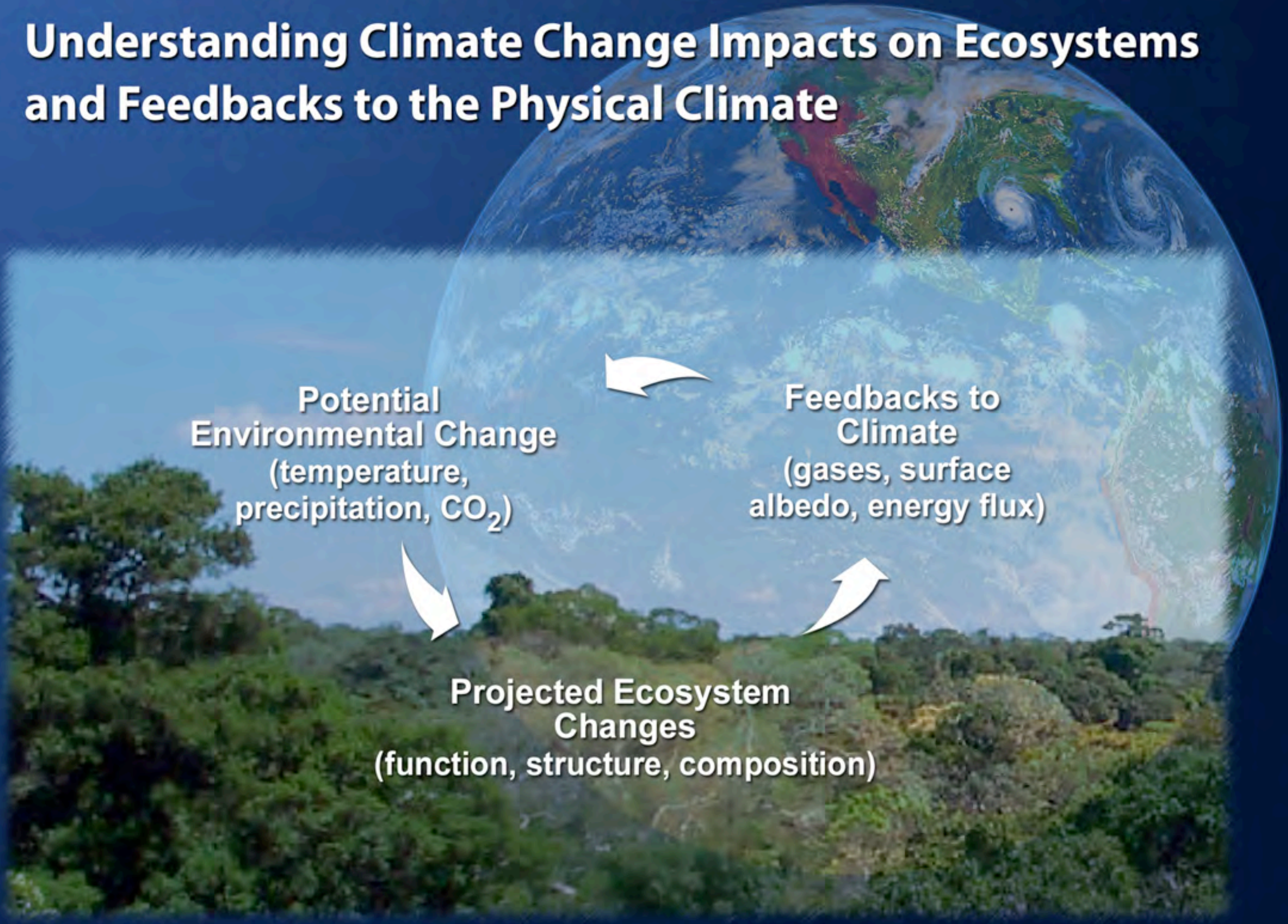
# Ecosystem Experiments

## Understanding Climate Change Impacts on Ecosystems and Feedbacks to the Physical Climate



Report of the Workshop on Exploring Science Needs for the Next Generation of Climate Change and Elevated $CO_2$ experiments in Terrestrial Ecosystems

14-18 April 2008 – Arlington, Virginia

## Front Cover

From the top and left:

- The Earth from space; front cover design by David Cottrell
- Wet tropical forest canopy (Photo credit – FLUXNET photo gallery). The superimposed text and arrows represent the hypothesized continuous and interrelated process of climate and atmospheric impacts, ecosystem changes, and subsequent feedbacks to the physical climate system.
- Free-air $CO_2$ experimental ring in Tennessee (Photo credit – ORNL #129762-97)
- Drying treatment infrastructure beneath Pinyon-Juniper Forests in New Mexico (Photo credit – Judd Hill)
- Infrared warming array over crops in Arizona (Photo credit – Bruce Kimball)
- Plot-scale air and soil warming in Manitoba, Canada (Photo credit – Paul J. Hanson)

# ECOSYSTEM EXPERIMENTS: UNDERSTANDING CLIMATE CHANGE IMPACTS ON ECOSYSTEMS AND FEEDBACKS TO THE PHYSICAL CLIMATE

Report of the workshop on
Exploring Science Needs for the Next Generation of Climate Change and Elevated-$CO_2$
Experiments in Terrestrial Ecosystems

14-18 April 2008
DoubleTree Hotel, Crystal City, National Airport
300 Army Navy Drive, Arlington, Virginia

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and Workshop Participants*

**A complete list of workshop contributors is located on the next page.*

16 June 2008

**Acknowledgement:**

This workshop was organized and operated by the Environmental Sciences Division Oak Ridge National Laboratory with support from the U.S. Department of Energy, Office of Science, Biological and Environmental Research. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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# EXECUTIVE SUMMARY

The dynamic natural carbon-cycle processes responsible for storing energy in the past are still functioning within today's terrestrial ecosystems to sustain life on Earth through the production of food, fiber, biofuels, breathable air, and naturally purified water. Furthering our understanding of how terrestrial ecosystems will respond to future climatic and atmospheric change is an essential component of an integrated climate change research program. Terrestrial ecosystem research is critical for evaluating the net greenhouse gas balance between the Earth's surface and atmosphere, where it contributes to climatic change. Projections of ecosystem modifications associated with climate change are also necessary for the evaluation of mitigation and adaptation strategies by policymakers and society.

The Department of Energy's Biological and Environmental Research Advisory Committee (BERAC) concluded in a report dated 16 October 2006 that DOE should "*Immediately plan and initiate a workshop(s) to plan the next generation of climate change and elevated-$CO_2$ experiments, incorporating multiple interacting climate change factors and potentially different elevated-$CO_2$ designs and/or technologies".* In response to that recommendation, DOE supported a community-based workshop to explore science needs for the next generation of climate change and elevated-$CO_2$ experiments in terrestrial ecosystems, held in Arlington, Virginia, from 14 to 18 April 2008. Participants in the workshop included a mixture of selected ecosystem experimentalists and modelers supplemented by human-dimensions and global climate modelers from universities, DOE national laboratories, and other federal agencies. The workshop included a small number of plenary lectures to provide context, but the focus was on small-group interactions tasked to discuss the critical scientific needs surrounding two general questions:

- What are the key scientific uncertainties surrounding the combined impacts and feedbacks of warming and changes in moisture status, in combination with elevated $CO_2$ concentration, on the functioning, structure, and composition of terrestrial ecosystems?
- What existing or new facilities and methods are needed to conduct long-term ecosystem-scale warming, precipitation, elevated-$CO_2$, or multiple-factor-manipulation experiments in the field?

In addition, breakout groups were tasked to identify (1) key science questions for the interpretation or projection of climate change responses or feedbacks, (2) terrestrial ecosystems demanding priority attention in future studies, and (3) the technological and measurement requirements needed to facilitate logical experiments or interpret ecosystem responses. Workshop conclusions addressing these and other areas are listed below.

***Climate Impacts Research.*** – Impacts are changes in the state or function of ecosystems attributable to climate or atmospheric change. Impacts can be adverse or beneficial. The body of available work indicates a clear need to resolve uncertainties in the quantitative understanding of climate change impacts. A mechanistic understanding of physical, biogeochemical, and community mechanisms is critical for improving projections of ecological and hydrological impacts of climate change. Characterization of long-term ecosystem responses is a requisite input to the estimation of ecosystem feedbacks via carbon, energy, and water budgets. A clear limitation to the development of such projections is the limited mechanistic basis for projecting geographic range shifts by species (or species composition change within a given ecosystem) and the consequence of such changes for the physical climate.

The most important drivers of long-term responses are temperature, water availability, and the composition of future atmospheres. Workshop participants believed that threshold and nonlinear effects of these key drivers were especially important and should be given a high research priority. Inundation of coastal terrestrial ecosystems, increased disturbance from fire, and increased biotic perturbations (e.g., herbivory, pests, and pathogens) were recognized as important secondary effects of climatic and atmospheric change.

Workshop participants concluded that it is not possible to predict future ecosystem responses from the historical record. One reason is that no broad historical record of natural plant exposures to projected elevated $CO_2$ levels is available for interpretation. Furthermore, it is likely that ecosystems long exposed to certain stable environments would exhibit different properties than ecosystems only recently exposed to such conditions. *Unprecedented rates of climatic change induced by anthropogenic greenhouse gas emissions demand that researchers conduct experimental manipulations to understand ecosystem responses to unprecedented future climates.*

***Climate Feedback Research.*** – Feedbacks are mechanisms connecting some element of the climate to a terrestrial ecosystem where an ecosystem response, in turn, influences the climate forcing. Uncertainty in the magnitude and, in some cases, the direction of key feedbacks between Earth's climate system and terrestrial ecosystems is one of the critical weaknesses in current projections of climate change futures. For example, increased $CO_2$ uptake and storage by terrestrial ecosystems creates a negative feedback on greenhouse gas forcing. Conversely, warming-induced metabolism of soil organic matter in northern ecosystems provides a positive feedback by releasing more greenhouse gases into the atmosphere. Identification of the overall dimensions of terrestrial-ecosystem feedbacks demands mechanisms for two-way coupling between climate and terrestrial ecosystems.

Major uncertainties must be resolved in how ecosystems with large areal extent and influence on the carbon cycle will respond to warming and to warming in combination with increasing $CO_2$ and changing water availability. While participants emphasized the need for understanding critical feedback processes in northern, high-latitude ecosystems and in wet tropical forests, they also recognized the need for new and continuing experimentation in temperate systems that also constitute a significant global carbon sink.

*Future terrestrial climate change research on feedbacks must include a portfolio of multifactor and multilevel global change experiments including warming, elevated $CO_2$, changed nutrient supply, and altered precipitation*. Single-factor or single-level studies do not provide an adequate basis for quantifying response surfaces needed to support mechanistic models of ecosystem response to climatic and atmospheric change. The portfolio of funded research should also include long-term experiments to address the time scales over which biogeochemical limitations or compositional changes in vegetation take place so that the implications for terrestrial forcing of the climate system can be quantified.

***Model-Experiment Interactions.*** – Workshop participants agreed that model–experiment interactions need to become a formalized component of climate change research. The interactions need to include pre-experiment planning and hypothesis generation, data organization and synthesis during experiments, and post-experiment interpretation of results. There must be a model framework that identifies critical processes to be informed by experimental data, and new experiments should be designed around modeled projections of logical hypotheses and anticipated interrelationships. Inclusion of mechanisms responsible for species changes (seed production, establishment success, and early growth) within mechanistic biogeophysical models of ecosystem function is essential for the projection of the fate of ecosystems and their organisms under climatic and atmospheric change.

***Priority Ecosystems.*** – Because all ecosystems are fundamentally important to local inhabitants and their livelihoods, next-generation research on climate change impacts should not arbitrarily exclude any ecosystems. However, in a conscious attempt to prioritize next-generation experiments, workshop participants agreed on some general principles to help select ecosystems for evaluation. Those criteria included:

- The inherent sensitivity of ecosystems to warming, $CO_2$, and precipitation change;
- The areal extent of ecosystems for global feedback concerns;
- The ability to serve as model ecosystems that allow for the testing of cumulative interactions (e.g., fast-growing or low-stature ecosystems), and
- The potential loss of critical ecosystems and the services they provide (e.g., coastal systems and surge protection, alpine and other systems critical to water supply, biodiversity, etc.).

Managed ecosystems, defined as those ecosystems intentionally subjected to a range of manipulations to provide food, feed, fuel, and fiber for human use, were highlighted for continued research attention. Current interest in the use of terrestrial land surfaces for the production of biofuels makes them a special type of managed ecosystem that DOE in particular should evaluate.

***Technological and Measurement Needs.*** –Research requires an integrated approach to research design and execution. Next-generation experiments must emphasize quantitative responses to climate (temperature and precipitation) and $CO_2$ at treatment levels that include and exceed conditions expected by the end of this century. Key strategies for the development of new experiments include:

- Conceiving experimental systems and designs capable of attributing cause-and-effect mechanisms for known environmental drivers
- Including studies of multilevel exposures to judge nonlinear responses,
- Incorporating trophic levels and island effects into plot-level experiments
- Incorporating the essence of disturbance regimes into experimental designs,
- Improving or establishing new methods for conducting environmental manipulations of *in situ* or model ecosystems,
- Utilizing new and unique experimental infrastructure for climate change manipulations to address both impacts and feedback questions,
- Understanding and acknowledging potential implications of step changes in experimental designs, and
- Developing and exploiting statistical and modeling tools for the interpretation of experimental results.

Workshop participants did not accomplish a full discussion of new and improved measurement technologies at this workshop. Therefore, they recommended one or more follow-on activities to identify and prioritize physiological and ecological measurement methods to achieve quantitative measurement capacities in support of model evaluation, improvement, and application to climate-change-effect questions.

**Summary.** – The conclusions of this workshop are consistent with other community evaluations. They reinforce the DOE Grand Challenges framework for ecosystem research, which identified experimental approaches as a required component of ecosystem research. Attention to the research needs outlined in this report will enhance the science community's capacity for projecting future climates and correctly identifying sensitive impacts and ecosystem responses worth mitigation or adaptation.

# 1. BACKGROUND AND JUSTIFICATION

Research to date has now identified clear climate trends that exceed normal expectation of "natural" variability, and ample data support the conclusion that greenhouse gas production from energy technologies represents a major driver of climate change (Solomon et al. 2007). Fossil-fuel consumption together with human land use represent the primary drivers responsible for future climate changes of concern. With the recognition of the cause and the likely magnitude of future climate and atmospheric changes, climate change science has transitioned to a focus on questions regarding the level of future climate change, and the impacts that those levels will have on natural and managed ecosystems. Global societies are demanding to know what will happen, when it will happen, where it will happen, and the extent to which climate changes will affect the capacity of humans to sustain or enhance their quality of life.

