes. The discussions that followed made it clear that there are many more key questions in experimental climate change science that cannot be addressed adequately, if at all, due to lack of appropriate research facilities. Participants recognized that such an ambitious program, clearly in the national interest and in the interest of sustainability of Earth systems, deserves substantial public funding.

The mood of the workshop was optimistic. Given the pressing need to improve understanding, and to reduce the huge uncertainties in the knowledge base in experimental climate science, the facilities of B2L need to be more widely available, and that as a matter of some urgency, the research community now needs to be assured of long-term access to the apparatus with adequate long-term support. As noted by one participant (Dubey, Los Alamos National Laboratory), B2L is uniquely equipped to address *"many of the imperatives enumerated by the recent NRC pathways report: What are the potential impacts of multiple stresses on ecosystems? What are the influences of episodic events on ecosystem responses to global change? What are the limits of environmental change beyond which ecosystems are not sustainable? Will ecosystems trigger biogeochemical cycles that exacerbate or stabilize human-induced environmental changes? How can ecosystems mitigate global change and enhance their adaptive capacity?"*

Within this context, participants were reluctant to dwell upon the huge array of unresolved issues in experimental climate change science that lay beyond the scope of B2L capabilities. Instead, the key science questions that they framed were circumscribed by the unique capabilities and potential of B2L as an apparatus and by our ability to form teams that take full advantage of the opportunities afforded by each experiment. Participants provided an extensive portfolio of hypotheses, research opportunities and collaborative possibilities (see excerpts from abstracts in Appendix 3). The optimistic spirit manifested itself in the movement by some participants to collaborate in short-term experiments as detailed later in this report.

The portfolio of ideas represented in the workshop shows considerable overlap, itself evidence of broad community endorsement of the research potential of B2L. The following sections were distilled from discussion panel summaries and plenary papers. They include many perspectives that evidently emerged in three previous workshops, but which were not subject to reports, and which had not been further articulated.

Lessons from research in the B2L ocean mesocosm

An outstanding example of the need to bridge observational and experimental climate change science is provided by the experiments of Langdon et al (2000) in the ocean mesocosm of B2L. One clear consequence of increasing atmospheric CO_2 concentration is a change in the chemistry of the surface ocean, with a lowering of pH and carbonate ion activity. Calcification by reef building corals is thought to be driven, in part, by a thermodynamic gradient favoring the precipitation of calcium carbonate, and the gradient is expected to decline with increasing atmospheric CO_2 concentration. It follows, hypothetically, that coral reefs, one of the great reservoirs of biodiversity, may be threatened by chemical as well as physical stresses (warm water incursions and sea-level rise) as a consequence of increasing atmospheric CO_2 concentration and global warming.

It has been extremely difficult to test this chemical stress hypothesis in open natural systems because the rate of CO_2 increase is so slow, and is complicated by uncontrolled changes in temperature, nutrients, predation and human interference. Chemical modification of seawater carbonate in open systems has been impossible, but Langdon et al (2000) were able to test this hypothesis in the self-sustaining, synthetic analog of a Caribbean coral reef ecosystem in B2L because the system was:

- closed. The carbonate chemistry of seawater in the 2,600m^3 synthetic ecosystem was readily manipulated. Accurate, continuous measurement of all physical and chemical parameters and the rate of calcification was achieved.
- controlled. Carbonate chemistry of the seawater was manipulated without perturbation of other physical chemical and biological factors, in a time frame of weeks rather than centuries.
- replicable in time. The experiments were repeated many times with the same system, in different seasons.
- supported. The support facilities, instrumentation and data acquisition and transfer systems were already established.
- appropriately modeled. The corals were an established part of a complex, 10-year old ecosystem modeled on a Caribbean lagoon with naturally sustained food webs.
- extrapolated. The convincing experimental evidence for a 40% reduction in coral calcification has now been extrapolated to natural systems.

A large number of experiments remain to be done in the B2L ocean, but the lessons so far from this research can be applied across most of the other synthetic model ecosystems in B2L.

1) Marine ecosystems: studies of pools, fluxes and residence times of carbon and other elements (N, P, Se, etc.) as rate limiting mechanisms for ecosystem responses to changing climate

Some core biogeochemical questions include:

- What are the effects of rising CO_2 concentrations on organic carbon production (gross and net primary production), calcification and dissolution of calcifying ecosystems? Measurements are required at both organismal and community scales.

- Effects of rising sea surface temperature on symbiosis and bleaching of coral: what is the relationship of impaired calcification to other interacting stresses such as the incursions of warm water and grazing?
- How do the C and N-cycles respond to elevated CO_2?
- What determines the ratio of net ecosystem photosynthesis and respiration in coral and other benthic communities in the light and dark?
- What are the effects of increasing water motion from storms on community structure and function? Water motion influences communities through breakage, biogeochemical mass transfer between water and organisms as well as altering input and output of materials. Some core biogeophysical questions include:
- What are the effects of rainstorm properties (droplet size and frequency) on transfer of gases into seawater?
- How do raindrop impact and wave action interact during mixing at the ocean surface?
- How do these factors interact with wind-generated aerosols?
- How does biological activity in the ocean influence the chemistry and physics of aerosol formation?

As already demonstrated in B2L (Langdon et al 2000), the closed, self-sustaining ocean-reef mesocosm can be manipulated chemically to test responses to changed carbonate chemistry. In principle, similar interventions are possible with all key mineral nutrients, but in addition, the power to change physical parameters such as temperature and mixing provides unequalled opportunities to obtain mechanistic insights into the above questions. Thus the inhibition of coral calcification by elevated atmospheric CO_2 concentration in equilibrium with seawater can be researched in concert with bleaching events associated with warm water incursions. The unexpected discovery that the ocean mesocosm respiration is stimulated in the light needs to be explored in relation to nutrient dynamics. Gas exchange between atmosphere and ocean can be researched as a function of wave action and rainfall patterns, and aerosol formation can be related to wind, waves and ocean biological activities (excreted biochemicals and polymers). Aerosol formation has potentially large effects on cloud formation and nutrient transfers between ocean and land. Few if any of the above questions can be researched in natural systems, and the control of parameters needed is simply unobtainable in the field.

2) Systems approaches in terrestrial ecosystems: using control-coefficients to understand responses to changing climate and their impacts on predictions of atmospheric CO_2 concentrations.

Experimental climate change science can contribute much to the predication of the function and composition of ecosystems in future climate scenarios in ways that are truly relevant to policy in this century. Predictions of the magnitudes of pool sizes, fluxes and residence times of carbon and other key nutrient elements as rate limiting mechanisms in global carbon budgets have been addressed with models derived from extensive observations on natural systems. Although we are rapidly approaching the CO_2 concentrations at which photosynthetic CO_2 influx is rate limited by Vmax, future ecosystems (and agricultural systems) will be limited by nutrients and other factors. It is disquieting that these models have a very limited experimental basis, and often rely on a few laboratory scale studies to parameterize processes over a vast area such as the Amazon rainforest. Usually it is not possible to obtain observational data on influxes of carbon in tropical rainforests with the accuracy needed to test the parameterizations. In fact, to quote IPCC: *"The range of uptake rates projected by process-based* *models for any one scenario is, however, considerable, due to uncertainties about (especially) terrestrial ecosystem responses to high CO_2 concentrations, which have not been resolved experimentally, and uncertainties about response of global NPP to changes in climate"* (IPCC, 2001).

Three large-scale observational approaches are presently in use to address this question: atmospheric inverse modeling, flux tower networks and remotely sensed Normalized Difference Vegetation Index (NDVI). Inverse modeling has the advantage of a global constraint but has poor space and time resolution. Flux tower networks offer the resolution in time, climatic zone and biome type to allow essential understanding of processes operating in aggregate. Although NDVI is a surrogate for green leaf area and correlates well with the pool of woody biomass in Northern forests (Myeni et al 2001), year-to-year changes in the biomass estimated from this index are some 2 orders of magnitude smaller than estimates obtained from the flux tower network. At the moment there are significant differences between the magnitudes of the regional terrestrial sinks estimated by the first two approaches, and the third lacks the sensitivity needed for CO_2 influx estimates.

Much progress has been made in understanding the regulatory interactions through the application of control theory (Kacser 1987), and Schulze and Stitt (1994) concluded *"Similar principles for control exist at vastly different levels of organization. The principles of control are analogous at the ecosystem, population, organism, and even of the enzyme reaction level."* The "new stable points" at which ecosystems will function after changes in climate conditions will also be dependent on the "pathway" to this new stability. The "pathway" presumably depends on the kinetics of the pools as the conditions change and also depends on the frequency and intensity of the change. In this respect control analysis must go beyond Kacser, to embrace nonlinear properties of the system (kinetic properties of impacts). For ecosystems, this would most likely involve more complex adaptive behavior than in a linear metabolic pathway. Experiments are required to test such a hypothesis and these might reveal phases of the system that are more important than others. These can be assessed by sensitivity analysis of kinetic properties of the system, thereby revealing functional biodiversity. In

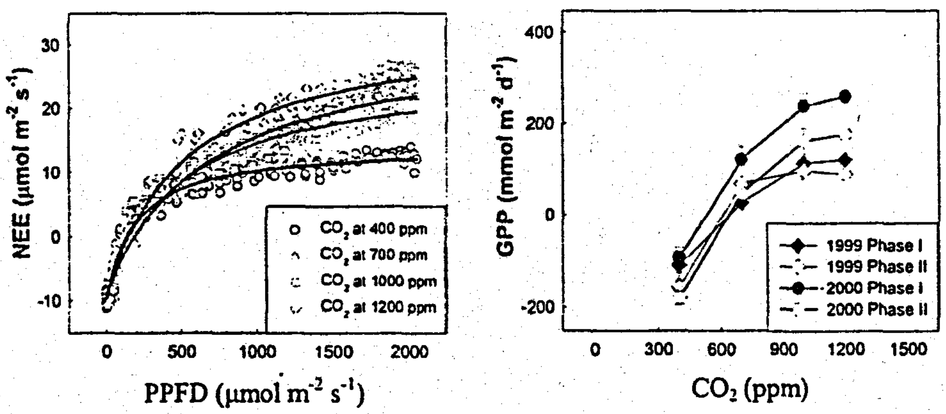


Figure 1: Light and CO_2 responses of the B2L rainforest in different experiments (Lin et al 2001)

principle there is every reason to suppose that this approach will serve well to untangle flux analyses in synthetic ecosystems. The formal requirements for flux analysis can be met in the mesocosms of B2L and such experiments would narrow the uncertainties associated with observational estimates, such as those obtained from flux towers.

Some relevant core questions posed during the workshop include:

- Do mesocosm fluxes match field CO_2 flux observations and how do these data compare with growth responses at FACE sites?
- What is the magnitude of future potential sources and sinks for carbon in terrestrial ecosystems?
- How does the CO_2 fertilization response scale from plants to ecosystems?
- Untested empirical relationships of respiration with environmental variables are being used for model predictions. Mechanistic understanding of respiration is needed at all scales.
- At what CO_2 concentration does CO_2 fertilization saturate, in which ecosystems and for what reasons?
- What is the nature, position and resilience of the terrestrial sink?
- How do ecosystem carbon fluxes respond to the frequency and magnitude of stress events (abiotic: temperature, water, nutrients; biotic: herbivory, pathogens)?

As already demonstrated by preliminary experiments in the B2L rainforest (Figure1; Lin et al 2001), sensitivity of measurement and rapidity of response in the existing closed mesocosms of B2L (or in other ecosystems in the facility that could be planted or renovated) allows systematic parameterization of these questions in synthetic ecosystems. Mass balance accounting, analogous to what we strive to achieve for the closed system of planet Earth, is readily achieved in the closed systems of B2L. Controls on concentration, temperature and precipitation, on frequency and scale of perturbation, when combined with easy access to different components of complex systems, provides an unparalleled tool for scaling up growth and canopy processes and injecting mechanistic insights to help validate modeling exercises.

3) Using B2L to complement and extend ecosystem level research done in FACE, flux tower and LTER programs

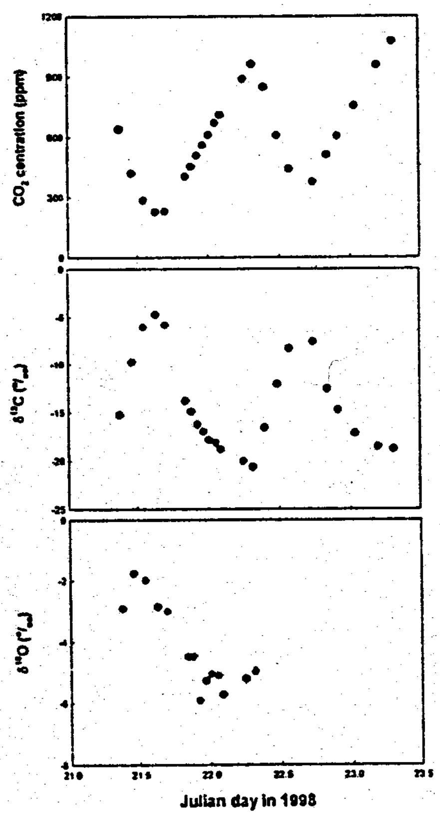
Over the past decade and a half, research on the responses of crops, trees and forests to elevated CO_2 using FACE has yielded valuable data, and has gradually increased in scale of observation, but there have been few manipulative experiments that operate at the scale of an ecosystem. A major intrinsic difficulty is that high CO_2 concentrations can only be maintained under current climatic conditions, and we are unable to study vegetation response to expected covariance between future climate and CO_2 concentrations. Another recurring, and only partly justified criticism of FACE is that, given the limitations of the system design, one cannot systematically combine other treatments with elevated CO_2. Key variables for manipulation include atmospheric CO_2 levels, temperature, precipitation (amounts and timing), and other atmospheric components (e.g., O_3 and N deposition). So far, FACE experiments have been able to accommodate only two or three such simultaneously interacting variables, and cannot yet accommodate controlled temperature in a realistic way. The effects of multiple, interacting variables should be conducted with critical ecosystems using measurements as a basis for good mechanistic models. Most of our modeling continues to focus on mean environmental conditions and each FACE ring can apply only one CO_2 concentration.

Using B2L, with a level of control that cannot be achieved with other facilities currently available, we can discover how do:

- episodic events shape the structure and function of ecosystems by measuring responses to the changing frequency and magnitude of episodic events at differing CO_2 concentrations, temperatures and precipitation regimes?
- cyclic environmental behavior (wet-dry cycles, multi-year droughts, etc.) impact ecosystems in climatic change contexts?
- time delays arising from perturbations affect ecosystem responses to changing climates. covariance of key parameters, such as the projected more rapid increase in night vs day temperatures, effects carbon cycling in the soil-plant atmosphere continuum?

4) Using the natural abundance isotopic composition of ecosystem components and gases in B2L to understand processes and mechanisms controlling biogeochemical cycles in natural ecosystems

Natural abundance stable isotopes have been extensively used to establish sources and sinks in biogeochemistry and to identify distinctive active compartments of biosphere. This is a major research tool to couple global scale processes with physiological processes in the biosphere. The volume ratios of atmosphere, plant and soil in the closed system of B2L daily amplify (2-10 fold) the signals observed annually in the planetary atmosphere (Figure 2) and thus facilitate the systematic partitioning of these processes and their integration into overall ecosystem responses. Signatures in the atmosphere



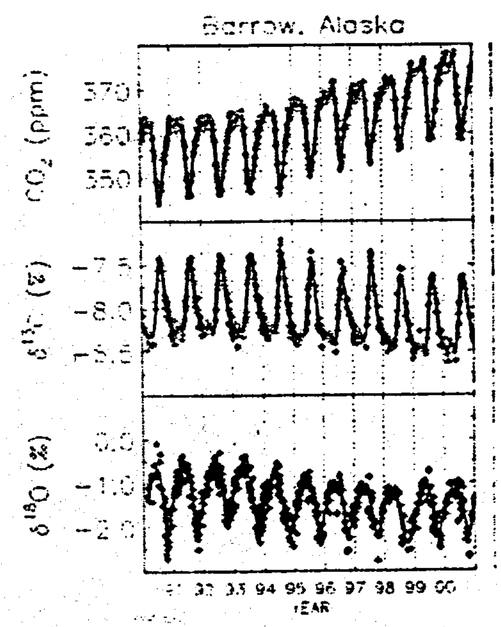


Figure 2: Enhanced sensitivity of stable isotope signatures of ecosystem metabolism in the atmosphere of B2L (left, Lin et al unpublished) compared to the atmosphere of Earth sampled over Barrow, Alaska (right, NOVA).

can be attributed to component processes in the soil-plant atmosphere continuum by exploiting the greater sensitivity in B2L, thereby partitioning these processes with greater precision. These techniques will facilitate partitioning of soil and plant respiratory fluxes, estimation of plant water stress responses on ecosystem water flux, and nitrogen fluxes, for example.