## 1.1 Ecosystems, Climate Change, and Energy Policy

Ecosystems of the past sequestered the majority of energy used today as fossil fuels through capture of solar energy via photosynthesis and storage as carbon-containing compounds. The same processes responsible for storing energy in the past sustain life on Earth today through the production of food, fiber, biofuels, breathable air, and naturally purified fresh water.

In addition to ecosystems' tangible role for sustaining life, terrestrial ecosystems currently represent a critical net sink for carbon dioxide released by fossil-fuel emissions. The natural or manipulated C sink capacity of Earth's ecosystems regulates the rate of increase of greenhouse gas concentrations in the atmosphere and subsequent warming of the Earth's surface. Future greenhouse gas concentrations are projected to cause climate changes that compromise the capacity of Earth's natural and managed ecosystems to remove $CO_2$ from the atmosphere and sustain production of desirable goods and services for human society, such as food and water for consumption or energy production.

The amount of climate warming depends on how quickly greenhouse gases, especially carbon dioxide, accumulate in the atmosphere. Carbon dioxide is released to the atmosphere by combustion of fossil fuels and clearing of forests, but it is also continuously taken up and released by plants and soil. Biological cycling of carbon through terrestrial ecosystems is an order of magnitude greater than is anthropogenically emitted each year (CCSP 2007). These natural flows of carbon into and out of plants and soil respond to changes in temperature, precipitation, and atmospheric carbon dioxide. This means that future climate warming depends both on human actions and on the response of plants and soil to a changing environment.

Current research progress has advanced ecosystem science to a position where the research community can now identify and prioritize key questions and variables for future study. Nevertheless, our understanding of plant and soil responses to changing temperature, precipitation, and carbon dioxide and their interactions are still insufficient. The magnitude and, in some cases, the direction of ecosystem responses to climate change is highly uncertain, limiting the capacity of science to uncover undesirable consequences, such as the failure of critical ecosystems or the rapid loss of additional greenhouse gases to the atmosphere. Such uncertainty represents a major weakness in our ability to predict the degree of future climate warming and how ecosystems will respond to that warming.

## 1.2 Workshop Charge and Goal

In August of 2006 the Biological and Environmental Research Advisory Committee (BERAC) was charged to undertake a review of the Free-Air $CO_2$ Enrichment (FACE) and open-top chamber (OTC) projects supported within the Office of Biological and Environmental Research, Climate Change Research Division, Terrestrial Carbon Processes Program of the DOE. That Committee was asked to review science and operational details of the DOE FACE and open-top chamber experiments focusing on the direct effects of elevated $CO_2$ on terrestrial vegetation and ecosystem processes. As a part of the report to that charge (Ehleringer et al. 2006), BERAC concluded that DOE should "*Immediately plan and initiate a workshop(s) to plan the next generation of climate change and elevated-$CO_2$ experiments, incorporating multiple interacting climate change factors and potentially different elevated-$CO_2$ designs and/or technologies.*"

As one response to this recommendation, and with financial support from DOE BER, a small steering committee met in November of 2007 to organize a research-community-based workshop for the review of science needs for "next-generation" climate change/ecosystem experiments and the infrastructure (extant and yet to be developed) that might be used to address the science needs. The stated goal of the workshop was to collect and discuss ideas from the scientific community concerning scientific questions and the infrastructural and operational requirements for the next generation of field experiments needed to determine (1) the potential effects of climate change and increasing atmospheric $CO_2$ concentration on the structure and functioning of terrestrial ecosystems, (2) feedbacks from terrestrial ecosystems to the atmosphere and climate system, and (3) the facilities and measurement capabilities needed to advance the science. The workshop served as a forum to assess science questions and experimental research needs concerning potential effects of climatic change on those terrestrial ecosystems considered important in the context of specific science questions being addressed.

The steering committee proposed the following questions to outline the science discussions and to stimulate critical evaluations of technologies and measurements needed to address how terrestrial ecosystem science issues might be supported by new experimental facilities.

### 1.2.1 Science questions and issues

- What are the combined impacts and feedbacks of warming and changes in moisture status, in combination with elevated $CO_2$ concentration, on the functioning and structure of terrestrial ecosystems?
- What are the unique contributions of vapor pressure deficit (VPD) and soil moisture as derived variables (resulting from the net balance between atmospheric water, precipitation, water use, and temperature) on terrestrial ecosystem responses to climate change?
- Are there thresholds of each of the above-mentioned factors that lead to nonlinearities or saturation responses of individual plants and communities?
- How might climate extremes and environmental variability impact ecosystems?

- What ecosystems are most “sensitive” to various climatic changes? How is sensitivity defined? What unique ecosystems occupying limited land area are highly valued by society (e.g., redwood forests) and deserve special attention?
- What levels of climate and environmental change might lead to ecosystem state changes? Will state changes happen gradually or abruptly?
- How might major disturbances (storms, fire, pests, and disease) interact with climatic change in affecting future structure and functioning of terrestrial ecosystems?
- What will be the consequences to coastal terrestrial ecosystems and their services of an acceleration of sea-level rise, and what is the tipping point where these ecosystems can no longer maintain themselves?
- What ecosystem processes are inadequately represented in mechanistic models? Will improvement in the understanding of these processes enhance prognostic projections of climate change response and feedbacks? Examples of such processes might include: carbon allocation above and below ground, tissue-specific decomposition rates, and mineralization of essential plant elements.

### 1.2.2 Technology and experimental-method questions

- What existing or new methods are appropriate for conducting long-term ecosystem-scale warming and precipitation manipulation experiments in the field?
- What existing or new methods are appropriate for conducting long-term ecosystem-scale elevated-$CO_2$ experiments in the field that use less $CO_2$ (per unit time for a given ecosystem volume), are more cost effective, and allow larger experimental plots relative to the existing FACE experiments?
- How can long-term ecosystem-scale warming, precipitation manipulation, and elevated-$CO_2$ treatments be most effectively combined in field experiments in important terrestrial ecosystems? How can these experiments be made cost-effective?
- What other climatic-change-relevant environmental variables must be closely monitored within multifactor or factorial manipulations of warming, precipitation change, and elevated $CO_2$?
- What spatial scales are required to address various science questions?
- What ecosystems are available to support “do-able” multifactor studies?

## 1.3 Workshop Structure and Organization

This meeting was organized as a workshop with limited plenary talks in support of parallel breakout discussion groups where the majority of the discussions took place. A pre-workshop survey was distributed to all workshop participants for completion prior to the workshop along with a description of the workshop goal and the key science and technological questions (Section 1.2 above) for consideration before their arrival.

All workshop participants were assigned to one of four breakout groups to discuss a range of similar questions and issues:

1. Terrestrial ecosystem feedbacks affecting climate and atmosphere, Ecosystem Response,
2. Long-term, Ecosystem Response,
3. Thresholds and Nonlinearities, and
4. Managed Ecosystem Responses.

The groups were charged with determining how the science community would logically, cost-effectively, and successfully implement and maintain future experiments to provide data applicable to modeling ecological effects of climate change and ecological feedbacks to climate change. The groups were asked to provide scientific justifications for their conclusions and to comment on the appropriateness and priorities for their research in both natural and managed ecosystems.

To optimize the opportunity for each person to express individual opinions, participation in the workshop had a planned limit of between 40 and 60 individuals. The steering committee was responsible for the selection of individual participants from a pool of potential contributors larger than could be accommodated (~130 persons). To allow continuity between this workshop and the previous BERAC panel evaluating extant $CO_2$ studies (Ehleringer et al. 2006), four members of that panel were invited, and two (Melillo and Ceulemans) were able to attend. In addition, the final list of workshop invitees (see Appendix B) included a mix of experimentalists and ecosystems modelers dominated by United States scientists but also involved international representatives with related expertise. This ecosystem-oriented core group was supplemented with experts on the human dimensions of climate change, climate modelers, and individuals with current knowledge of new experimental and measurement technologies. DOE program managers and representatives from other federal agencies also attended the workshop and offered their comments.

The workshop conclusions presented in this document represent the combined opinions of a broad spectrum of ecological researchers.

## 2. WORKSHOP FINDINGS

Each breakout group provided individual written summaries for consideration and consolidation into this report. The following sections highlight next-generation science questions and experiments related to (1) climate change impacts on ecosystems both long-term and threshold-response issues, (2) terrestrial-ecosystem feedbacks to the climate system, (3) the utility of model–experiment interactions in a continuous improvement loop, and (4) the prioritization of ecosystems and experiments for future work. Additional sections of this report highlight the need for new technologies and measurements to support next-generation experiments and briefly summarize similar recent reports.

### 2.1 Climate Change Impacts on Ecosystems

Experimental manipulations of global change factors [including temperature, water availability, $CO_2$, $O_3$, and the availability of elements (typically N)] have been conducted in managed and natural ecosystems to identify ecosystem responses (Rustad 2008). Of the few studies for which manipulations have been continued over a decade (e.g., Oren et al. 2001; Norby et al. 2005; Finzi et al. 2007), findings have transitioned from short-term physiological and biogeochemical changes to intermediate and long-term shifts in cumulative processes reflecting progressive nutrient limitation (PNL), shifts in the recalcitrance of organic matter, and changes in species dominance. Some of these changes were predicted by ecosystem models, and some were not. An emergent conclusion of such studies is the clear need to understand long-term responses to climate and atmospheric changes and the need to characterize thresholds and nonlinearities potentially responsible for driving rapid and abrupt change.

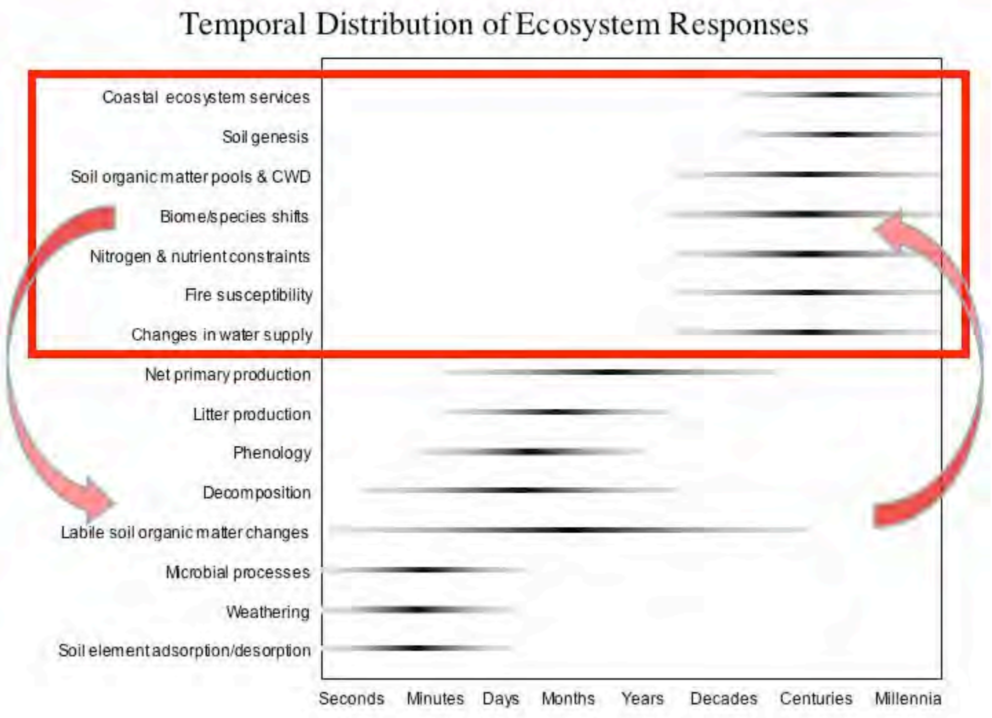

Figure 1. Ecosystem responses (both functional and structural) to climate change drivers through time. Critical processes defining long-term responses are included in the red box. Figure drawn by Lindsey Rustad.

### 2.1.1 Long-term ecosystem responses

Long-term functional and structural ecosystem changes resulting from global change must be understood to improve representation of ecosystem feedbacks to additional climatic change (via carbon, energy, and water cycles) and thus continued projections of ecological impacts. From the perspective of feedbacks, major uncertainties must be resolved in how ecosystems with large areal extent and influence on the carbon cycle (e.g., boreal forest, wet tropical forest) will respond to warming and warming in combination with $CO_2$ increases and altered water availability. From the perspective of both feedbacks and impacts to climatic change, there is little mechanistic or empirical basis for projecting geographic range shifts by species, species composition change within a given ecosystem, or the subsequent ecosystem consequences on the physical climate. The impacts of climatic and $CO_2$ changes on water supply and water quality are also poorly quantified and are a critical area for ecosystem research because of the role ecosystems play in modulating the hydrologic cycle within watersheds.

*Critical Drivers of Long-Term Ecosystem Responses*

The most important but least understood drivers of long-term responses are temperature, water availability, and the composition of future atmospheres. Anthropogenically accelerated changes in these drivers will in turn alter landscape disturbance regimes, such as fire and vulnerability to insect outbreaks. Concurrent changes in land use will add to these pressures and constrain the ability of ecosystems to respond. Very little is understood about the combined impacts of all of these drivers. Nevertheless, researchers have produced good data for some response variables and ecosystem combinations in response to these drivers. For example, considerable information is available on the response of grasslands to precipitation changes (Harper et al. 2005; Knapp et al. 2002), and the response of developing forests to atmospheric change has received substantial recent research attention (King et al. 2005; Norby et al. 2005; McCarthy et al. 2006a; Palmroth et al. 2006; Finzi et al. 2007). Unfortunately, large, whole-ecosystem warming experiments have not been attempted for any ecosystem though some long-term soil warming studies have been conducted for large plots (Melillo et al. 2002). The complex nature of simultaneous warming responses for both autotrophic and heterotrophic organisms and biogeochemical cycling mediated interactions demand that whole-system experimental approaches be developed and used to judge long-term effects of climate change.

*Temperature as a driver*

Temperature influences all biological processes, but mechanisms for temperature-driven changes in respiratory or decomposition processes remain unresolved. Projected changes in temperature are large and will be developing quickly over the next decades, they are also projected to be much greater at high than low latitudes, and they are somewhat greater inland than along coasts (Meehl et al. 2007). Increasing temperatures can have direct effects by exceeding thresholds for physiological function of living organisms, through the stimulation of decomposition and mineralization of essential elements, and through reductions in soil moisture, which may in turn be compounded by alterations in precipitation regime (Rustad et al. 2001). Temperature effects on mineralization will control long-term responsiveness of a variety of ecosystems to future climate and atmospheric conditions (especially the responsiveness to elevated $CO_2$ levels).