Core questions include:

- can whole ecosystem carbon allocation patterns and residence times be determined by switching between CO_2 supplies that differ in isotopic composition?
- can isotopes provide measurements of C fluxes and stocks from all possible compartments, such as the whole ecosystem, leaf, stem, soil chamber (the enclosed soil compartment) various trenching in-growth and screening treatments, soil faunal components, and leachate DIC, DOC?
- how can ^{18}O labels in precipitation and in water vapor, with controlled humidity, be used to examine overall water budget, evaporation versus transpiration, leaf steady state assumptions, to test robustness of Craig-Gordon evaporative enrichment model, and influences on ^{18}O in CO_2 of the air?
- is it possible to quantify N_2 production using label applied as nitrate-^{15}N label, and to examine the nitrogen cycle in detail, especially denitrification?

5) Using remotely sensed optical signals to calibrate carbon fluxes in B2L for application in other natural ecosystems

The controlled environment of B2L mesocosms provides an ideal test-bed for developing, evaluating and calibrating remote sensing devices that will facilitate the integration of biophysical photosynthetic parameters up and down scale, and informed by images of canopy architecture, estimate CO_2 influx and calibrate this against whole mesocosm gas and isotope exchange measurements. New optical technologies will enable us to measure the efficiencies of primary photosynthetic processes at a distance and calibrate these with independent observations of gas and isotope exchange in these mesocosms in B2L. With imaging methods that will provide volumetric estimates of growth, we will be able to close the loop and predict plant productivity and growth in natural habitats using optical methods based on the driving processes of photosynthesis themselves.

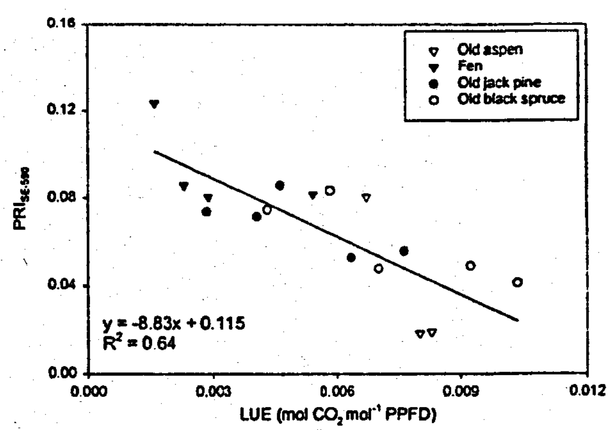


Figure 3: Correlations between remotely sensed PRI from a helicopter and light use efficiency (LUI) estimated from eddy flux measurements in a boreal forest (Nichol et al 2000).

Unlike other current methods that use surrogate, optically sensed parameters to empirically correlate biomass and production processes, it is now possible to focus on biophysical signals that report on the process of photosynthesis itself. These techniques, already applied at the level of leaves and individual plants have become powerful integrative tools that have revolutionized research in environmental plant sciences in the laboratory and in the field. Figure 3 shows the field calibration of remotely sensed Photosynthetic Reflectance Index (PRI) against light use efficiency estimated for different boreal forest canopies from eddy flux tower measurements of CO_2 influx (Nichol et al 2000). We are confident that development and calibration of new tools can be achieved more rapidly and with far greater precision using the gas exchange and controlled environment capabilities in B2L.

Core questions include:

- will measurement and modeling of canopy light environments with distributed sensors of direct and diffuse radiation, permit integration with remotely sensed images of canopy architecture and chlorophyll fluorescence?
- can miniaturized chlorophyll fluorescence/PAR sensors be networked for in-situ spot assessment of photosynthesis throughout vegetation types in the B2L biomes and integrated with remotely sensed reflectance and chlorophyll fluorescence?
- can remotely sensed photosynthetic data be calibrated using radiative transfer, leaf chemistry and physiological process models, with independently measured fluxes of CO_2 and isotopes in B2L?

The remote sensing methodologies to be developed can be applied to any natural ecosystem and will substantially advance the capacity to assess carbon fluxes in the terrestrial biosphere while also providing robust tools to predict the impact of factors such as water stress, high or low temperature stress, pathogens and nutrient limitations on productivity in ecosystems. For example, stress can result in a five-fold variation in photosynthesis rates without a detectable change in NDVI or canopy structure (Gamon et al 1997). Modeling studies that link global circulation models (GCM) to atmospheric transport and physiological models (SiB2) have shown that ignoring stress responses may lead to erroneous conclusions about global carbon balance (Sellers et al 1996). Moreover, we expect to deploy the instruments in the mesocosms of B2L for use by researchers collaborating off-site (the concept of B2L as an Open Ecological Observatory for experimental climate change science, advanced below).

6) Modeling methodologies and validation

Modeling is a natural and indispensable component of all research undertaken in B2L. Workshop participants envisioned experiments of limited duration (months to years) from which process-based models could be developed, followed by removal and re-establishment of ecosystems enclosed in B2L to verify and refine model performance under conditions providing suitable contrasts.

Core questions include:

- can comprehensive modeling and computational expertise be used to develop a system of simulations ("Virtual Biosphere 2") that will provide an evolving framework of analysis, learning, and control?
- how will elevated CO_2 affect nonlinear responses of organisms to environmental variation, and how will these responses cascade across biological, spatial, and temporal hierarchies?
- can generalizations be made across different types of systems (e.g., terrestrial and marine, desert and rainforest)?

Credible, general models are surely the key to making reasonably well-bounded predictions of biospheric responses to changes in atmospheric chemistry and concomitant changes in climate. Researchers at Columbia University and Los Alamos National Laboratory are confident that comprehensive modeling and computational expertise can be used to develop a system of simulations

("Virtual Biosphere 2") that will provide an evolving framework of analysis, learning, and control. These will integrate existing ecosystem/soil/ocean/atmospheric process models to open a powerful new validation and control regime for earth system modeling and simulation science. The resulting "virtual biosphere" model will allow quantification and prediction of complex environmental dynamics in three-dimensional space. Closure of B2L with regards to material flow and energy simplifies the model's physics, allowing research to isolate details of ecosystem processes, biogeochemical cycles, and couplings. Its intermediate size and controlled complexity should allow us to develop scaling methods that include process level details and capture the essence of spatio-temporal heterogeneity. B2L offers a significant signal/noise advantage over field sites in investigating trace gas fluxes, isotope exchange and soil chemistry and microbiology. In addition, physiological drivers (temperature, humidity, soil composition, CO_2, etc.) can be spanned independently over a wide dynamic range on relatively small time scales, promising the development of robust and calibrated Earth system models.

Evidence for often abrupt past climate change means that we need to understand the non-linear dynamics of the forced climate system at the level such that abrupt transitions or 'Climate Surprises' occur. This means a shift in emphasis from conventional OAGCMs alone to a focus on fully coupled 'Earth System Models' where processes like vegetation succession, cryosphere dynamics and ocean nutrient input from geophysical processes on land are included as well as conventional 'fast' meteorological ocean, atmosphere and biospheric processes. In this way, we can overcome one of the primary constraints facing our ability to predict ecosystem carbon sequestration in a future world of increased CO_2 and warmer climate through mechanistic models; i.e., models that are based on the first-principles of biophysical and biochemical relationships and require only parameterization of initial conditions.

7) Understanding biocomplexity (biodiversity) as a foundation of robustness in ecosystem responses to changing climate

Core questions include:

- what is the role of diversity (biocomplexity) in the couplings and feedbacks that seem to assure robust system responses to climate change?
- is high spatial variability the basis for stability?

The synthetic ecosystems of B2L are models, not replicas, but models with sufficient biocomplexity (biodiversity) to discover and manipulate feedback relationships in the soil-plant-atmosphere continuum. The desert mesocosm, with a complex of seven soil types is ideally suited for such projects, because biocomplexity in the soil biota and its relationship to soil metabolism is an important but poorly understood element of experimental climate change science.

Obviously, it is unlikely that all aspects of food webs in ecosystems can be reproduced, if for no other reason than that macro and microorganisms from outside the ecosystem are excluded from migration into B2L, but the advantages of containment and control are obvious. Experience of the first missions in B2L documented significant changes in biodiversity following closure, and we have to learn how to sustain experiments with mixtures of plants herbivores, and other trophic interactions. It was clear then, and remains clear now, that we understand little about how initial conditions determine outcomes, and that closure leads to unsustainability at higher trophic levels.

These questions can be answered in B2L because biodiversity can be manipulated in synthetic ecosystems and subject to controlled treatments in a closed system to identify functional consequences of biocomplexity. In managing a facility such as B2L, experiments with higher level consumers should follow the more simple producer response studies described above. However, the closed systems can be isolated from invading species, and the changes in species compositions and abundances, as well as genetic profiling of organisms, can be monitored with time. Containment also enables calibration of molecular measures of microbial activity (e.g., rRNA:rDNA ratios, level of specific mRNA within cells) with "volumetric productivity" of microbial communities in soils for specific key microbial processes.

8) How can we develop a collaborative environment to support an inclusive multi-user facility for experimental climate change science? The concept of B2L as an open ecological observatory

The cognizant research community has little experience relevant to the long-term operation of an apparatus such as B2L, so management of the facility is itself an important experiment. It is clear from activities in the B2L ocean mesocosm that researchers with shared objectives can make very creative use of the apparatus in the short-term. As the possibilities for long-term support become moreclear, a high priority needs to be given to management plans. These should seek to optimize the opportunities for flexible, creative engagement of individual researchers, while sustaining the necessary level of team activities that will be needed to handle multi-disciplinary approaches to the discipline.

Core questions include:

- how can multi-user access to B2L be extended to research groups remote from the site?
- to what extent can the instrumentation and modeling facilities be organized to broaden public outreach and education, explaining its role, the vision, the instrumentation, and the ecological significance of measurements?

A particular concern expressed was the ability of the B2L to accommodate multiple and lengthy, simultaneous experiments by researchers who, by virtue of complexity of the project, will normally work in teams drawn from various institutions. Fortunatel, this problem is not unique to the B2L, and in fact is of major interest to DOE. Software invented to support collaborative research work remotely at the Environmental Molecular Sciences Laboratory of the Pacific Northwest National Laboratory (Chonacky; (http://www.emsl.pnl.gov:2080/docs/collab/CollabHome.html), such as the CORE2000 tools and the Electronic Laboratory Notebook is already being used by a research group at B2L. The EMSL is also a shared user facility and could be a model for organization of B2L as a shared user facility. By virtue of this experience, we concluded that all of the above research programs can be integrated into a platform for research, education, and outreach. Moreover, the continued development of these tools by DOE, with new work in the National Collaboratories and DOE Science Grid projects, assures their continued improvement and functionality for future use in this type of application.

Preliminary steps have already been taken to achieve off-site direction of projects (CAM carbon budgets in the B2L test module are manipulated and modeled from UCLA). Sensor and control data, as well as measurement systems data, can be made available with appropriate security, and access to educational materials from B2C courses can be provided via the B2C servers.

An open ecological observatory (OEO) at B2L can provide the following:

- on-line access to instrument operation for research collaborators
- unrestricted access to the raw data for modeling for a qualified community of specialists
- the real-time observation (instruments will be equipped with video-camera streaming the data to Ethernet in real-time) for undergraduate and high school

- a public outreach and education component of the observatory, explaining its role, the vision, the instrumentation, and the ecological significance of the measurements.

The IT servers at B2L are now fitted with the fastest available broad band optical fiber, and the research network is being redesigned to facilitate access to CO_2 and environmental control data in the mesocosms. The B2C is a unit of the Columbia Earth Institute (CEI) and together they will establish a distributed ecological laboratory, making B2L the hub for research in experimental climate change science.

9) How do we create an intellectual center for experimental climate change science that will become a nucleus for development of new theories and methods for field research in the natural ecosystems of Biosphere 1?

Obviously, the ultimate objective of experimental climate change science is better understanding the response of natural ecosystems to changing climates. Experience shows that facilities-led experimental programs invariably draw creative researchers together and promote discovery, understanding and applications.

B2L AS A MULTI-USER FACILITY

Experience Thus Far

Research coordination at B2L has been guided thus far by an external research committee that will be broadened to assume Research Advisory Committee functions in 2002, as new Columbia University research leadership faculty take up appointments. Experience has shown that, at this stage of application of the unique apparatus to experimental climate change science, investigator driven research activities have produced creative outcomes. The following collaborations have been developed in the course of planning this workshop, and within the constraints of start up budgets, are being implemented immediately:

- Discussion of the poorly understood soil parameters in the intensive forestry mesocosm led to an invitation to form a "swat team" of research expertise from Oak Ridge National Laboratory and other institutions. A proposal prepared by Paul Hanson is under consideration, with additional interest from the Russian Academy of Science Institute of Soil Science, the NZ Institute of Horticultural Research, Argonne National Laboratory, and the University of Chicago. It is beyond the resources of Columbia University to fund this project entirely at this time, but matching funds from ORNL and CU could achieve this goal.
- Collaborators in the cottonwood project 2002 will include researchers from the Swedish poplar genome project (Göran Sorrensen, Plant Sciences Center, University of Umeå, Sweden), and from wood biochemistry (Andrea Polle, Forest Botany Institute, Univesität Göttingen, Germany).
- Examination of the roles of C/N ratios in the soil-plant-atmosphere continuum as determinants of fluxes of these elements will be the basis of a JSPS postdoctoral fellowship application from Osaka University.
- The potential for imaging of plant growth and remote sensing of ecosystem CO_2 influx in B2L is being researched by students from the University of Tokyo, and the Phytosphere Division, Research Center Jülich, with instrument development being undertaken by researchers at Rutgers University and elsewhere. An NSF-IDEA proposal engaging researchers from the

Carnegie Global Ecology and University of Arizona has been submitted, and elements of the program are being pursued with funding from Columbia University and Humboldt Foundation grants.

- A team from the University of Edinburgh will exploit the high sensitivity flux measurement of volatile organic emissions in the closed mesocosms of B2L. They wish to bridge their small-scale growth chamber data, to their measurements in the Brazilian rainforests, with data from controlled environments in B2L.

These outcomes of workshop confirm community acceptance of the opportunities at B2L, and confirm the last 6-years experience of the B2L Research Committee at Columbia University. Given access to a core funded facility like B2L, creative and committed researchers quickly devise experiments that exploit the unique potential of the apparatus and lead to influential publications (Appendix 3). The further development of B2L as a multi-user facility should acknowledge the following parameters and recognize that comparable facilities are unlikely to be available elsewhere in the foreseeable future:

- Columbia University and Decisions Investments Corp. have invested more than $30m in renovation of B2L and support of research in the proof of concept mode 1996-2001, and both partners are committed to some $30m further investment through 2005.
- Columbia University is in the process of appointing six research leadership faculty in the following areas:

Terrestrial plant ecophysiology, with ability to lead research in the diverse biomes of B2L.
Biological oceanography, with emphasis on plant activities in the B2L ocean biome.
Soil science, with emphasis on instrumentation or microbiology needed to integrate soil and above ground processes.
Stable isotopes as integrators of complex system behavior and indicators of component processes in different biomes of B2L.
Radiation based remote sensing as integrators of complex system behavior and indicators of component plant processes in the biomes of B2L.
Modeling of B2L as a system, and of complex earth systems that include plants.

- These appointments will provide the intellectual infrastructure for research in the B2L apparatus, in much the same way, for example, that MSU professors drive the research agenda at the MSU-DOE Plant Research Laboratory.
- In the marine mesocosm, the most active multi-user mesocosm in B2L, teams of investigators have self-assembled and now undertake 18 projects, 10 involving researchers from outside Columbia University. A total of 20 investigators are engaged, with on-site Columbia research faculty participating in 6-7 projects each.
- Multi-user interest in collaborative programs in other mesocosms is growing rapidly (witness the collaborations developing in the cottonwood program above).
- Depending on the level and mode of engagement of DOE and/or other agencies, jointly agreed research management plans, consistent with the above principles, will be devised. It is premature to specify details at this point, but questions such as: Who would have access? How would use priorities be developed? How many scientists could use Biosphere 2 at one time? need to be addressed.

Recommendations in Support of a Multi-User Facility

In the words of one of the participants (George Hendrey, Brookhaven National Laboratory) *"What is needed is a vision of an initiative that can serve the scientific interests of a broad spectrum of scientists, yet is focused in such a way that real progress will occur in understanding how the world works. The initiative needs to be broad in several dimensions... if it is to be supported by the science community, it needs to provide new resources to many fields such as soil microbiology and biogeochemistry, forest community dynamics, ecosystem modeling and many others."*

Such an initiative within the mission of DOE that took advantage of the enormous private investment (more than $200M thus far) that fortuitously has made B2L available as an indispensable prototype apparatus for experimental climate change science, should consider that:

- if an agency such as DOE engages with Columbia University in the operation of the facility, arrangements based on proven collaborations, such as the MSU-DOE-PRL or other models, should be explored. Two important elements of such an engagement are core support for the operation of the apparatus itself (currently $4M p.a.) and new competitive project funding opportunities for investigators.
- it may be desirable to develop close relationships with groups in specific national laboratories, or among several agencies, as part of a research consortium of national and international users of the facility, perhaps along the lines of NCAR.
- it may be desirable that a senior researcher, experienced in multi-user research facility operation in the area of experimental climate change science at a national laboratory, be funded at B2L to assist Columbia faculty engagement with national laboratory staff, including joint and adjunct appointments.