*Water availability as a driver*

Water is a fundamental factor in determining the structure and function of terrestrial ecosystems. The direct effects of altered precipitation patterns include changes in precipitation amounts as well as timing. Both are currently predicted to change in complex patterns across the globe with increasing precipitation expected at high northern latitudes and reduced precipitation in areas currently subjected to water limitations (Christensen et al. 2007). An increasingly dynamic hydrologic cycle is predicted to lead to more variable and intense storms, with longer intervening dry spells between major precipitation events (Christensen et al. 2007; Seager et al. 2007).

Environmental changes that alter water dynamics will have profound impacts on the underlying ecology of ecosystem processes and both direct and indirect consequences on the global hydrologic cycle. Direct consequences will occur through altered precipitation amounts and distribution, and indirect consequences through effects of other global change factors (e.g., $CO_2$, temperature, N, and species composition) on water relations. Decreased water availability will decrease stomatal conductance and photosynthesis and increase plant susceptibility to attack from insects and pathogens (McDowell et al. 2008). Extreme water shortage may cause plant mortality which could cause a large shift in ecosystems from carbon sinks to carbon sources because of reduced photosynthesis and increased decomposition of necromass (Kurz et al. 2008).

*Atmospheric $CO_2$ concentration as a driver*

Considerable effort has been expended to understand ecosystem responses to $CO_2$, and in some cases $O_3$, with very important findings. Highest among these is that, over years to a decade, elevated $CO_2$ concentrations stimulate accumulation of net primary production (i.e., biomass) in young plantations (Norby et al. 2005). Short-term leaf level physiological responses to elevated $CO_2$ are also very well characterized for a range of crop and wild plants. So, given the substantial amount of understanding of elevated-$CO_2$ responses, why is more research needed? Despite the relatively large amount of understanding of physiological responses to elevated-$CO_2$ responses, there are clear omissions in our understanding. For example, despite the relatively long-term manipulations of existing FACE experiments and the knowledge gained form these experiments, no experiment has as yet shown the predicted decline in $CO_2$ stimulation attributable to nitrogen limitation. Models used in IPCC assessments of net carbon emissions for the 21st century differ by hundreds of petagrams, depending on whether a nitrogen (N) limitation feedback is included. Additionally, these studies have been conducted using limited ranges of $[CO_2]$ that are lower than predicted future concentrations (Canadell et al. 2008; Raupach et al. 2008), and the response of photosynthesis to rising $[CO_2]$ is nonlinear.

**The Case for high $[CO_2]$.** – Plants respond to rising $[CO_2]$ through increased photosynthesis (A) and reduced stomatal conductance ($g_s$). All other effects of rising $[CO_2]$ on plants and ecosystems are derived from these two primary responses (Ainsworth and Rogers 2007). The response of A to rising $[CO_2]$ is nonlinear (Fig.2). Most of our understanding of the response of plants and ecosystems to rising $[CO_2]$ is limited to the initial slope of this response curve, where the stimulation in carbon gain with rising [$CO_2$] is maximal. However, as [$CO_2$] rises beyond the inflection point, gains in carbon acquisition per ppm increase in [$CO_2$] are markedly reduced; at the same time increases in nitrogen and water use efficiency are predicted. Given the major influence nitrogen supply and water supply have on ecosystem productivity, this portends critical uncertainty about ecosystem response to [$CO_2$] higher than those used in FACE experiments to date.

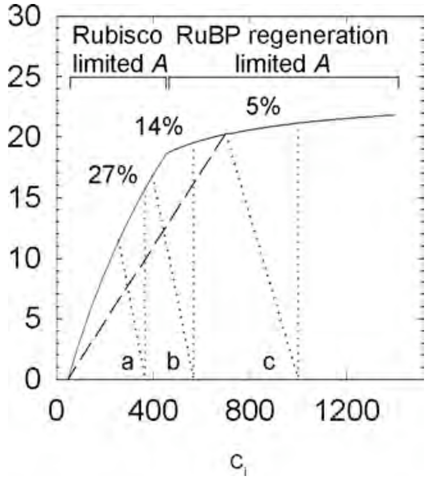

Figure 2. The response of photosynthesis (A) to the internal [$CO_2$] (ci). The response is nonlinear with two phases; an initial slope where A is limited by the caboxylation capacity of Rubisco and a second phase where A is limited by the capacity to regenerate RuBP. The A-ci response curve was reconstructed from the mean values for Rubisco and RuBP regeneration limited photosynthesis obtained from tree species grown at FACE sites (Ainsworth and Rogers 2007). The impact of gs on ci is shown by the blue dotted lines and the intersection of these lines with the A-ci curve indicates the operating point at three atmospheric [$CO_2$] (a, 367 ppm; b, 567 ppm; c, 1000 ppm). The gs is reduced by 20% and 50% at 567 and 1000 ppm, respectively. These [$CO_2$] represent the current and elevated [$CO_2$] from forest FACE experiments (a and b respectively) and a projected 1000 ppm [$CO_2$] (c). The broken line indicates the possible 40% reduction in Rubisco content possible at 1000 ppm that could occur without a reduction in A. The intersection of the red dotted lines with the A-ci response indicates the potential A in the absence of stomatal limitation. Stomatal limitation at 367, 550, and 1000 ppm is estimated to be 27%, 14%, and 5%, respectively. Figure submitted by Alistair Rogers.

**Water use efficiency enhancement under elevated $CO_2$.** – In order to assimilate $CO_2$ into sugar, plants must open their stomata, and in doing so they lose water. As [$CO_2$] increases plants reduce stomatal conductance to balance the increase in atmospheric [$CO_2$] ($c_a$) with the increase in *A* such that the ratio of $c_a$ to $c_i$ remains constant at ~0.7 (Long et al. 2004). The result is that at 567 ppm $g_s$ is reduced by 20% and, if this relationship is maintained at 1000 ppm, $g_s$ would be reduced by 50%. The reduction in $g_s$ can be seen in Fig. 2 as the decreasing gradient of the blue lines for the three [$CO_2$] (a, 367; b, 567; c, 1000). Another result of the nonlinear response of the $A$-$c_i$ curve is that the limitation of $g_s$ on *A* is markedly reduced as [$CO_2$] rises. The red dotted lines in Fig. 2 show the *A* possible in the absence of a diffusive barrier, and the blue dotted lines show the effect of $g_s$ on $c_i$. By comparing the *A* possible at infinite $g_s$ (the intersection of the black response curve and the red line) with the *A* under normal conditions (the intersection of the black response curve and the blue line), it is possible to calculate the stomatal limitation on *A*. As [$CO_2$] increases from current (a, 367 ppm) to the elevated [$CO_2$] typical of FACE studies (b, 567 ppm) and up to a future 1000 ppm [$CO_2$] (c), the stomatal limitation on *A* drops from 27% to just 5%. At high [$CO_2$], large reductions in water use are possible with only a modest impact on C acquisition.

**Contrasting $CO_2$ responses of plant biotypes.** – In the FACE experiments completed to date, C4 photosynthesis has not been directly stimulated by elevated [$CO_2$], and carbon gain has only been improved by amelioration of stress during periods of drought (Leakey et al. 2004, 2006; Long et al 2006; Ottman et al 2001; Wall et al 2001). The qualitative difference between C4 and C3 photosynthetic responses to elevated $CO_2$ is not stated in the report (pages 12, 13, 14 summarise A/ci curves, ci/ca ratios for C3 species but not C4s) but will have a major impact on the response of biofuel (miscanthus and switchgrass) and C4 grain (corn, millet, and sorghum) dominated agroecosystems, as well as natural systems (savanna and prairie). Therefore, it is particularly important to understand the elevated $CO_2$ □ soil moisture content interaction in C4 species, and they are a model system in which to test changes in drought tolerance without the complicating direct stimulation of photosynthesis observed in C3 species.

### *Coastal inundation of terrestrial ecosystems as a driver*

Coastal ecosystems will need to adapt to future sea level rise or fail. Current levels of anthropogenic warming will lead to sea level rise for centuries to come because of the time scales associated with climate processes and feedbacks (Solomon et al. 2007). Current projections for 2090 to 2099, suggest the estimated range for the B1 scenario (minor greenhouse gas increases) is 0.18 to 0.38 m, and the estimated range for the A1FI scenario (dramatic greenhouse gas increases) is 0.26 to 0.59 m. Such projected levels of sea level rise will impact terrestrial ecosystems along coastlines with gradual topographic relief. The previous IPCC-based estimates do not included melting of polar ice caps in their projections of sea level rise because the models of such processes are currently inadequate. Using an empirical method to account for ice melt, Rahmstorf (2006) projected sea-level rise by 2100 of 0.5 to 1.4 meters above the 1990 level. Even the lower limit of this projection would submerge the majority of coastal wetlands, all except those in macrotidal regions, and move the ocean boundary well inland.

The complicated nature of diurnal, seasonal, and storm-driven tides superimposed on the gradual increase of sea levels make the development and testing of sea level inundation a complex activity that needs to be addressed.

### *Change and Disturbance Leading to Species Changes*

Another poorly characterized ecosystem response to climatic change is the natural transition between species or vegetation types in different ecosystems. In some cases, these transitions are hypothesized to be gradual (i.e., it may take decades for long-lived dominants to die, even when the climate is no longer favorable to their long-term survival or to the recruitment of their seedlings). In other cases, rapid transitions are likely (e.g., disturbance events); the capacity to project future mortality based on climatic factors for most species simply does not exist. It is difficult to predict large-scale disturbances, yet such disturbances interact strongly with climate and atmospheric conditions. The mountain pine beetle, for example, has infested 14 million hectares of land in British Columbia (Kurz et al. 2008). One cause of this record outbreak has apparently been unusually mild winters in recent years, with temperatures rarely dropping below the -40 °C needed to kill the beetle larvae.

Conversely, results from some precipitation-manipulation studies show unexpected resilience of ecosystems (Hanson et al. 2001; Hanson and Wullschleger 2003). Elevated $CO_2$ has also been shown to confer protection against damage from ice storms (McCarthy et al. 2006b). A research agenda is needed that tests the vulnerability of ecosystems to extreme weather and climate, allowing one to project the future death of a species or transitions between biome types in a region.

The extent to which fire frequency may increase in such places as the Amazon or boreal forest ecosystems is another example of potential large-scale disturbances that are not yet fully understood. Improving the representation of such disturbances in global models should be possible by introducing stochastic simulations of fire, pests, and other agents of regional change. Additional insight may also be gained from studies of paleoecology and climate.

Changes in ecosystem type, such as transitions from forest to grassland or grassland to desert have large ecosystem consequences. Whether ecosystems change as a result of invasion, migration, shifts in relative dominance, or periodic disturbance the largest changes in structure and functioning will likely through changes in the basic vegetation type or the dominant species. Major changes in species composition may also have large impacts (e.g., deciduous trees replacing evergreens). In general, relatively little is known about the process of species replacement driven by climate change. The current generation of biogeography models treat the competition during establishment with some detail, but they are vague in treating the processes that create gaps or clearings. The point at which replacement occurs is also poorly understood. It could be gradual decline, it could be followed by replacement, or it could be that the dominants are killed in a large-scale event, by fire or insects, and then replaced.

### 2.1.2 Threshold and nonlinear ecosystem responses to climate and atmospheric change

Nonlinear effects are important and should be a high priority for research. Nonlinear and threshold effects refer to (1) any curved or stepped ecological response to forcing, such that the derivative of the response is not constant and the magnitude of response cannot be determined from observations at just two levels of forcing or (2) a complex ecological response to forcing characterized by feedback processes where a simple chain of causality is replaced by more complex interactions. Where these complex interactions include positive feedback processes, even small initial perturbations can potentially lead to large system responses including ecotype conversions, hysteresis, and a large change in community composition. An improved understanding of nonlinear effects of the first type is needed to quantitatively predict the ecological impacts of climate change. For instance, manipulative experiments with $CO_2$ gradients have shown numerous nonlinear responses, including thresholds in the productivity of secondary plant chemicals, N mineralization, soil respiration, and microbial biomass (Gill et al. 2002, 2006). An improved understanding of nonlinear effects of the second type is important because many of these changes may be difficult to reverse and because they are characterized by especially large feedbacks to climate and impacts on ecosystem goods and services.

Thresholds can lead to two sorts of ecosystem effects:

- Dramatic changes (increases or saturation) in the relationship between ecosystem processes (e.g., NPP or evapotranspiration) and environmental drivers (temperature, $CO_2$, or moisture) for incremental changes in the driver.
- Step changes in the ecosystem (e.g., conversion of grassland to shrubland) including large-scale mortality of the extant populations and communities.

Changes in community composition (type conversion) represent one of the most critical and poorly understood issues in the field. For example, changes in vascular and nonvascular plant functional types (e.g., woody encroachment or annual dominance of previously perennial communities) will have a dramatic effect on all aspects of ecosystem structure and function. Changes in plant species composition will be accompanied by alterations in community structure, such as vertical and horizontal architecture, with important consequences for animal and microbial populations. Changes will also occur in most ecosystem functions, such as carbon and nutrient cycling, soil attributes (e.g., moisture holding capacity and structure), productivity, and competitive relationships among different components. Expected property changes include albedo, flammability/fuel loads, and vulnerability to pests.

*Current Science and Gaps in Understanding*

The participants at the workshop identified a number of major limitations in the current knowledge about climate change effects on and feedbacks from terrestrial ecosystems:

- Future realities cannot be predicted from past observations. Past research has primarily focused on understanding the response of equilibrium conditions to environmental drivers. The study of transient processes is inherently much more difficult and has only rarely been attempted.
- Thresholds and nonlinearities in response surfaces to climatic change factors have not been quantified.
- It is not clear what triggers an ecosystem to cross thresholds.
    - What processes triggered by climate change cause a type change?
    - How and which aspects of climate change will push ecosystems across thresholds?
    - Is there a distinction in community responses to acute versus chronic periods of “stress”?
- No capacity exists to predict the relative importance of acute or extreme events as compared to chronic change on ecosystem response.
    - Which matters most, shifts in long-term means or shifts in variability and occurrence or extremes?
    - When and how could low-level or moderate perturbations lead to large changes because of nonlinearities and thresholds in response that are large enough and fast enough to be considered abrupt?
    - Will there be perturbations that push ecosystems (even those without important nonlinearities) over thresholds that are irreversible?
- Short-term ecosystem functional responses (minutes to years) and long-term equilibrium compositional expectations are comparatively well understood; decadal-to-centennial-scale dynamics are poorly understood.