CONCLUSIONS

Given the above extensive menu of science questions and hypotheses that the research community identified as needing to be addressed, and that are relevant to the mission of DOE, this report concludes with suggestions as to how the only available facility (B2L) could be sustained to meet this need. Since the private funding for the operation of B2L is only available through 2005, Columbia University proposes to proceed in partnership with DOE, at the highest level, to sustain the facility for experimental climate change science. The partnership needs to:

- test effective engagement of national laboratory personnel with Columbia faculty in B2L programs. There is no experience of significant engagements of this sort. Discussions at the workshop led Barry Osmond to request a proposal from Paul Hanson, Oak Ridge National Laboratory, that could support engagement in the cottonwood campaign during 2002. The cost of this proposal ($400K, 2002-3) is beyond the resources presently available to Columbia for this purpose. Similar proposals, directed to a "virtual Biosphere" model, have been initiated from Los Alamos National Laboratory.
- identify specific new program opportunities that should become the foundation of DOE partnership with Columbia in experimental climate change science.
- immediately project a new program initiative in experimental climate change science (notionally $50M p.a.) based on interdisciplinary, multi-user research programs in B2L and other facilities yet to be constructed. Parts of this initiative should provide for:

- renovations in B2L, such as replacement of present temporary partitions isolating the mesocosms with more robust air-locked partitions, replacements of soils as deemed necessary, and relocation of open salt water scrubber systems from the basement plenum (estimated $2.5M, 2003-4).
- secure funding to replace that presently contributed by the owner that would enable DOE to support B2L operations in partnership with Columbia. This should include a provision for maintenance at 20% p.a., and renewable subject to site visit on a 5-year cycle as at MSU-DOE-PRL, making the multi-user facility available in a context analogous to that of a research vessel or telescope (estimated $5M p.a. commencing 2005).
- construction of other facilities for experimental climate change science (to be determined).
- additional competitive project funding for expanded inclusive multi-user research programs for collaborative, interdisciplinary projects in B2L and other facilities (to be determined).

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APPENDIX 1

PROGRAM AND PARTICIPANTS

Friday December 14

Check-in 1500-1800 (Hotel lobby)
Biosphere 2 Laboratory tours available
Dinner 1800-2000

Setting the context (Visitor Center)

2000-2030 Welcome and introduction (*Barry Osmond and Ed Bass*)
2030-2130 *Riccardo Valentini* (Director, CarboEurope and Euroflux networks)

Saturday December 15

Experimental Climate Change Science: needs and opportunities (Visitor Center)

0900-0920 Department of Energy perspectives (*Jerry Elwood*)
0920-0940 Columbia Earth Institute perspectives (*Michael Crow*)
0940-1000 Program perspectives (*Jeff Amthor*)
1000-1020 Workshop parameters (*Norman Chonacky*)
1020-1100 Coffee
1100-1200 Finding the niche for experimental global change science
Joe Berry (Carnegie Institution, Department of Global Change Biology)
1200-1400 Lunch

Experimental Marine ecosystems (Catalina Conference Center)

1400-1500 Panel presentations. (Chair Atkinson with Allen, Coelho, Falkowski, Glenn, Langdon and others)
1500-1530 Research presentation (*Chris Langdon*)
1530-1600 Coffee
1600-1730 Panelist-led group discussions
1800 Dinner
1900 Observing time at Biosphere 2 telescope
2000-2030 Experimental Marine ecosystems panel reports (Visitor Center)
2030 *Paul Falkowski* (Institute of Marine and Coastal Sciences, Rutgers)

Sunday December 16

Experimental Terrestrial Ecosystems (Catalina Conference Center)

0900-1000 Panel presentations (Chair Drake with Dubey, Hanson, Hendrey, Leuning, Matsuo, Medrano, Terashima)
1000-1030 Research presentation (*Guanghui Lin*)
1030-1100 Coffee
1100-1230 Panelist-led group discussions
1230-1400 Lunch
1400-1430 Experimental Terrestrial Ecosystems panel reports

Soil-plant atmosphere continuum (Catalina Conference Center)

1430-1530 Panel presentations (Chair Colwell with Dougherty, Kudeyarov, Lynch, Miller, Norby, Travis, Yokota)
1530-1600 Research presentation (*Ramesh Murthy*)
1600-1600 Coffee
1630-1800 Panelist-led group discussions
1800 Dinner
2000-2030 Soil-plant atmosphere continuum panel reports (Visitor Center)
2030 *Detlef Schulze* (Max Planck Institute for Biogeochemistry, Jena)

Monday December 17

Integrative Technologies Climate Change Science: stable isotopes (Catalina Conference Center)

0900-1000 Panel presentations (Chair Bowling with Evans, Gonzalez-Meler, Ribas-Carbo, Suits, Trumbore)
1000-1030 Research presentation (*Dan Yakir*)
1030-1100 Coffee

1100-1230 Panelist-led group discussions
1230-1400 Lunch
1400-1430 Integrative Technologies: stable isotopes panel reports

Integrative Technologies: remote sensing and other methods (Catalina Conference Center)
1430-1530 Panel presentations (Chair Clothier with Kolber, Kobayashi, Rascher, Walter)
1530-1600 Research presentation (*Caroline Nichol*)
1530-1600 Coffee
1600-1730 Panelist-led group discussions
1800 Dinner
2000-2030 Integrative Technologies: remote sensing etc panel reports (Visitor Center)
2030 *Klaus Lackner*, (Earth and Environmental Engineering, Columbia)

Tuesday December 18
Modeling and management (Catalina Conference Center)
0900-1000 Panel presentations (Chair Noble with Huxman, Leuning, Peterson, Smith and others)
1000-1030 Research presentation (*Vania Coelho*)
1030-1100 Coffee
1100-1230 Panelist-led group discussions
1230-1400 Lunch
1400-1430 Modeling and management panel reports

Summary and recommendations (Catalina Conference Center)
1430-1500 Summary, Los Alamos National Laboratory (*Paul Rich*)
1500-1530 Summary, Columbia Earth Institute (*John Mutter*)
1530-1600 Overall summary (*Barry Osmond*)

1600-1630 Coffee
1630-1700 Concluding comments on report preparation (*Norman Chonacky*)
1800 Dinner and departures

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APPENDIX 2

EXCERPTS FROM ABSTRACTS

(not all participants presented abstracts, and some presented abstracts but were unable to attend the rescheduled meeting following events of September 11 2001)

EXPERIMENTAL TERRESTRIAL ECOSYSTEMS

Bert Drake (Smithsonian Environmental Research Center)

Our understanding of the relationship between interacting environmental variables and the carbon, water, and nutrient cycles lacks both a conceptual and experimental framework.

- what is the magnitude of the future potential sink for carbon in terrestrial ecosystems?
- what is the present carbon content of terrestrial ecosystems?
- how do key biogeochemical cycles regulate long-term carbon sequestration and what are the time scales over which these processes operate?
- which processes constrain carbon sequestration and effectively limit the carrying capacity?

Manvendra K Dubey (Los Alamos National Laboratory)

While research programs are expanding from physical aspects of climate to include the carbon and water cycles, a more holistic experimental program that tackles interactions and couplings amongst them and to nutrients is needed.

- What are the potential impacts of multiple stresses on ecosystems?
- What are the limits of environmental change beyond which ecosystems are not sustainable?
- Will ecosystems trigger biogeochemical cycles that exacerbate or stabilize human-induced environmental changes?
- How can ecosystems mitigate global change and enhance their adaptive capacity?

Paul J Hanson (Oak Ridge National Laboratory)

For terrestrial ecosystems of interest, the standard for manipulative experiments should be to conduct realistic manipulations of relevant changes at representative scales with adequate replication. Key issues important to climatic change assessments that need to be understood which are tied to large scales or long time periods include:

- physiological responses to chronic vs. acute change, mature tree growth under realistic conditions
- inter-plant competition for water in realistic edaphic settings (e.g., deep soils) biogeochemical cycling of limiting elements
- seed production, seedling establishment
- tree mortality (including threshold temperature and/or moisture levels), gap phase dynamics.

George Hendrey (Brookhaven National Laboratory)

Many fields such as soil microbiology and biogeochemistry, forest community dynamics, and ecosystem modeling need to work together in a geographically broad based program that must have a long time frame. Important questions that can't be answered with current capabilities include:

- will simultaneous changes in temperature, CO_2 and O_3 result in no net increase in NEE for un-managed ecosystems?
- can process-level information gained from experiments conducted at the plot-scale can be applied to regional-scales with well defined error estimates in the spatial domain?
- are process-level models based on "first principals of ecology" developed from experiments conducted at the ecosystem-scale in one type of forest are equally valid for application to a different type of forest?
- do forest experiments with multiple plots encompassing tens of square meters in which atmospheric variables are manipulated, accurately represent regional forest ecosystem responses to long-term (decadal) changes in those variables?

Travis E Huxman (University of Arizona)

While we may be able to evaluate short-term responses of terrestrial vegetation to climate change, there is great difficulty in measuring long-term ecological and evolutionary aspects of global change. The following questions may have an important role in controlling biosphere response to climate change:

- What is the potential for an evolutionary response in terrestrial ecosystems that would affect our prediction of future ecosystem function? Our current scale of experimentation (both spatial and temporal) is insufficient to evaluate the potential for an evolutionary response in plants. It is difficult to avoid small population dynamics that confound results in glasshouse and growth chamber experiments. In FACE rings, gene flow into and out of the treatment plots is not controlled, and agents of selection, such as pollinators or herbivores are not confined to the FACE treatment. If land cover change is a dominant feature of global change, evolutionary responses of plants may play an important role in controlling shifts in vegetationHow do trophic interactions behave and feed back on vegetation composition? Confining herbivores, granivores and secondary consumers in treatments associated with a global change variable is not currently an experimental option, yet the role of higher trophic levels in controlling vegetation composition in terrestrial ecosystems is recognized as important.

- What is the role of precondition at the ecosystem scale in determining a response to global change? By analogy with our understanding of the role that pre-condition plays in the response of individual species to a climate perturbation (e.g., the role that water status plays in regulating the CO_2 response of plants), what is the role of a larger scale system 'pre-condition' (such as protracted drought) in defining a response to a climate perturbation?

Richard J Norby (Oak Ridge National Laboratory)
Understanding terrestrial responses to climatic change involves issues of scale, and this is particularly so for forest ecosystems. Simply put, forest trees are big and they live a long time. There are no manipulative experiments addressing the effects of warming, or the interaction between CO_2 and warming, at a forest stand scale. Future research requires that the experimental scale be increased to a catchment scale so that critical biotic and abiotic interactions are represented. Some key research questions include:

- Do the physiological responses of individual trees to elevated CO_2 lead to sustained increases in forest NPP?
- If forest NPP is enhanced by elevated CO_2, how long is the additional carbon that enters the ecosystem retained in plant biomass or soil?
- Will differential species responses to CO_2 and warming alter the composition and structure of forests?
- How will critical ecosystem services, especially water supply, be impacted by atmospheric and climatic change?

What is the minimum scale that ecosystem-relevant observations can be made of biotic interactions with CO_2 and climate change effects?

Hipólito Medrano and Miquel Ribas-Carbó (University of Balearic Islands, Spain)
Semi-arid regions, like the Mediterranean, are characterised by a long-lasting drought period, which usually happen together with high irradiance and temperature. Global change models predict an increased drought severity in these regions, caused by increased average temperature (i.e. increased potential evapotranspiration), as well as due to decreased overall precipitation. Nevertheless, there are very few studies on the ecophysiological response of plants to a combination of high CO_2, high temperature and drought.

Ernst-Detlef Schulze (Max Planck Institute for Biogeochemistry, Germany)
Several large scale experiments have been carried out in the past to study single processes. New experiments should address community level-questions rather than single factors. If I had the experimental facilities, I would test the following hypotheses or questions:

- will ecosystems under constant conditions will ever reach an equilibrium?
- do ecosystems need a minimum size for stability?
- is high spatial variability the basis for stability (chaos research)?
- does maximum C storage in soil profiles depends on the soil macrofauna?
- does the statistical treatment of experimental data ignore interpretation of extremes?

Uli Schurr (Research Center Jülich, Germany)
Biosphere 2 would be probably best used in analyzing kinetics of biomes, as I guess it will be difficult to do long-term or steady state experiments in B2 for various reasons (in long-term experiments it will always be asked, if the biome is really similar to "the rainforest", etc., which is hard to say). Long-term experiments will not allow many users to take part in the experiments and thus less important as a central facility. Long-term experiments will probably be less cost-efficient. Subjecting the biomes to environmental changes will cause adaptation processes with different time constants according to the turnover time of individual pools in the biomes. For example in the soil there are probably important but very slow exchanging pools compared to the aboveground. I guess that it will therefore (a further argument against steady-state experiments) be very difficult to reach a new steady state in all pools of the biomes, if there is a steady state at all. It also

requires the development of new techniques, which are less invasive and the simultaneous involvement of a number of scientific disciplines. It should aim for an analysis of pool size and pool dynamics in the biomes. Analysis of kinetics of adaptation is

- highly relevant for the impact of global change on individual biomes
- difficult to do in the field, as too many parameters vary,
- well suited to the facility, as it allows to adjust conditions rather fast,
- lifts the restrictions of replicates, as the dynamic itself is replicable
- of great value scientifically, as it indicates the boundaries/ range of adaptive kinetics of biomes.

Ichiro Terashima (Osaka University, Japan)
The C/N balance in plants changes with the increase in the concentration of atmospheric CO_2. This affects various processes of C and N cycling in the ecosystem as well as in the plant. In particular, mineralization processes in the soil and N use in the tree species should be studied.

- C/N ratio of the litter increases and thereby enhances immobilization of nitrogen. Then, the concentrations of nitrate and/or ammonium would decrease and decelerate plant growth. The slow growth may restore C/N balance of the litter.
- Function of mycorrhizal fungi. Do they also immobilize N? Alternatively, does regulation of fungi by host plants results in enhancement of mineralization?
- Models for the tree growth should be improved so that they can be the basis of IBM models. We have recently proposed a branch growth model, which is in the form of the differential version of the Shinozaki's pipe model theory.

EXPERIMENTAL MARINE ECOSYSTEMS

Marlin Atkinson (University of Hawaii)
Experimental facilities are required to create closure/ mass balances and manipulate variables, objectives that it is almost impossible to achieve in the field. It is predicted that climate change will:

- increase surface ocean aqueous CO_2, decreasing CO_3. Measurements are required at both organismal scale and community scale of the effects of rising CO_2 concentrations on organic carbon production (gross and net primary production), calcification and dissolution of calcifying ecosystems.
- increased frequency and magnitude of storms. Water motion influences communities through breakage and alteration of community structure, mass transfer between water and organisms and can set limits to biogeochemical exchange processes.
- alter water runoff patterns, increasing nutrient and sediment loading to near-shore systems.
- increase surface ocean temperatures, stimulating coral bleaching.

Wally Broecker and Chris Langdon (Columbia University)
Experiments are needed to study the effects of a CO_2 doubling on marine ecosystems. It is likely that there will be many unexpected consequences. Simulating a CO_2 doubling in even a small piece of a natural ecosystem and observing the response on time scales from days to years is a difficult and expensive proposition. For the foreseeable future the use of model systems (mesocosms) will play an important role in providing answers and pointing the way to new testable hypotheses in the following areas:

- the impacts of light, temperature, nitrate concentration and carbonate ion concentration on the growth and ecology of coralline algae,
- the role of rainfall in gas exchange,
- the role of water turbulence (as opposed to wind stress) on gas exchange,
- the role of turbulence in nutrient uptake by coralline algae.

Jonathan Allen (Arizona State University)
Air-sea interactions are potentially significant in global energy budgets through aerosols and relationships with cloud formation. Some key questions include:

- how are fluxes of DMS and organic coating of sea-spray aerosols related top wind, waves, and bubbles?
- how are these aerosol components related to ocean biology?
- how is gas exchange governed by sea-surface state?