### *Ecological Processes Driving Nonlinear Ecosystem Responses to Abrupt Change*

Changing climate forces ecosystems through tipping points and across thresholds through several mechanisms, including mortality of the dominant plants, failure of the dominant plants to reproduce or reestablish, a change in the disturbance regime, and a change in the physical characteristics of the site (for example, permafrost melt, water table changes, and soil changes). One of the most obvious changes in ecosystems in response to changing climate is dominant-plant mortality. Key processes responsible for nonlinear/abrupt change include:

- Mortality of dominant/keystone species
- Physical or chemical state changes (permafrost or snow melts, soils flooded and become anaerobic, large soil loss/gain, etc.)
- Failure of plants to produce viable seed, germinate, or establish
- Disturbance (fire, flood, wind, invasive species); changes in the frequency, type, or intensity of disturbance
- Positive feedbacks within the ecosystem and up to the micro or regional climate

Many abrupt changes to ecosystems come from changes in disturbance regimes outside of the range of historic variability. One example is the introduction of invasive annual grasses into arid land ecosystems. These annual grasses produce heavy fuel loads that promote fire and out-compete existing vegetation. These changes result in a type shift from diverse perennial shrublands to annual grasslands.

One of the largest unknowns in predicting abrupt changes in ecosystems is an understanding of the different processes and mechanisms that control mortality of perennial plants. Ecosystem properties that may predispose ecosystems to nonlinear or threshold changes include:

- Having characteristics that currently lie close to a physical state change (e.g., permafrost, water table, lack of buffering, or already experiencing rapid change)
- Existence close to physiological tolerance limits (ecotones)
- Interactions and reinforcements between climate and nonclimate stresses or factors (e.g., drought, invasives, and/or pests)
- Competitive interactions and feedbacks with other species (realized vs. fundamental niches)
- Limited regeneration capacity, seed dispersal distances, and long generation times if extant species are lost, and
- Low genetic diversity.

For a given set of climatic/atmospheric drivers, are there certain groups of organisms that are at the limits of their physiological tolerances under current conditions and that would be expected to go extinct under climatic change scenarios? Examples include mountaintop species (e.g., loss of alpine habitat will lead to extinction of alpine species and ecosystems) and coastal species (e.g., rapid sea-level rise will lead to flooding of low-lying habitats at a more rapid rate than species can migrate inland) and species restricted to the poleward edge of continents or large islands. Can (and will) species distributions change when local thresholds are crossed? Current models of species distributions (climate envelope models) are based on a mixture of the realized and fundamental niches of species. Models of animal distributions are based on their habitat defined by plant distributions, not on either the realized or fundamental niches of the animals themselves.

- Rates and means of organism dispersal need to be determined for a variety of climatic change scenarios.
- The potential for colonization of new environments is contingent on the fundamental niche of a species; on interactions and feedbacks with species in the new environment (all species in an ecosystem will not move or migrate at the same rate); and on novel niche axes in the new environment (There will be new combinations of temperature, $CO_2$, and soil moisture that do not currently exist. Can they be created experimentally?)

*Statistical Tools and Approaches for Threshold Change Detection with Time*

Identifying thresholds and change-points in time-series or phase-plane data is an active area of statistical research. In general, data requirements are larger than are contained in most ecological datasets (on the order of 50 to 100 observations or time-steps [e.g., years]); detection requires an underlying statistical process model (which is rarely defined for ecological systems); and clear definitions of thresholds and change points are required (for which there is not general agreement among the ecological community). New analyses suggest that an indicator of climate change must signal an impending threshold at least 20 to 40 time-steps (e.g., 20 to 40 years) in advance in order to provide adequate lead-time to prevent or mitigate the state-change (Contamin and Ellison in review). Ecosystem ecologists and statistical modelers must work together in all aspects of model development, experimental design, implementation, and analysis to make rapid progress in meeting the challenges of interpreting and using data from ecosystem experiments aimed at identifying thresholds and state changes in ecosystems.

## 2.2 Terrestrial-Ecosystem Feedbacks to the Climate System

Uncertainty in the magnitude and, in some cases, the sign of key feedbacks between the climate system and terrestrial ecosystems is one of the critical weaknesses in the current understanding of climate change futures (Solomon et al. 2007). For the purpose of this report, a feedback was considered to be a mechanism or chain of mechanisms connecting some element of climate to a terrestrial ecosystem, with an ecosystem response, which in turn influences the climate forcing (Fig. 3). Identification of the overall dimensions of terrestrial ecosystem feedbacks demands mechanisms for two-way coupling between climate and terrestrial ecosystems. A primary goal of terrestrial ecosystem feedback research is to reduce the risk of inaccurate predictions of future climate change by confronting models with the best mechanisms for expressing climate–ecosystem feedbacks, and formulating results from the most capable models as testable hypotheses to guide the design of new experimentation.

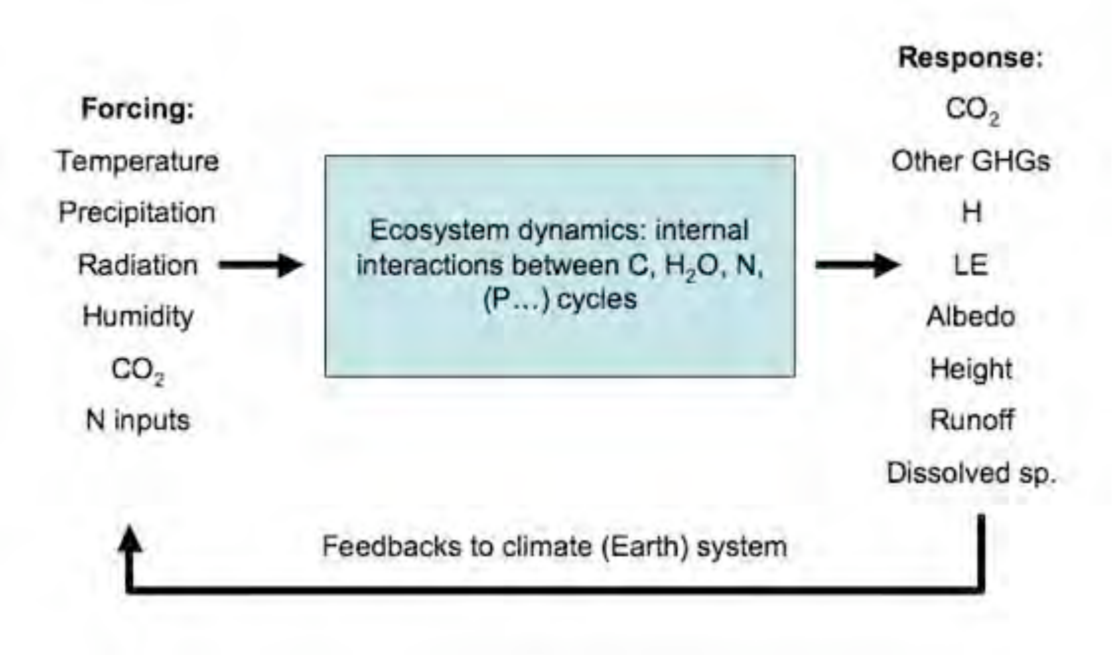

Figure 3. Summary diagram of climate-ecosystem feedbacks showing forcing, ecosystem dynamics, and feedback response. In the diagram N = nitrogren, C = carbon, P = phosphorous, H = sensible heat transfers, and LE = latent energy transfers related to water evaporation or transpiration. Figure by Peter Thornton.

### 2.2.1 Critical feedbacks between climate and terrestrial ecosystems

Starting with the conceptual model above and considering the current state of knowledge from measurement, experimentation, and modeling, the following annotated list describes critical climate-ecosystem feedbacks that must be understood to enable efficacious climate model projections. It is followed by more detailed descriptions of the processes involved for each feedback and discussion of the most serious knowledge gaps.

- **Net greenhouse gas fluxes** ($CO_2$, $CH_4$, and $N_2O$): A primary response of ecosystems to many changes in environmental forcing is a shift in the net flux (difference between inputs and outputs) of $CO_2$, as well as changing fluxes of $CH_4$ and $N_2O$. Changes in these net fluxes feed back to the climate through radiative forcing.
- **Albedo**: Climate forcing can alter the structure and composition of vegetation, soil, and snow, leading to changes in how much incoming radiation is reflected back toward the atmosphere (albedo). These changes have an immediate impact on the atmospheric radiation budget.
- **Surface energy balance**: In addition to albedo, climate forcing can alter other characteristics of the terrestrial surface, such as height, surface roughness, and stomatal behavior, producing changes in the balance between sensible- and latent-heat fluxes.
- **Dust and aerosol production**: Climate forcings, such as changes in patterns of precipitation and surface wind speed, can lead to changes in the generation and transport of dust and other aerosols. Feedbacks to the climate system from this process include the direct influence of aerosols on the atmospheric radiation budget, influence on albedo from dust deposition on snow, influence on ocean productivity and

greenhouse gas flux through the form and content of iron in dust deposited over the oceans, and influence on greenhouse gas fluxes through transport of phosphorus into ecosystems where it is a limiting nutrient.

### 2.2.2 Terrestrial ecosystem processes that influence feedbacks

The atmosphere-land feedback between climate forcing and the carbon cycle can be characterized in terms of two responses: a direct response of net ecosystem exchange of carbon (NEE) to increasing $CO_2$ concentration, initiated through photosynthetic carbon uptake, and a response of NEE to surface weather forcing factors, typically represented as an NEE response to changing temperature.

One powerful approach for understanding the climate-carbon feedbacks is to integrate our knowledge of ecosystem dynamics as components of global coupled climate system models. This approach provides a self-consistent framework for extending knowledge gained through observation and experimentation up to the global scale and also allows for exploration of very long time-scale dynamics. Multiple examples of this approach exist now, and preliminary results from coupled climate–carbon-cycle simulations are summarized in the recent IPCC report (Denman et al. 2007). A conclusion from that report is that the feedback between carbon storage in terrestrial ecosystems and radiatively forced climate change leads to net losses of carbon from land ecosystems under greenhouse-gas inducing additional climate change. This has been characterized as a *positive* feedback to the process of climate warming. Because the consensus on this topic is derived from models that do not explicitly represent nutrient-cycling processes, the results and conclusions regarding the future direction of climate change remain highly uncertain.

A growing body of evidence from experimental and observational studies supports the long-held theoretical notion (Rastetter et al. 1992; Comins and McMurtrie 1993; Kirschbaum et al. 1994, 1998) that the climate–carbon-cycle feedback in terrestrial ecosystems is sensitive to the interactions of carbon and nutrient cycles between plants and soil microbial communities. Luo et al. (2004) outlined a framework to describe N limitation of ecosystem C accumulation at elevated $CO_2$. This concept, known as progressive N limitation (PNL) is distinct from the effects of elevated $CO_2$ and N supply. Whereas soil N availability can determine the initial response to elevated $CO_2$, PNL expresses the concept of diminishing N availability. In PNL, available soil N becomes increasingly limiting as C and N are sequestered in long-lived plant biomass and soil organic matter (Fig. 4).

The PNL concept is built on the principal that the formation of organic material requires a certain amount of N and other nutrients in a relatively fixed ratio with C (i.e., if a plant is to sustain productivity, it must match the increased carbon acquired at elevated $CO_2$ with additional nitrogen). When plants are N-limited at elevated $CO_2$ a suite of short- and long-term mechanisms can act to prevent or alleviate PNL. In the short-term, PNL may be temporally delayed through increased N-use efficiency, through soil exploration by fine roots and mycorrhizae, and through increases in the C:N in plant and soil organic matter pools. In the long term, a combination of increases in biological N fixation, decreases in leaching and gaseous N loss from the soil, and enhanced retention of deposited N may act to prevent PNL, but these responses are heterogeneous, largely unquantified, and poorly understood.

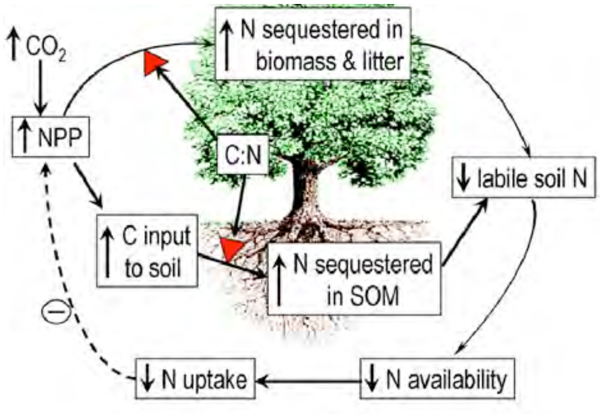

Figure 4. Feedback processes at elevated [$CO_2$] that lead to progressive nitrogen limitation. Increases in productivity result in sequestration of N in plant biomass or soil organic matter. With time, the result is reduced N availability for plants and a long-term reduction in NPP. (From Luo et al. 2004 with permission).

The consequence of ignoring constraints by N availability is an under-prediction of the growth in atmospheric $CO_2$ on the order of tens to hundreds of PPM through 2100. The uncertainty in the terrestrial sink makes it very difficult to develop rational strategies for $CO_2$ mitigation and adaptation. Several Earth-system models now include an explicit treatment of coupled carbon-nitrogen (C-N) cycling in terrestrial ecosystems, and several more groups have C-N development projects under way. It is important that this coupling mechanism be included in climate modeling efforts to appropriately capture terrestrial ecosystem carbon capture capacities with time. Coupled climate–C-N models capture at least some aspects of the PNL hypothesis and may provide a framework for understanding how ecosystem dynamics interact with changing $CO_2$ concentrations, rising temperature, and changing precipitation regimes (Fig. 5).