SOIL-PLANT-ATMOSPHERE CONTINUUM

Frederick Colwell (Idaho National Environmental and Engineering Laboratory)

Conservative estimates indicate that more than half of the world's biomass consists of microorganisms in the earth's soils, subsurface sediments, marine waters and other environmental media. Yet, because they are exceedingly diverse, usually cannot be grown in culture, and discrete on the scale of the individual microbial cell, evaluation of the phenotypic, genotypic, and ecological traits of microorganisms in the environment has been a slow process. The following questions concern the functions of microorganisms in earth systems, are relevant to the issue of climate change, and are difficult to resolve given the current state of technology:

- How will the metagenomes for key soil habitats change as climate (e.g., moisture, temperatures, and selected gases) changes?
- Will key microbial functions that correspond to the cycling of specific elements change along with alterations in the metagenomes?
- Traditional measures of microbial activity disturb soil communities. How can microbial activities be measured in situ so that they are not significantly altered?
- How do molecular measures of microbial activity (e.g., rRNA:rDNA ratios, level of specific mRNA within cells) correspond to "volumetric productivity" of microbial communities in soils for specific key microbial processes?

Bryan Travis et al (Los Alamos National Laboratory)

Does microbial biomass significantly affect the climate? The Biosphere 2 resource provides a unique opportunity to address this question, through a combination of monitoring, experimentation and modeling. Clearly, the microbiology and soil chemistry of the different biomes can be monitored at sufficient resolution to permit detection of relationships between atmosphere and soil conditions.

- Techniques such as PCR analysis allow determination of which microbial species are present and in what abundances, and how they are distributed spatially, and assays of metabolic by-products can reveal changes in microbial activity.
- Pore water and soil grain chemistry will impact microbial activity and must also be monitored.
- These data can constrain and calibrate quantitative models of microbial activity coupled to water and gas fluxes.
- Models must not only capture microbial metabolic dynamics, but also couple it to the time-dependent flow of gases and water through the soil-air interface.

Michael Miller (Argonne National Laboratory)

A primary determinant of a mycorrhizal fungal community is climate, through the effects of vegetation on pedogenic processes.

- The predominant mycorrhizal fungus in a system and its contribution to biogeochemical processes are also determined by the state, concentration, and distribution of nutrient ions in soils.
- Recognition of feedback by climate and soils on mycorrhizal fungi reveals little about the response of systems to disturbance or to more subtle climatic insults, but rather points to the difficulty and complexity of scaling up to predict larger-scale ecosystem responses.
- We need to be able to identify those lower-level processes that help determine why plants grow where they do, but in a manner that integrates across scales.

Brent Clothier and Steve Green (Horticulture and Food Research Institute, New Zealand)

Roots, the big movers of water and chemical in soil, are often the arbiters that determine both the direction and magnitude of mass and energy flows near the Earth's surface. Thus the impact of any climate changes on Earth systems will, probably to a great degree, be controlled by changes induced to the functioning of the myriad of biophysical mechanisms operating in the rootzone. Harper noted that *"plant root systems present the research worker with many of the great unresolved problems in plant sciences"*. Here we list several conundra that we have, thus far, been unable to resolve in our rootzone studies.

- Roots are hidden from easy view. Although new devices to gain vision with greater acuity of root activity are available, but difficulties remain in linking root form with root functioning. However, we still have a long way to go, and new devices that record remotely, and better integrate spatially, are required.

- Water is the vehicle for transporting nutrients and contaminants through the root zone, and we have a reasonably good grasp of root water-uptake, but not so with discriminating between passive and active uptake mechanisms of chemical uptake by roots.
- Soil is not a uniform, isotropic medium: rather macropores, fissures, and cracks lead to rapid and preferential flows of water and solutes that can be far reaching. Plant roots are often the creators, and sustainers, of these high-velocity flow networks, and better observations, and improved topological descriptions of these transport networks, are needed.
- Improved hardware, and off-the-shelf software packages have led to the development of comprehensive numerical models of rootzone processes and plant growth. Application of these models requires so many parameters that many current models are probably incapable of validation. Nonetheless, good models, applied wisely, will help predict the impact of climate change on the functioning of earth systems.

Jonathan Lynch (Penn State University)
The productivity of terrestrial ecosystems is limited by mineral nutrients and several aspects of climate change interact to determine nutrient bioavailability, thereby modulating or fundamentally altering ecosystem responses. These interactions include:

- Manganese toxicity is prevalent in many humid and subhumid forests, and uptake is modulated by precipitation, acid deposition, and CO_2. Interacting with light flux, temperature and UV, Mn toxicity creates species specific oxidative stress in leaves.
- Low phosphorus availability is a primary limitation on plant growth through regulatory interactions during metabolism, and influences on carbon allocation and soil biotic relationships.
- Low calcium availability in most forest soils is exacerbated by acid deposition and human activities. Growth responses to CO_2 and N deposition will increase Ca demand, and deficits could accelerate biotic stress.
-

Susan Trumbore (University of California, Irvine)
Our process level understanding of soil metabolism is inadequate as a basis for ecosystem carbon flux models. Key unknowns include:

- Are there "rules" for allocation of photosynthetic products (metabolism, storage, construction above-or below-ground), and for the overall residence time of C in living plant tissues, that vary between functional plant types and respond differently to changed climate and nutrient availability?
- What controls the year-to-year variation in CO_2 emission from soils (and ecosystem)? In other words, how is CO_2 emission partitioned into above- and below-ground components, metabolic plant respiration versus heterotrophic decomposition, and what variables control each? Are there "rules" that can be used to scale across ecosystems or biomes to predict the flux of C from ecosystem to atmosphere (and its overall residence time in the ecosystem)?
- What determines the amount of C respired by living roots, is the C respired by living roots coming from storage pools or fresh photosynthetic products, does it vary according to soil physical conditions (moisture, temperature) or respond more to plant activity (seasonality, photosynthetic uptake rates). The same kinds of questions can be asked for heterotropically produced CO_2 (how much comes from what kind of organic matter substrate), and which component of soil fauna (fungi versus bacteria, macrofauna versus microfauna) controls decomposition of organic matter in soils, when?
- How can we identify the status of soils as gaining or losing carbon? At present, we can determine the capacity for storage on a variety of timescales, but not how soil is functioning instantaneously. Are fluxes too small for this to be a significant question?

STABLE ISOTOPES AS AN INTEGRATING TECHNOLOGY

Miquel A. Gonzalez-Meler (University of Illinois at Chicago)
Increasing evidence indicates that raising atmospheric CO_2 enhances GPP in most ecosystems, however, the extent to which NEP will respond to rising CO_2 and climate is still unresolved due, largely, to our inability to reliably determine ecosystem respiration (ER) or any of its components. Recently, stable isotope techniques of ^{13}C and $^{18}O/^{16}O$ of respired CO_2 and $^{18}O/^{16}O$ of O_2 have helped to evaluate the biotic and abiotic effects on autotrophic and heterotrophic respirations. Research on components of ER should address the following questions:

- To what extent does ER control sequestration of atmospheric carbon in forested ecosystems and how is it affected by a changing environment?

- What are the components of ER that exert the greatest leverage in determining the direction and magnitude of C sequestration as CO_2 concentration rises?
- What are the main physiological processes involved in the response of components of ER to CO_2 and climate?

Jeffrey M. Heikoop (Los Alamos National Laboratory)
An experimental environment is required that is somewhere between the oversimplified bench scale and the overly complex natural environment in order to understand isotopic signals of plant response to environmental change. Necessary experiments require that environmental parameters can be varied both in isolation and in combination.

- Identifying the carbon and nitrogen isotopic signatures of CO_2 enrichment, water availability, and nutrient loading in wetland plants -- potential tool for monitoring environmental change and reconstructing history of plant response to past change.
- Develop isotopic proxy records of past surface ocean productivity (as affected by limiting micro-nutrients, nitrogen supply, temperature etc.) from the proteinaceous skeletons of deep-sea corals – reconstruct history of surface ocean productivity as affected by past environmental change to better predict effects of future change – use shallow water analogues (azooxanthellate) in Biosphere 2 ocean.
- Test the fidelity of nitrogen isotopes in tree wood (following appropriate pretreatment) as an indicator of nitrogen sources that have affected tree growth – go back through time in dendrochronological record to see if increases in atmospheric deposition of reactive nitrogen have influenced plant growth in various settings.

REMOTE SENSING

Zbigniew Kolber (Institute of Marine and Coastal Sciences, Rutgers University)
Ambient CO_2 concentration, nutrient limitation, and drought or temperature stress, all affect photosynthesis by selectively controlling the biosynthesis, molecular assembly, and functional coordination between molecular components of the photosynthetic apparatus. The photosynthetic status of terrestrial vegetation can be determined by the rates and efficiencies of the primary stages of light-driven photochemistry. The resulting changes in photosynthetic performance can be objectively assessed from a remotely measured fluorescence signal induced by a laser excitation source. The methodology for remote measurements of photosynthetic parameters in terrestrial vegetation, called LIFT (Laser Induced Fluorescence Transient) technique, has recently been developed within the NASA Instrument Incubation Program and can measure the yield of the primary photochemistry, and the kinetics of photosynthetic electron transport, remotely, at a distance of 10 to 50 meters. These measurements will be used to:

- identify the photosynthetic signature of vegetation response to changes in CO_2 concentration and various types of natural/ anthropogenic stresses in terrestrial ecosystems
- develop a methodology for remote/autonomous measurements of photosynthetic characteristics in different types of installation and experiments related to climate change;
- design a strategy for long term monitoring of the photosynthetic characteristics in terrestrial vegetation.