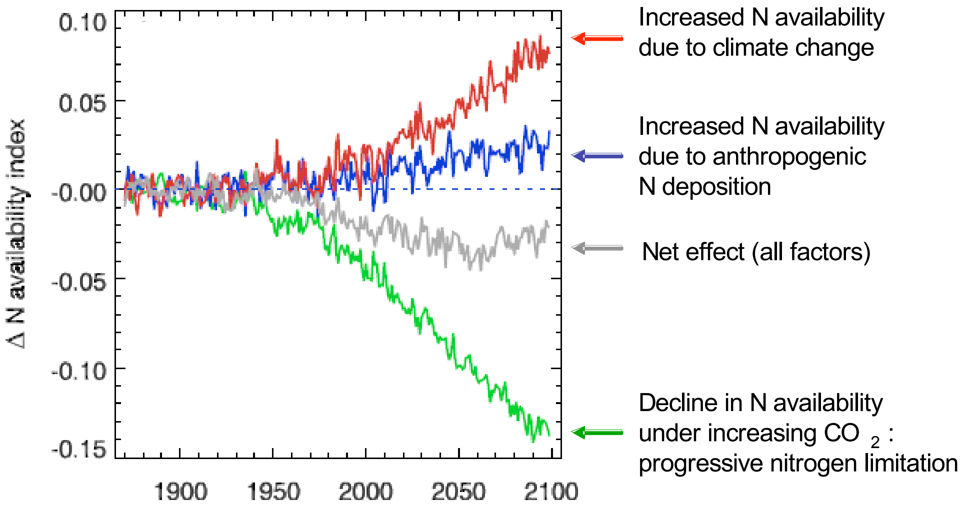

Figure 5. Representation of multiple influences on N availability in a coupled climate–C-N model (Thornton et al. 2007). Progressive nitrogen limitation under rising $CO_2$ concentration (green line), is offset by increasing availability because of climate change (red line) and anthropogenic N deposition (blue line), resulting in an overall modest decline in N availability under a scenario of future climate change.

Critical components of the terrestrial nitrogen cycle remain poorly understood, and poorly represented in the current generation of Earth system models, including the representation of denitrification losses. A recent model comparison of terrestrial denitrification models (Li et al. 2005) showed that there is a large variation in the simulated $N_2$ gas fluxes from agricultural systems. The DayCent and DNDC biogeochemical models predicted similar $N_2$ gas fluxes; however, some of the engineering based agricultural models simulated order-of-magnitude-higher $N_2$ gas fluxes from denitrification. Unfortunately, databases of relevant observations for evaluating model projections were not available.

### *Sensitivity of Decomposition to Changing Temperature*

Another uncertainty in the area of climate–carbon-cycle feedbacks is the sensitivity of various fractions of the soil organic matter (SOM) to changing temperature (Davidson and Janssens 2006). Experimental data show that the labile SOM pools have high Q10 values at low soil temperatures and lower values at higher soil temperatures; however, it is still difficult to predict the temperature sensitivity of soil carbon decomposition (Lloyd and Taylor 1994; Kirschbaum 1995, 2000). Global ecosystem models use the same temperature curves to predict change in the decomposition rate of the different soil organic matter pools. If decomposition of resistant SOM pools have a different sensitivity to changes in soil temperature compared to SOM labile fractions, then the global models will incorrectly estimate the release of carbon from the soil associated future increases in soil temperature.

Readily observable carbon efflux rates in most studies tends to be dominated by the decomposition of more labile fractions so that the knowledge of temperature sensitivities is largely that of the more labile fractions, yet the long-term response of soil processes to temperature shifts will be determined more strongly by the temperature sensitivity of the more resistant fractions. Coûteaux et al. (2001), Bol et al. (2003), and Bååth and Wallander (2003) all addressed the questions of differential temperature sensitivity of fractions with different decomposability, but none could find any systematic reasons to suggest that recalcitrant fractions of soil-organic carbon should have a different temperature sensitivity than the more labile fractions. In a more recent study, Conant et al. (2008) used a variety of comparisons and concluded that more recalcitrant carbon did have a stronger temperature response than more labile carbon. It is important to know whether more resistant fractions would have the same temperature sensitivity as the more labile fractions (e.g., Thornley and Cannell 2001).

### *Controls over Methane Fluxes*

Within the vast soil carbon reservoirs of peatlands, methane production is tied closely to newly produced carbon from plant productivity and root exudates (Schütz et al. 1991; Happell et al. 1993; Whiting and Chanton 1993; Megonigal et al. 1999; Updegraff et al. 2001; King et al. 2002). Because of this linkage to plant productivity, a consistent response to elevated-$CO_2$-enhanced photosynthesis in wetlands is an increase in $CH_4$ emissions ranging from 50 to 350% (Vann and Megonigal 2003). Changes in plant-community composition affecting photosynthate supplies to ecosystems may alter $CH_4$ emissions via modified photosynthate supply, oxidation of the rhizosphere, and transport of $CH_4$ to the atmosphere.

### *Albedo Feedbacks*

Surface energy balance affects local or regional climate through the amount of net radiation received (a function of albedo), and its partitioning into latent heat, sensible heat, and ground heat flux (important where soils are cold). In a variety of ecosystems, it has been shown that vegetation composition has a strong effect on albedo (ecosystems can vary in albedo by a factor of 10) and on the partitioning of net radiation into sensible and latent heat.

These differences in turn can influence local climate. In northern ecosystems, there is a huge difference in albedo between snow-covered surfaces, forest tundra, tundra dominated by large shrubs not covered by snow in the winter, and open tundra. Differences in summer radiation partitioning among tundra, shrub tundra, and forest also result in greater atmospheric heating over shrub tundra or forests (Chapin et al. 2005). Long-term changes in vegetation composition toward shrubs and forest are expected under climate warming, as shrubs increase in abundance in tundra and tree lines move north. Changes in surface energy balance associated with changes in vegetation composition are likely to act as a positive feedback to climate warming.

### *Fire/Permafrost Melting/GHG Feedbacks in Northern Ecosystems*

Northern ecosystems (taiga and tundra) are important for the global C cycle because they store large amounts (nearly 40%) of the world's soil carbon (Gorham 1991), which could cause a strong positive feedback to further warming if it is mineralized because of warming of the soil and mineralization of N (see paragraph above). Disturbance may also cause rapid and catastrophic loss of soil carbon because of accelerated occurrence of fire and rapid permafrost melting (thermokarst).

Fire is normally very rare in tundra ecosystems, and previous fires were relatively small in extent and not very severe. Fire and thermokarst represent a pathway for release of large amounts of soil carbon to the atmosphere and a substantial positive feedback via greenhouse gas emissions to further warming.

Permafrost melting and the development of thermokarst may lead to the production of methane if it occurs in aquatic ecosystems. Thermokarst along lake margins can produce substantial amounts of methane release through ebullition in Siberian lakes (Walter et al. 2006). Changes in hydrology associated with permafrost melting in arctic ecosystems may affect the relative release of carbon as methane vs. $CO_2$ and strengthen the feedback to the atmosphere.

### *Dissolved Organic Matter Transport*

Rivers are globally important conduits for carbon transport (Fig. 6). The magnitude of aquatic carbon transport will be influenced by changes in the hydrologic cycle, land-use change, and feedbacks between terrestrial landscapes and climate. Carbon flows from the terrestrial landscape to rivers, wetlands, and the sea as dissolved organic carbon (DOC), as particulate organic carbon (POC), or as dissolved inorganic carbon (DIC) or alkalinity. The latter is a result of chemical weathering of soil minerals. Contemporary weathering may have a significant influence on the postindustrial global carbon cycle.

Erosion of organic carbon from soil represents a major pathway for carbon transport. River discharge of organic carbon accounts for about 20% of soil carbon erosion, mobilizing ~1.4 Gt carbon annually (Smith et al. 2001), which is roughly equivalent to the total carbon discharged by rivers into the sea (Fig. 6) irrespective of DOC and DIC flux. There is a great deal of uncertainty regarding the magnitude and control of aquatic carbon transport; however, we do know that the human-caused changes are globally significant.

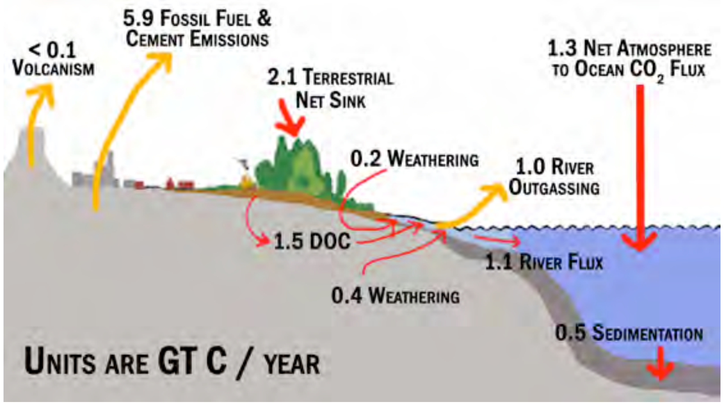

Figure 6. Net global carbon fluxes (modified from Sabine et al 2004). Note that the flux of carbon in rivers to the sea is nearly equal to the flux of carbon from the atmosphere to the sea. The river carbon pump delivers approximately equal parts DOC and DIC (alkalinity).

## 2.3 Model–Experiment Interactions

The integration of modeling and experimental activities has been discussed in workshops and symposia for years with little action. The science community must move forward and formalize the expected pathways and standards for model–experiment interactions.

Observations and experimental manipulations alone cannot generate sufficient input data for all relevant science questions. The complexity of the integrated climate-biosphere system exceeds our capacity for controlled, multifactorial experimentation. Concurrent changes in temperature, precipitation, nitrogen deposition, ozone concentration, disturbance, and species composition, layered across a complex landscape rule out the perfectly designed in-field manipulation. Models are clearly needed to capture scientific knowledge about effects of climatic (temperature and precipitation) and atmospheric change (e.g., elevated $CO_2$) on important ecosystems within robust yet flexible models with high spatial and temporal resolution. Such models must be quantitative, include appropriate mechanisms, be valid within a defined range of uncertainty, and capable of addressing questions of concern to society for the range of possible future greenhouse gas atmospheres and their associated climates and the trajectory they take to reach a given future condition.

Development, testing, and sensitivity analysis of models are a primary requirement of global change science, and synthesis with models needs to occur not only at the end of a study but also at the beginning of research projects for the development of hypotheses and to inform experimental designs. Tools for evaluating future climate responses from regional to global scales will be dependent on the use and further development of mechanistic models that can be integrated through time and space for prognostic estimates of future ecosystem response. Such models must include a robust theory for ecosystem biogeochemical cycling to forecast interannual changes in net greenhouse gas flux to the atmosphere and productivity components for managed and natural ecosystems. Models must also reflect a theory of species fitness and population dynamics and species migration to adequately capture the fate of extant vegetation and the likely composition of current ecosystems in 50 to 100 years.

Mechanistic models may be viewed as repositories of accumulated understanding of ecosystem dynamics. Therefore, field experiments are potential tests of model validity as well as investigations of crucial processes or interactions. Putting the concept of a combined model–experiment interaction into practice could require:

- That proposals include model-derived predictions (hypotheses), stated quantitatively;
- That experimental results be compared directly with a priori predictions; and
- That “modelers” and “experimenters” work together on a daily basis.

### 2.3.1 Essential model–experiment interactions

Although model development and experimental manipulation during the past decade have increased our understanding of the potential feedback effects of climate change on the function of the biosphere, two broad classes of uncertainties remain: (1) uncertainties resulting from the lack of communication/synthesis of current experimental results and their availability to the modeling community and (2) uncertainties caused by model parameterizations and parameter estimations. Both sources of uncertainties must be resolved in order to compare, indeed integrate, models and experiments and to develop a cutting-edge portfolio of climate change experiments that inform $CO_2$ mitigation and adaptation at the national level.

Models may be applied to the selection and design of new experiments. Physical conditions that obtain in specific experimental circumstances might be simulated by models, and such simulations used to project distributions of environmental variables across space and time for use in the specification of experimental plot sizes. Such data could be used to evaluate the cost and logistics of alternate multifactor experimental designs. Observed data from climatic change experiments have been used to test ecosystem models. Most of this work has been done after field experiments were completed, and there has been very little feedback between the use of the models and design of the field experiments. Researchers of the PHASE prairie climate change experiment in Wyoming employed the DayCent model, before the experiment started, to simulate the predicted ecosystem responses to changes in atmospheric $CO_2$ and warming for the experimental site (Parton et al 2007). The predictions from the model will be tested using observed data sets collected during the 5-year experiment. This experiment will allow a true validation test of the model. Many of the field observations measured in the field experiment were designed to test the predictive power of the model. Differences between the model results and observed data sets will lead to changes in the model and improvements in our understanding about the expected response of grassland to potential future changes in the climate.

For models to be optimized for use in post-experiment syntheses, a priori descriptions and evaluations of key processes to be quantified and measured for hypothesis tests should be done. In the context of long-term hypotheses, models should also be used to evaluate the progressive nutrient limitation, potential influence of disturbance dynamics (fire, insects, and wind), and the characterization of changing species distributions with time. Models might also suggest when critical response thresholds might be achieved, and such information could form an argument for sustaining or completing ongoing long-term studies

### 2.3.2 Types of models needed for climate change experiments

A number of types of models need to be developed further to facilitate pre-experiment hypothesis development, data synthesis during experimental operation, and/or post-experiment interpretation of results. Spatially resolved and fully evaluated model(s) of ecosystem functioning and structure are needed to address the interacting effects of warming, precipitation change, and atmospheric composition at spatial scales that can be integrated upwards for multiple policy applications. Spatially resolved coupled biosphere-atmosphere models that characterize exchanges of $CO_2$ (and $CH_4$) and energy between the land surface and atmosphere are needed at relevant temporal scales to provide greenhouse-gas-exchange estimates for use within coupled climate models. Finally, models of ecosystem structural and compositional changes that contain adequate functional mechanisms are needed to allow simulations of ecosystem transients and the fate of individual species or species-functional types in response to climate change over decadal to century time scales. Models capable of projecting ecosystem structural and compositional changes are needed to feed land-cover change to coupled climate global-circulation or Earth-system models and to provide key land-use predictions for integrated assessment activities.

Improved biogeography models constitute a special need. Current gap and biogeography models based on climate envelopes (Hijams and Graham 2006) are able to describe the distribution of species and plant functional types (PFTs) within a given equilibrium environmental space. In response to changed environmental conditions, however, such models often inappropriately apply equilibrium-adapted PFTs and their biomes to newly projected climate conditions without regard to the transient processes involved. These models often lack clear mechanisms for the dynamic processes that occur during the displacement of species or PFTs in response to altered conditions. Hence, there is poor predictive ability of the transient pattern of a change from one distribution to another. Further development of gap and dynamic vegetation models to incorporate ecophysiological mechanisms is key to a capacity for understanding threshold responses to climate change.

An important objective for the next generation of experiments should be to produce data that can inform Dynamic Global Vegetation Models (DGVMs). Three strategies can be imagined:

- exposure of intact communities to environmental drivers with observations of changes in plant community composition;
- understanding of the mechanisms that lead to community composition change including detailed observations of seed dispersal, germination, seedling establishment, and mortality of different PFTs under different combinations of atmospheric and climatic change; and
- long-term climate change manipulations across transition zones, such as in savanna-forest ecotones.

### 2.3.3 Keeping models current

*C*haracterization of the response of ecosystems to climate and atmospheric change (warming, precipitation, and elevated $CO_2$) requires that global land surface models contain up-to-date mechanisms of response for these key environmental drivers and the response variables of interest. A closer and formalized tie between modelers and experimentalists is encouraged to ensure that the latest ‘lessons-learned’ from ongoing climate change studies are fully incorporated into the terrestrial models exercised for global change experiments. Where existing results suggest quantitatively important changes for variables of stakeholder interest (GPP, biomass production, N-availability, etc.) or key processes that might control greenhouse gas feedbacks to the climate system, updated or expanded model mechanisms should be considered within global land-surface models.

### 2.4 Priority Ecosystems and Climate Change Treatments

Because all ecosystems are fundamentally important to local inhabitants and their livelihoods, it is clear that everyone has a stake in understanding the influence of climate change on the terrestrial ecosystems that occupy their own backyard. To that extent, next-generation research on climate change impacts should not arbitrarily exclude any ecosystems. However, in a conscious attempt to prioritize next-generation experiments, workshop participants agreed on some general principals to help select ecosystems for evaluation. Those criteria included:

- the capacity to provide challenging test of model concepts;
- the inherent sensitivity of ecosystems to warming, $CO_2$, and precipitation change;
- the areal extent of ecosystems for global feedback concerns;
- the ability to serve as model ecosystems that allow for the testing of cumulative interactions (e.g., fast-growing or low-stature ecosystems); and
- the potential loss of critical ecosystems and the services they provide (e.g., coastal systems and surge protection, alpine systems and ecosystems critical to water supply, etc.)

#### 2.4.1 Ecosystems needed for impact research

Workshop participants concluded that there was not a single metric for prioritizing the “importance” of one ecosystem versus another in the context of ecosystem responses to climate change. An ecosystem’s areal extent had obvious implications to what humans might value, but characterization of quantitative impacts from warming, precipitation change, and elevated $CO_2$ were necessary for all ecosystems valued by humans. Workshop participants did agree that ecosystems near or approaching a threshold level of environmental change driving functional, structural, or compositional impacts would be a valuable research target (See also Section 2.1.2).

#### 2.4.2 Ecosystems needed for climate-feedback research

In contrast to the lack of clear prioritization of ecosystems for impacts research, to address global terrestrial feedbacks, ecosystems having large areal extent *and* the potential to impact the magnitude of global greenhouse gas fluxes were a clear priority. Uncertainties for the global carbon cycle argue for emphasis on understanding climatic and $CO_2$ controls on (1) the terrestrial carbon cycle and natural capacities for carbon sequestration, (2) the fate of long-term pools of carbon in soil organic matter and coarse woody debris, (3) the redistribution and change in nitrogen (and other nutrient) capital of ecosystems, and (4) nitrogen and other nutrient constraints to C sequestration (e.g., progressive nitrogen limitation, successional change in community). Based on preliminary consideration of the critical climate-ecosystem feedback mechanisms listed above, two regions were identified as very-high-priority areas for new experimentation: high-latitude northern ecosystems (including tundra, boreal forest, and boreal peatland) and wet tropical forests (including both primary and secondary forest types). Workshop participants also concluded that continued work on temperate forest ecosystems was still critical to terrestrial feedbacks research given their combined areal extent and outstanding questions regarding long-term limitations to their carbon uptake capacities under climatic and atmospheric change.

Future terrestrial climate change research on feedbacks must include a portfolio of multifactor global-change experiments including warming, elevated $CO_2$, and other variables critical to limiting the functioning of the ecosystem carbon cycle (e.g., nutrient additions to reveal limitations). The specific variables to be included in future manipulations will be dependent on current understanding of a given ecosystem and the hypothesized sensitivity of that system to change.

### 2.4.3 Justifications of ecosystem choices and possible experiments

A number of ecosystems were highlighted as being especially important targets for new research for the characterization of climate change impacts or because they simply represented a major source of uncertainty regarding biospheric feedback to the physical climate systems. Figure 7 illustrates the prioritization just discussed for studies of either impacts or feedbacks. The following list details arguments for research attention on several biomes and includes additional supporting text and descriptions of key research needs and designs for some ecosystems.

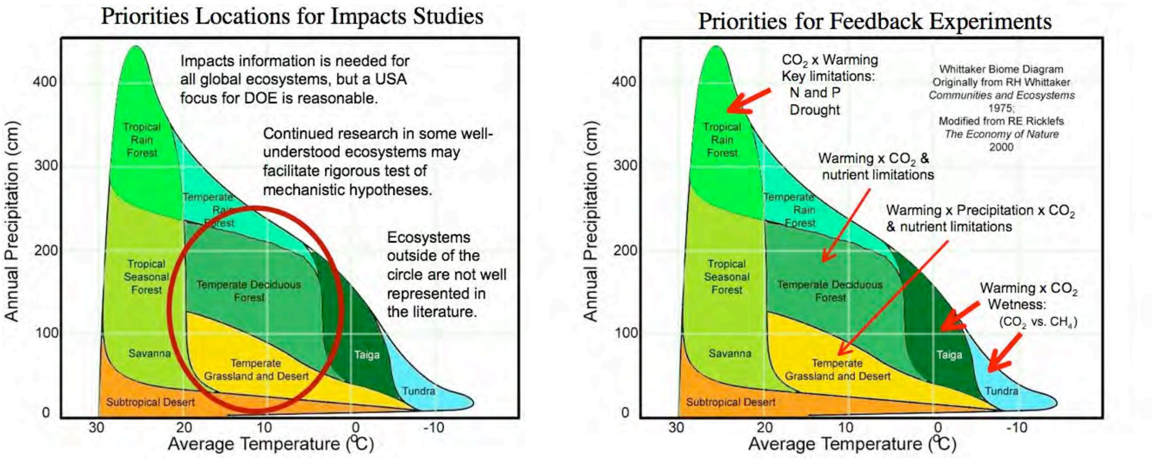

Figure 7. Ecosystems relevant to climate change impacts research (left graph) and those emphasized for climate feedbacks research (right graph). Bold arrows represent high-priority research.

*Arguments for Research on Northern High-Latitude Ecosystems*

The primary motivation for research on these ecosystems is their dominant role in the global carbon cycle and albedo feedbacks because they occupy 90% of the peatland area and 19–33% of global land carbon are in boreal peatland. Most wetland soil carbon resides in northern peatlands (> 40 cm of surface soil organic matter). That carbon may be particularly vulnerable to climate change because of greater-than-average predicted temperature increases at higher latitudes (Meehl et al. 2007). If this soil carbon is oxidized as $CO_2$ or $CH_4$, it will have dramatic effects on atmospheric greenhouse gas concentrations.

Climate models suggest that this region will experience the largest warming under climate change (Meehl et al. 2007). In addition, changes between wet and dry conditions may, in turn, convert many ecosystems between sources and sinks for $CO_2$ and greatly modify $CH_4$ emission rates.

Permafrost changes in arctic ecosystems are expected to lead to nonlinear step-change responses in the state of the system with strong anticipated responses to soil-warming manipulations. Wetlands common to boreal and arctic ecosystems are important ecosystems with respect to feedbacks to global climate change because they contain ~19% of the global soil-carbon pool (220 Pg C in North American wetlands alone; Bridgham et al. 2006). Wetlands are also responsible for 15 to 40% of global $CH_4$ emissions (Forster et al. 2007). Although $CH_4$ is at much lower atmospheric concentrations than $CO_2$, it has 25 times the global warming potential, making it responsible for 18% of human-induced radiative forcing (Forster et al. 2007). Methane fluxes from wetlands have provided an important radiative feedback in past climates (Chappellaz et al. 1993, Blunier et al. 1995, Petit et al. 1999, Spahni et al. 2005). Moreover, recent global warming may have resulted in increased $CH_4$ emissions from wetlands (Fletcher et al. 2004, Wang et al. 2004, Zhuang et al. 2004, Chen and Prinn 2006). Thus, evidence suggests that $CH_4$ fluxes from wetlands provide an important climate feedback.

These ecosystem have been shown to be unresponsive to $CO_2$ manipulation, but sensitive to altered nutrient status (Shaver et al. 2001). Nutrient availability is expected to increase in tundra soils in the future because of faster mineralization under warmer conditions and, to a lesser extent, to anthropogenically induced N deposition leading to enhanced NPP. It is likely that old organic matter in arctic soils may be destabilized under greater nutrient availability because of the simultaneous stimulation of microbial populations and because carbon stocks will decrease. Long-term fertilization and warming experiments in tussock tundra have caused changes in species composition, NPP, aboveground biomass, and soil organic matter stocks. Under fertilization, aboveground NPP was doubled, and biomass increased by approximately a factor of 8 over 20 years as dominance shifted to deciduous shrubs (Shaver et al. 2001). At the same time, there was a loss of nearly 2000 g $m^{-2}$ of soil C in fertilized plots, and no net retention of nitrogen in the soil (Mack et al. 2004). Soil C was lost primarily from deeper organic and mineral soil pools, while C and N accumulated in litter and upper soil pools (Mack et al. 2004).

Finally, this ecosystem's high carbon stocks may be subject to rapid loss from warming-induced exacerbation of the fire cycle under climate change.

**Recommended experimental treatments and conditions for northern high-latitude ecosystems:**

- Warming treatments might include multiple levels of whole-ecosystem warming, including the highest levels consistent with a range of $CO_2$ futures.
- $CO_2$ exposure levels (perhaps 700 and 1200 ppm) should be conducted. Past work showed low sensitivity to $CO_2$, but mineralization from warming could eliminate a key limitation.
- Experiments should be replicated in both dry (upland) and wet (lowland) areas
- Nitrogen addition-treatments might be added to test element-supply limitations.

- A replicated factorial experimental design was recommended with multiple levels to allow thresholds or compensatory responses to be revealed. In situ studies were preferred.

*Arguments for Research on Wet Tropical Forest Systems*

The primary motivation for experimental research on wet tropical forests was the characterization of their role in global carbon-cycle feedbacks. Wet tropical forests occupy approximately 50% of Earth's live biomass, 25% of the global gross primary production, and 10% of global land area . Large areas of tropical wetlands also represent an important global source of $CH_4$. They are also an important repository of Earth's biodiversity. Global models disagree on the sign of the climate–carbon-cycle feedback in tropical forest. Experiments might resolve this issue. The combined manipulation of $CO_2$ and temperature in wet tropical forest or plantations was suggested as being critical for testing model projections of large amounts of carbon accumulation and ecosystem vulnerability to drought. A key uncertainty for modeling tropical-ecosystem feedbacks to the global carbon cycle is the degree to which their behavior would be limited or enhanced under warming-induced nutrient feedbacks. Both nitrogen and phosphorous limitations were highlighted. Questions about the response of tropical ecosystems to elevated $CO_2$ (Hickler et al. 2008) include the magnitude of the $CO_2$ fertilization effect and effects on water use efficiency or rooting depth that might offset drought impacts driven by warming (and/or uncertain changes in precipitation). Rapid turnover of above- and belowground carbon pools in this warm, wet environment make the ecosystem sensitive to changing climate. Finally, Because wet tropical forests are a dominant repository of biodiversity, it is essential that the impacts of accelerated climate change be understood for the characterization of the susceptibility of this ecosystem in the future.

**Recommended experimental treatments and conditions for wet tropical forest ecosystems:**

- Multiple $CO_2$ levels (perhaps 700 and 1200 ppm)
- Warming (consistent with $CO_2$ projections whole-system warming preferred, possible application of soil warming)
- N and P additions to evaluate critical limitations of C exchange capacity
- Water status limitations (drying)
- Studies replicated for both primary and secondary forests
- A replicated factorial experimental design was recommended, and in situ studies were preferred. Multiple levels of environmental variables were recommended to allow thresholds or compensatory responses to be revealed.
- To identify logical locations for tropical research a study of feasibility as a precursor to large research investments was recommended. Suggested locations for such studies were Brazil, Costa Rica, Puerto Rico, Northern Australia, Hawaii, and Malaysia

*Arguments for Continued Attention on Midlatitude Forest Ecosystems*

While much is already known about the response of midlatitude temperate forest ecosystems to climate change environmental drivers, their dominance in populated areas of the United States and throughout Europe keeps them high on the list for new experiments related to carbon carbon-cycle feedbacks and climate change impacts. Midlatitude forests continue to exhibit a significant carbon sink that needs to be quantified as a carbon-cycle feedback to climate. Progressive nutrient limitation may place a long-term limit on that feedback and [is???] yet to be fully quantified or understood. Some of the existing FACE and warming experiments located in midlatitude forest ecosystems continue to produce information on processes controlling carbon sequestration. Where continued learning about these processes is assured, existing experiments represent a cost-effective approach to obtaining long-term data on ecosystem responses to climate change; these experiments are mature enough (i.e., 10 to 15 years) to inform us on slow ecosystem processes. Information on slow ecosystem processes may not be obtained readily from new, multifactorial experiments. The experiments, targeted at assessing interaction effects, will begin to generate new knowledge early on and will do so on ecosystems not represented by existing FACE experiments. Effects anticipated from slow-to-develop nutrient limitations or effects on the reproductive capacities of large trees might also be studied in mature forests exposed to the requisite treatments.

Sustaining extant long-term studies or the initiation of the next series of multi-year manipulations should be fully justified through a model-experiment planning exercise. Model projections of long-term responses are needed to organize our hypotheses about the temporal duration of treatment exposure needed to “reveal” important treatment responses and feedbacks. Homeostatically adjusted biomass distributions, water and element cycles, and the full engagement of reproductive activities represent features of mature forests that need to be incorporated into next-generation experiments.

Pollutant exposure is the greatest for these ecosystems because they overlap with large human population centers and may lead to potentially important interactions that would need to be understood to project response under climate change.

**Recommended experimental treatments and conditions for midlatitude forest ecosystems:**

- Sustained operation of some existing long-term FACE studies
- Initiation of $CO_2$ □ warming studies in mature ecosystems known to be nutrient limited to achieve a rapid test of element limitations
- Warming □ nutrient additions □ soil moisture □ $CO_2$ studies for model ecosystem/mesocosms representing most plant functional types with high replication
- Elevated $CO_2$, warming, soil moisture controls on seedling germination, and establishment for individual species (field, mesocosm, and greenhouse) to characterize potential biodiversity changes and the genetically controlled vulnerability of species
- Species-level responses and community interactions in mixed community
- Experiments across transition zones
- Key species removal and additions □ global change factors to accelerate community change (including invasives)
- Disturbance regimes (e.g., vulnerability to fire and insect pests)

- A replicated factorial experimental design was recommended, and in situ studies were preferred. Multiple levels of environmental variables were recommended to allow thresholds or compensatory responses to be revealed.