These goals are achievable in B2L where the instrumentation can be calibrated against net CO_2 exchange during manipulative experiments in different types of environments, on scales relevant to natural ecosystems.

Kenji Omasa (University of Tokyo)
Phytobiological IT is the concept for measurement and analysis of complex biomes and for solving earth system questions systematically by joining a lot of research technologies, especially remote sensing. Phytobiological information on cells, individual plants and biomes should be obtained by image sensing technologies as well as ordinary experiments and field survey. Image sensing technologies provide spatially a lot of functional information as well as structural information on cells, individual plants and biomes. New technical trends in the image sensing technologies are hyper-spectral, hyper-spatial, three-dimensional, and active sensing (see references). Our phytobiological information system (PIS) is a management system with functions of database and modeling using the measured data. In order to cope with problems at global levels, this system should be connected with geographical information system (GIS) and expert-knowledge system via networks on the Internet, and should be opened for education and policy making as well as research. I think that we need such a system to solving earth systems questions in climate change science.

Uwe Rascher (Columbia University, Biosphere 2 Center)
The accessibility to the outer canopies in B2L facilitates remotely sensed integrative narrow waveband reflectance measurement that can be compared with single spot measurements of effective quantum yield of photosynthesis and high resolution imaging of both, effective quantum yield of photosynthesis and dynamic growth rate. Appropriate mathematical tools and methods can be applied to understand the spatial and temporal dynamics of complex systems. These include: cellular automaton techniques for analysis of spatio-temporal variations during the endogenous CAM-rhythm of an anatomical simple leaf can be used, to quantify heterogeneity, fluctuation and the fractal dimension of borderlines in images.
external, periodic stimulation can be applied to extract internal dynamics from medium-sized experimental model systems, which consists of a few (5-8) dynamic pools only, can be set up to test mathematical methods, which will be used to recalculate dynamic properties of the component pools from system measurements.

MODELING

Ray Leuning (CSIRO Land and Water, Australia)
Potential responses of the terrestrial biosphere are far more numerous than can ever be studied using experimental methods alone. The response surfaces are complex and there must be a strong modeling effort that is closely integrated with the experimental program and vice versa. Some questions which may be answered by a combined modeling/measurement program are:

- does vegetation acclimatize to changes in mean temperature, humidity and CO_2 concentrations?
- do terrestrial ecosystems become saturated with carbon?
- what are the interactions between nutrient supply and carbon storage capacity?
- how does species composition change in a high CO_2 world?

Dr. Andrew Peterson (Columbia University, Biosphere 2 Center)
Development of a mechanistic understanding of how elevated CO2 can affect nonlinear responses of organisms to environmental variation, and how those responses may cascade across biological, spatial, and temporal hierarchies. Can generalizations be made across different types of systems (e.g., terrestrial and marine, desert and rainforest)?

- ·How does environmental variation at different time scales ranging from seconds to years affect these nonlinear processes?
- Development of a mechanistic understanding of how increasing levels of CO_2 and predicted changes in climate variability will affect species coexistence in terrestrial plant communities, and what are the consequences for ecosystem function.
- Development of a better understanding of how elevated CO_2 may affect weather and climate variation at local to regional scales.

Paul Rich (Los Alamos National Laboratory)
Biosphere 2 can serve as a biocomplexity laboratory that bridges greenhouse experiments with models at meso, regional, and global scales, in particular focusing on implications of elevated carbon dioxide and climate change. A critical issue in the environmental sciences is the couplings and feedbacks (associated with biocomplexity). Los Alamos National Laboratory's (LANL) expertise in biocomplexity theory could be coupled with Biosphere 2 capabilities to

- produce a "virtual biosphere" model for quantification and prediction of complex environmental dynamics in three-dimensional space with the goal to predict ecosystem/atmospheric responses.
- scale B2L measurements and modeling efforts with field studies
- validate the model in semiarid ecosystems, specifically the Rio Grande Basin and the Jemez Mountain Gradient (LANL NERP). The spatially explicit modeling approach can account for dynamic shifts along environmental gradients, as well as changes in patch extent and connectivity with time.

NEW APPROACHES

Seiichi Matsuo (Research Institute of Innovative Technology for the Earth (RITE), Japan)
RITE was established in July 1990 as an international research hub to promote development of innovative environmental technologies & increase of CO_2 sinks. After being founded, RITE has been working on CO_2 fixation, utilization & sequestration under the full support of the Japanese government. RITE also plays an important role in the CO_2 stock related projects and the Japanese government is totally sponsoring the following projects:

- new earth research project
- desert-greening project
- project for fixation of CO_2 by utilizing used paper
- research and development of technologies for reforming CO_2-containing natural gas using solar energy
- CO_2 ocean sequestration project
- CO_2 underground storage project.

Akiho Yokota (Nara Institute for Science and Technology, Japan)
We are engaged in the "Creating Desert-Greening Plants" project in both RITE and NAIST. This research is based on the chloroplast gene manipulation technology. We have already created tobacco plants that can survive severe drought and high-light conditions. During the course of the research, we succeeded in synthesis of a large amount of a foreign protein in tobacco chloroplast. This will open the window for utilization of plant chloroplasts as a protein-manufacturing factory in the future. The project consists of the following projects:

- creating plants with RuBisCO that can fix CO_2 more efficiently than the present plant RuBisCO,
- creating plants with strong electron sinks that can protect plants from excess photon energy stresses,
- creating plants that can synthesize commercially valuable materials.

The value of these designer plants in future climates can only be assessed in comprehensive controlled, closed facilities such as B2L.

MINORITY OPINION
On the question of whether this a consensus report ...

The B2L report generally reflects what the B2L insiders presented to the rest of us at the workshop. I personally do not agree with many of the specific conclusions or general tone of the report, and I do not think that it reflects the views of many of the "outsiders" who attended the workshop. The report might well have been written before the workshop and without benefit of the discussions that transpired. I am not especially surprised by this - I was very much aware during the workshop that the summary reports that were presented by insiders did not at all reflect the discussions of the breakout sessions. The report also suggests that a lot of DOE's requested agenda (infrastructure, costs) was discussed, but I heard very little, at least in open discussion. I think this report should be presented for what it is - a marketing tool for B2L and not a consensus report of an independent science community.

A few specific points -

Over and over I heard non-B2L participants attempt to point out that this was not a facility designed for ecosystem research; rather it should be consider a large and unique growth chamber in which specific mechanisms of response can be tested. The report, however, continues the view that large-scale ecosystem research will indeed be conducted there and will address the important priorities expressed by May and in the National Assessment and Pathways reports. I see some of my research priorities and questions for global change science presented in the report; what is missing, however, are my comments (which were supported by others) that these questions could not be addressed at B2L.

A number of people pointed out the impossibility of doing every sort of experiment that was being suggested. It is not possible to be simultaneously conducting short-term studies (quick replication in time) and long-term studies and multi-factor manipulations (multi-year drought cycles) in these facilities. The report, however, presents all of these possibilities simultaneously. The soil problem was about the only aspect of infrastructure I heard discussed openly. The problems with the soil were considered very important by most of the outsiders, yet this is largely glossed over in the report. Light quality was barely discussed. The difficulty in achieving mass balance in the agricultural bays I heard mention only in private conversation.

A budget discussion would have been interesting, but I never heard any of it. The budget numbers in the report (e.g., $2million per FACE experiment) certainly is not accurate. An open discussion at the workshop on federal budget priorities and how B2L might rank with the other demands on the budget would have been interesting.

I have no objection to B2L preparing a report extolling the facility's virtues, and I do not wish to be a naysayer about B2L's possible contribution. Nevertheless, I do not think this report should be presented as a consensus report of the science community (many of whom declined to attend because they wanted no part of it). And regardless of what the "vote" is on this report, I do not want it to suggest that it reflects my views.

Sorry to be a troublemaker!
Best regards,
Rich Norby

APPENDIX 3
BIOSPHERE 2 LABORATORY PUBLICATIONS 1998-2001

1998
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