*Arguments for Continued Attention on Savanna Ecosystems*

Savannas occupy a key transition zone for the identification of sensitive early indicator responses and are of interest from the perspective of long-term climate change impacts on the function, structure, and composition of this ecosystem. With global warming, the role for drought and fire are important within this ecosystem, and the susceptibility to fire would be expected to be exacerbated by the loss of trees. Tropical and temperate grasslands, dominated by C4 species, contribute ~25–30% of global terrestrial productivity (Gillon and Yakir 2001) and are therefore of interest as a key component for climate feedbacks.

**Recommended experimental treatments and conditions for savanna ecosystems:**

- Warming (multiple levels) combined with precipitation treatments (amounts and phase to be considered)
- Elevated $CO_2$ (a key variable driving differential effects for C3 or C4 plant species that potentially converge in a highly competitive manner in Savanna ecosystems)
- A replicated factorial experimental design was recommended, and in situ studies were preferred. Multiple levels of environmental variables were recommended to allow thresholds or compensatory responses to be revealed.

*Arguments for Continued Attention on High-Altitude Ecosystems*

As ecosystem type that matters to people from a largely aesthetic perspective the primary motivation for experimental research on such ecosystems is to evaluate their vulnerability to climate change. The total global land area occupied by such ecosystems is small making their contribution to climate feedbacks of minor concern. These ecosystems are considered sensitive system because climate change leaves the adapted organisms no place to migrate. High altitude systems have an important role in regional hydrology (especially in the western United States), and their survival or demise may impact water yield and quality for future human use.

**Recommended experimental treatments and conditions for high-altitude ecosystems:**

- Warming (multiple levels)
- Elevated $CO_2$ (lower priority in western high-elevation ecosystem)
- Altered precipitation amounts and phase (multiple levels)
- Experiments focusing on the hydrologic effects would be most appropriately evaluated at or scaled to watershed or small catchment scales.
- A replicated factorial experimental design was recommended, and in situ studies were preferred. Multiple levels of environmental variables were

recommended to allow thresholds or compensatory responses to be revealed.

*Arguments for Continued Attention on Semi-Arid and Desert Ecosystems*

The primary motivations for continued or new climate change experiments on semi-arid or desert ecosystems is an understanding of the likely impacts of climate change on extant organisms, but some consideration of feedbacks is warranted given the land covered by this biome. These ecosystems cover 35% of Earth's land surface (~20% of the land area in the conterminous United States), and they may be playing a larger role in modulating global atmospheric $CO_2$ levels than previously thought (e.g., Jasoni et al. 2005; Wohlfahrt et al. 2008). Some considered these ecosystems to be a "canary in the coalmine" indicator of climate change because they are already on the edge in regards to their ability to sustain productivity because of the tightly constrained resources (Gitlin et al. 2006). Semi-arid ecosystems' capacities to exchange carbon with the atmosphere are sensitive to $CO_2$-induced changes in ecosystem water use efficiency, woody- or invasive-species encroachment, and especially susceptibility to fire. There is also a need to understand the location of the net carbon uptake by arid ecosystems. It is not clear if current net primary production represents a partitioning of carbon storage to vascular plants or cryptobiotic crusts. Cryptobiotic crusts also play an important role in the control of wind erosion (dust mitigation), and it is unclear how climate change will impact this service. Finally, they are considered critical ecosystems because they have a large impact on river water (e.g., the Colorado River and alpine mountain snowfall) and groundwater aquifer recharge (by snowfall in high mountain ranges of deserts) and are used for drinking, agricultural irrigation, and energy production and cooling.

**Recommended experimental treatments and conditions for midlatitude forest ecosystems:**

- Precipitation □ **$CO_2$** in basin or lowland ecosystems
- Warming ± precipitation □ **$CO_2$** in high elevation mountains
- A replicated factorial experimental design was recommended, and in situ studies were preferred. Multiple levels of environmental variables were recommended to allow thresholds or compensatory responses to be revealed.

*Arguments for Continued Attention on Coastal Ecosystems and Rivers*

Climate change impacts on coastal ecosystems and rivers are regarded as important because of the role that these ecosystems play as a high-value provider of ecosystem services to humans. They are also importance as a sink, transporter, and transformer of carbon between terrestrial ecosystems and oceans.

Coastal ecosystems, at risk from rising sea level, have a disproportionately high importance to human populations throughout much of the world. Even though coastal systems account for only a small fraction of the U.S. and global land area, these roles magnify the significance of their footprint. They are highly valued as desirable living spaces, destinations for tourism, locations for manufacturing and marine transportation, military installations, and recreational opportunities. Barrier islands and adjacent wetlands moderate flooding and serve to protect inland development from periodic storms. They also filter sediment and process nutrients and contaminants introduced by runoff from developed uplands.

In an ecological context, coastal ecosystems are highly productive and provide nutrition and habitat for commercially important biological resources. They act as nurseries for species that have major recreational and commercial value. They are likely to maintain their relative elevation until the rate of sea-level rise exceeds a tipping point (Morris et al. 2002). The tipping points vary among estuaries but are within the range of rates of sea-level rise that are likely during the 21st century.

**Recommended experimental treatments and conditions for midlatitude forest ecosystems:**

- Experiments to understand the loss of protective, productive coastal wetlands and forests as consequence of sea level rise (inundation manipulations with brackish or saltwater). Key interactions with warming are unknown. Much is known about their response to elevated $CO_2$, but it should continue to be included as an important interacting factor in the capacity of $C_3$ plants to survive in the face of periodic inundation.
- Replicated factorial experimental designs are recommended, and in situ studies are preferred.
- Model or constructed ecosystems might be useful tools for evaluating the mechanisms of climate change response in such ecosystems.
- Multiple levels of environmental variables were recommended to allow thresholds or compensatory responses to be revealed.

### 2.4.4 Managed ecosystems needed for impact and climate-feedback research

Managed ecosystems are defined as those ecosystems intentionally subjected to a range of manipulations to provide food, feed, fuel, and fiber for human use. Plant functional types range from small stature herbs to large, woody trees and are often characteristic of early successional, disturbance-prone habitats. Areal extent can range from individual fields or forest patches to the landscape and approach or exceed the extent of natural ecosystems on a regional basis. Most global change experiments to date have focused on managed ecosystems and/or early successional, disturbance-prone species.

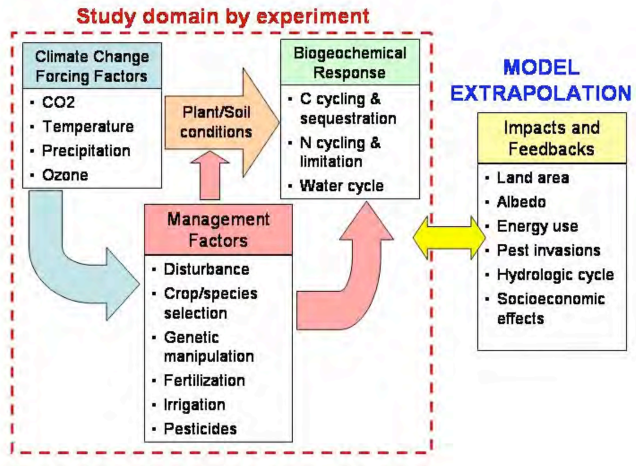

Figure 8. Interactions of management practices and global change in influencing biogeochemical cycles and land feedback to climate change.

Why managed ecosystems? Beyond their intrinsic importance as commodity providers, studying managed ecosystems in an empirical and theoretical context provides a number of important scientific opportunities:

1. The large spatial cover of managed ecosystems suggests that their response to global change will have important feedbacks to the climate system.
2. Because managed ecosystems by definition are amenable to manipulation, they hold promise for manipulating key attributes that can potentially mitigate aspects of global change.
3. Because of their economic importance, many managed ecosystems are populated by plants amenable to advanced genomic/metabolomics and computational technologies. The availability of microarrays for soybean and poplar, for example, permits a more complete understanding of the response of these species to global change.
4. The homogeneity of most managed ecosystems make them uniquely suited to large-scale experiments where less replication may be necessary to detect responses.
5. Because managed ecosystems are populated by plants representing the spectrum of plant functional types, research conducted in these ecosystems is "translational." Research on managed ecosystems provides a basic understanding that is applicable to nonmanaged systems. In many cases they are model systems.
6. Food, feed, fuel, and fiber are the central outputs of managed ecosystems, and understanding how these systems will respond to global change is fundamental to food security and our socioeconomic system.

Important questions in these systems include: (1) How does climate change interact with ecosystem management? (2) What are the genetic differences in response to $CO_2$ and temperature? (3) How do environmental changes interact to affect biogeochemical cycling? (4) How can we best characterize ecosystem responses to environmental change over broad ranges and identify thresholds and nonlinearities? (5) How will management and environmental change interactively affect the land surface properties that feed back to climate change?

Selection of ecosystems for study and the nature of experiments to be done should be prioritized with the following considerations:

- Potential for new scientific insights that inform our understanding of ecosystem response to climate and atmospheric change.
- Ability to design unique experiments addressing natural dynamics (e.g., disturbances, which are a natural part of managed ecosystems), application of available genomic or metabolomic tools, homogeneity of the stand, and other attributes of managed ecosystems.
- Importance of feedbacks to the climate system through important biogeochemical cycles (carbon, nitrogen, etc), the water cycle, or land-surface changes (e.g., albedo). This criteria applies to current managed systems but might be emphasized in the future in the context of widespread utilization of land area for the growth and development of bioenergy crops.
- Consideration of economic impacts (threats or opportunities) from climate change responses of current and future crops; including new scientific insights that may inform decisions about crop adaptation strategies.

At the present time there is increasing interest in biofuels. Converting land presently used to produce food, feed, fiber, or unmanaged ecosystems to biofuels will likely have large impacts on regional C sequestration, water and nutrient cycling, albedo, and surface energy balance. Development of a large-scale biofuels industry represents an area of incredible uncertainty regarding impacts of ecosystem management on carbon-sequestration potential and biosphere feedback to climate change. Therefore, there is a pressing need to determine the likely effects of intensive production of woody and nonwoody bioenergy crops on C sequestration (soil C storage and in displacement of fossil fuel $CO_2$ emissions), water and nutrient cycling, and surface energy balance.

### 2.4.5 International versus domestic research sites

There is a perception among some researchers that agencies are reluctant to fund field research outside of the United States. The group discussed this issue and noted that DOE has funded several projects outside of the United States. The group endorsed the need to evaluate and select research projects based on scientific importance, irrespective of location. Global climate change is a global problem driven by global greenhouse forcing; improved predictions of climate change require improved characterization of the global feedbacks of ecosystems to climate. Past research on the ecological impact of climate change has emphasized research in the United States, and it is difficult to argue that U.S. ecosystems are understudied compared to ecosystems in locations like the tropics. The group suggested an open approach that makes room for studies in the United States, which build on what is already known, take advantage of cost efficiencies by working near established institutions, and address questions of immediate societal concern. It also recommends the inclusion of the opportunity for studies outside of the United States that consider globally important but understudied ecosystems.

## 2.5 New Manipulative Technologies and Measurement Needs

### 2.5.1 Experimental design hurdles and needed improvements

Research capable of assessing the comparative sensitivity of ecosystems to climate change or identifying key attributes of ecosystems that make them vulnerable to change and crossing thresholds will require an integrated approach to research design and execution. Next-generation experiments must emphasize quantitative responses to climate and $CO_2$ at treatment levels that include and exceed conditions expected by the end of this century.

Key strategic issues include:

- Separating the response to the initial driver from the indirect internal responses, thereby tracing the chain of causality
- Incorporating trophic levels and island effects into plot-level experiments (or designing new experiments)
- Incorporating disturbance into experimental designs
- Better understanding and acknowledging the effect of step changes in experimental designs
- Utilizing unique experimental infrastructure for climate change manipulations to address both impacts and feedback questions.
- Developing and employing statistical and modeling tools

A common concept emerged from the discussions: conducting field-scale, multifactor experiments supported by small, simpler, lab/greenhouse studies to resolve mechanistic response curves and to model system behavior. Where possible, new experiments must be done at scales required to understand system-level responses, controls, and feedbacks. Experimental systems should be able to control and/or adequately monitor multiple factors, be able to distinguish cause-and-effect from mere correlation, and push the envelope in research capabilities. Although there was a clear preference for attempting future research *in situ*, the need to make headway in addressing process responses critical to our predictive capacities might demand the application of model systems for the rapid clarification of mechanisms.

For pragmatic reasons, experiments are generally forced into applying unrealistic treatments, such as step changes in $CO_2$ concentration or temperature. This is usually necessary to balance sample size and other logistical constraints with the desire to obtain measurable responses that are discernable above the typical noise of any environmental or physiological observation. While step changes are unrealistic and do not reflect the changes that are actually to be expected under any realistic climate change scenario, the workshop participants concluded that it was not possible to develop a perfect experimental approach and suggested moving forward with studies designed to unveil the general features of environmental response for a full range of environmental conditions.

It is desirable to consider including disturbance and higher trophic levels in future experimental designs. It is likely that many of the major vegetation transitions in the coming decades will be facilitated by large-scale disturbance and possibly mediated by consumers. Because fire and consumer demographics are likely to be implicated in so many of the transitions, it is worth exploring possibilities for adequately incorporating their effects in experiments.

### 2.5.2 Need for new and improved experimental technologies

*Temperature Manipulations*

It is important to recognize that there are no existing warming studies that maintain year-round 24-hour-per-day treatments both above and below ground have been conducted, and few have applied temperature differentials as large as those projected by current IPCC assessments (Meehl et al 2007; Christensen et al. 2007). To appropriately capture plausible carbon cycle (and other trace gas responses) to warming, experimental targets for warming must be expanded to include and perhaps exceed the temperature differential projections from coupled-climate models. We should not be satisfied by addressing warming at “doable” treatment levels of 1 to 3 °C when projections suggest differential temperature ranges as much as 6 to 8 °C at high latitudes. We need to determine the extent to which functional responses to low differential temperatures (1 to 3 °C) differ from the response to higher differential temperature futures (5 to 8 °C).

Infrared (IR) heating under open field conditions has been proven to work for short canopies (<1–2m), small temperature increases (2–3° C), and small plots (up to 6m diameter). Higher temperatures and larger plots are feasible but need some development and will be expensive. Recent technological discussions of the application of infrared heating arrays are available to drive the application of this technology to short-stature vegetation at a range of areal distributions (Kimball 2005; Kimball et al. 2008). In such systems appropriate management of relative humidity in the atmosphere remains a concern. Furthermore, infrared heating remains unproven for large-stature ecosystems.

Greenhouse or enclosed-space systems for warming experimental plots may be needed to achieve higher projected temperature ranges, and continued development of the technologies for such treatment systems is essential. Workshop participants recognized that the acceptance of chambers or structures within an experimental design would introduce various perturbations (light, turbulence, etc.) that should be fully characterized to adequately interpret such studies.

Space-for-time substitution experiments to achieve a range of temperature conditions were discussed, but confounding variables like photoperiod, incident light levels, precipitation, and soil characteristics (to name a few) were considered a serious impediment. Such confounding limits the suitability of such approaches for the development of cause-and-effect relationships that are needed to extend experimental results through model projections. Vegetation/soil monolith redistributions along natural elevation gradients (thus excluding photoperiod concerns) might be pursued for small-stature vegetation. Multifactor modeling could help address at least some confounding factors.

*Carbon Dioxide Manipulations*

Current technologies provide us with a range of methods for the manipulation of ecosystem exposures to atmospheric $CO_2$ at a range of spatial scales from small to large, including: growth chambers, greenhouses, open-top chambers, tunnel systems, and free-air $CO_2$ enrichment (FACE) in a variety of incarnations. Of these technologies, those that allow vegetation to be exposed *in situ* or when planted directly into natural soils are preferred. FACE has been shown to be feasible for nearly all ecosystems.

We need to employ experiments using $CO_2$ exposures at much higher concentrations than has previously been the norm for FACE. Such exposures are possible with the current FACE technologies if the cost of exposure is not an obstacle and if one is willing to accept increases in variability around the average exposure levels. A number of new FACE array concepts (gradient, grid, and honeycomb) are being considered to facilitate the application of $CO_2$ at higher concentrations and a range of spatial scales.

Options for obtaining $CO_2$ to support next-generation studies were also discussed. Some traditional industrial sources for $CO_2$, especially ammonia fertilizer and ethanol plants, might disappear or become limiting during the next 10 to 20 years because of changing market conditions in these industries. The future availability of potential $CO_2$ sources will need to be considered when designing and citing long-term experiments. This attention to detail will be especially important if the experiments expect to take advantage of the □$C^{13}$ ratio in the added $CO_2$. Opportunities exist for the extraction of $CO_2$ from landfills, and emerging technologies might make possible the direct $CO_2$ extraction from air as a source of $CO_2$ for experiments.

*Precipitation Manipulations*

Technologies for precipitation exclusion and water addition at fixed or variable intervals were not extensively discussed at the workshop because they were regarded as being largely available and adaptable for many ecosystems. Unique treatment applications have been published for a range of ecosystems and plot scales (e.g., Beier et al. 2004; Fay 2000; Hanson 2000; Penuelas et al. 2004). Nevertheless, groundwater levels, lateral flow pathways, and rooting depth represent physical and biological variables often overlooked that should be considered during design and development of precipitation treatments or soil moisture monitoring in conjunction with other environmental treatments (especially warming).

*Fire*

It was considered likely that many of the major vegetation transitions in the coming decades would be facilitated by large-scale disturbances, especially fire. Because fire is likely to be implicated in so many of the transitions, it is worth exploring possibilities for incorporating its effects in experiments. Three ways of doing this were discussed:

1. Burning the plots before erecting the experimental manipulation: This approach has been used successfully on a scrub-oak system in open-top chamber experiments in Florida (Day et al. 2006; Johnson et al. 2003).
2. Planning for a controlled burn sometime after the initiation of the experiment: This option would require careful management of the infrastructure, as well as a serious evaluation of the possible effects of the treatments on susceptibility to fire. The workshop participants were not aware of an experiment that purposely took this approach, but the unintentional wildfire at Jasper Ridge supported a number of publications that adopted this approach opportunistically.
3. Using one or more treatments that mimic aspects of fire, without actually burning the site: Possible treatments could be as simple as removing live biomass, or they could be as complex as moving live biomass off the plots, burning it, and returning the ash.

### 2.5.3 Need for new and improved measurement technologies

Workshop participants did not spend sufficient time discussing the need for new or improved measurement technologies. Nevertheless, a few key measurement needs were noted, as reflected in the pre-workshop survey results summarized in the following list of variables and processes suggested to be simulated poorly in current ecosystem model by workshop participants. In the following list, the “count” in parentheses represents the number of survey respondents recommending the need for more work on the listed variable.

- Species specificity and biodiversity (□7)
- Biogeochemical cycling (C and other elements) (□6)
- Carbon allocation to growth (□4); also emphasized in group discussion
- Plant mortality (□3); also emphasized in group discussion
- Seed production/dispersal (□2); also emphasized in group discussion
- Seedling establishment (□2); also emphasized in group discussion
- Plant water status (□2)
- Fine root production
- Physiology (acclimation, respiration, photosynthesis, and N fixation)
- Plant recruitment; species migration also emphasized in group discussion
- Competition
- Animal responses
- Soil mineralization and carbon turnover rates
- Plant nutrient uptake

Genomic tools were discussed as a means to understand the genetic basis for higher-level responses to environmental change (QTLs, etc.) through the characterization of a wide range of physiological and developmental processes for plants, fungi, and microbial communities. To the extent possible, genetic control over the responses of these processes should be characterized under a range of controlled temperatures for different genotypes within a species. Intra- and inter-specific variation in the effects of environmental factors (e.g., drought and temperature) on molecular, biochemical, and physiological processes underlie the diversity of plant responses to global change which drive complex changes in ecological interactions and ecosystem function. The recent development of high-throughput, genomic and metabolomic profiling tools (Jackson et al. 2002; Hall 2006) presents a huge opportunity to advance understanding of these mechanisms.

While not extensively discussed at the workshop, the application of remote-sensing data from satellite or aircraft platforms was viewed as a key measurement interface between experiments and models. To scale plot-scale experimental results across Earth's terrestrial surfaces will require the extrapolation of mechanistic understanding through models to the land-cover characteristics occupying target regions or continents. Evaluation of the capacity to use remotely sensed characteristics of current ecosystems to infer landscape functions or rates of change under current environmental variability can lead to improvements in ecosystems models even though it cannot take the place of experiments that address future conditions for which we have no measurable analogs.

New measurement approaches are needed for the quantitative evaluation of key processes previously proven to be intractable and for understanding and projecting ecosystem responses to climate change.] Without improvements in quantitative measurement methods to be employed in next-generation experiments, attempts to improve ecological forecasts will be inhibited.

### 2.5.4 A new way to conceive experimental work

One group of workshop participants suggested a two-stage approach to the design and funding of such integrated research proposals. That approach would not replace the support of single-investigator projects but would offer an alternative funding mechanism to address key large-scale questions. An investigator (a single principal investigator or with colleagues) would have the option of submitting a planning proposal to hold one or two meetings to formally design an integrated research approach for addressing issues beyond those historically funded by single investigator or relatively small multi-investigator collaborations. Such studies might require multiple sites along gradients (climatic, ecological, structural, or process level) and/or require scientists with multiple disciplines to collaborate. The intent of the planning meeting(s) would be to enlist and commit the expertise necessary to conduct such innovative research. Teams that included expertise in statistics and modeling to inform the experimental design, treatment structure, and the responses to measure would be strongly encouraged.

## 2.6 Related Reports

Several workshop, committee, and small-group reports preceded this workshop. Reflecting on how the conclusions from those efforts compare and contrast with the findings summarized here provides a broad picture of the research community's views on the goals and needs for next-generation ecosystem experiments.

In 2001, DOE and Columbia University sponsored discussions on "Earth System Questions in Experimental Climate Change Science" that might be considered in the specific context of the Biosphere 2 Laboratory (B2L; Osmond 2002). That report suggested that the science community saw some value in the complex manipulative capacity of B2L that might be applied to the evaluation of mechanisms of ecosystem responses to controlled environmental change, but it did not identify science questions or priority ecosystems for consideration. Participants at the current workshop favored replicated *in situ* studies (where possible) but agreed that experiments designed to uncover mechanisms rather than to test explicit future climate and atmospheric scenarios were the appropriate future direction.

The BERAC Subcommittee (Ehleringer et al. 2006) concluded that single-factor experiments would not be a sufficient source of information as the science community moves forward with future analyses of climate change impacts. It suggested that future DOE BER experimental research might be expected to consider multiple factors associated with ongoing and projected future climatic changes. Conclusions from this workshop, conducted in response to a recommendation of the BERAC Subcommittee, provide the conceptual framework for planning, evaluating, and siting next-generation studies to address climate change impacts and feedbacks research.

A National Research Council report (NRC 2007) titled "Understanding Multiple Environmental Stresses" concluded that (1) many examples of important atmospheric-ecosystem interactions existed, but few, if any, were thoroughly understood; (2) the community with expertise needed to address questions in atmospheric-ecosystem interactions was relatively small; (3) experimental, observational, and modeling/simulation techniques were needed to explore multiple environmental stresses because the interactions unfold only on long time scales or large spatial scales; (4) multifactor experiments are required; and (5) there was an explicit need to generate the capability to manipulate multiple variables and conduct experiments over appropriate spatial and temporal scales. These overall conclusions are consistent with the findings outlined in this report, but this workshop believed that experiments based on multilevel manipulations of single environmental change factors continue to have value and should not be excluded as the community moves forward with multifactor studies in selected ecosystems.

The European Science Foundation sponsored an INIF/International brainstorming workshop in Rome, Italy, 5-7 December 2007, entitled "FACEing the Future: Planning the Next-Generation of Elevated $CO_2$ Experiments on Crops and Ecosystems." That workshop conducted focused discussions on the need for additional elevated-$CO_2$ studies in crop and natural ecosystems but emphasized the need to understand the future responsiveness of crop systems to further society's ability to project food, fiber, and biofuel production capacities with climate change. They also concluded that multifactor responses were important but did not make that the focus of their discussions or report. Their conclusions are consistent with the findings reported here, and reiterate the need to combine experimental and modeling efforts as a key method for moving climate change science forward.

The Smithsonian Institution convened a meeting on the "Effects of Elevated $CO_2$ on Plant and Ecosystem Processes" 23 and 24 of January 2008 to address questions related to those discussed at this workshop. Key conclusions regarding science issues that represented remaining needs and uncertainties included:

- Interactions of global-change factors (combined manipulative, observational, and modeling approaches needed),
- Ecosystem responses that have a direct feedback on climate forcing (e.g., land-atmosphere exchanges of energy and matter),
- Need to prioritize critical and understudied ecosystems for future research,
- Recognition that tipping-point ecosystems exist (e.g., northern forests/tundra where large stores of carbon are vulnerable to warming and drying resulting in massive GHG releases),
- Food security and agro-ecosystems (e.g., vulnerable agro-ecosystems whose demise is predicted to have important impacts on world food supply),
- Identification of general principles of ecosystem responses to GC that can be incorporated into climate change models, and
- Capacity to predict logical shifts in ecosystem boundaries and structure.

Like the conclusions summarized here, that group found manipulative experiments to be "an indispensable approach for improving our predictive understanding of ecosystem responses to global change."

In March 2008 BERAC sponsored a workshop titled "Identifying Outstanding Grand Challenges in Climate Change Research: Guiding DOE's Strategic Planning" (Dickinson and Meehl 2008). The workshop covered the full range of climate change science covering coupled-climate modeling, cloud chemistry, aerosols, ecological effects and feedbacks, and human dimensions research related to the consequences of climate change. Regarding the subject of ecosystem research, the Grand Challenges workshop concluded that ecosystem processes and changes as a part of the climate system represented a unique topic in climate change studies that required experimental approaches to better predict future changes. Such a conclusion emphasizes the importance of the subsequent workshop that was just completed.

Finally, the Executive Summary of the recent Climate Change Science Program, Synthesis and Assessment Product 4.3 "emphasize[d] that improvements in observations and monitoring of ecosystems, while desirable, are not sufficient by themselves for increasing our understanding of climate change impacts. Experiments that directly manipulate climate and observe impacts are critical for developing more detailed information on the interactions of climate and ecosystems, attributing impacts to climate, differentiating climate impacts from other stresses, and designing and evaluating response strategies" (Backlund et al. 2008). The authors of that report also concluded that institutional support for such experiments remained a "concern."

During the past 8 years, various members of the scientific community have met to emphasize the importance of ecosystem research to climate change science and to evaluate science questions and ecosystems for prioritization. As a reinforcement of past conclusions, participants of the current workshop concluded that a combination of experimental work supported by model-based hypotheses and followed up by model-based interpretations of results provides a logical framework for the next generation of experiments on climate change. This workshop recommends next-generation experiments that focus on a range of warming and elevated-$CO_2$ futures as modified by water and nutrient limitations. Such experiments are to be conducted in important ecosystems, but the primary emphasis should always be the development or improvement of process-level mechanisms to enhance future forecasts.

# REFERENCES

Ainsworth EA, Rogers A (2007) The response of photosynthesis and stomatal conductance to rising [$CO_2$]: mechanisms and environmental interactions. *Plant Cell and Environment* 30:258-270.

Bååth E, Wallander H (2003) Soil and rhizosphere microorganisms have the same Q10 for respiration in a model system. *Global Change Biology* 9:1788-1791.

Backlund P, Janetos A, Schimel DS, Hatfield J, Ryan M, Archer S, Lettenmaier D (2008) Executive Summary. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Washington, DC., USA, Page 6 of 362 pp.

Beier C, Emmett B, Gundersen P, Tietema A, Penuelas J, Estiarte M, Gordon C, Gorissen A, Llorens L, Roda F, Williams D (2004) Novel approaches to study climate change effects on terrestrial ecosystems in the field: Drought and passive nighttime warming. *Ecosystems* 7:583-597.

Blunier T, Chappellaz J, Schwander J, Stauffer B, Raynaud D (1995) Variations in atmospheric methane concentration during the Holocene epoch. *Nature* 374:46-49.

Bol R, Bolger T, Cully R, Little L (2003) Recalcitrant soil organic materials mineralize more efficiently at higher temperatures. *Journal of Plant Nutrition and Soil Science* 166:300-307.

Bridgham SD, Megonigal JP, Keller JK, Bliss NB, Trettin C (2006) The carbon balance of North American wetlands. *Wetlands* 26:889-916.

Canadell JG, Le Quere C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007) Contributions to accelerating atmospheric $CO_2$ growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America* 104:18866-18870.

CCSP (2007) The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implication for the Global Carbon Cycle. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [King AW, Dilling L, Zimmerman GP, Fairman DM, Houghton R, Marland G, Rose AZ, Wilbanks TJ (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, North Carolina, USA, 242 pp.

Chapin FS, Sturm M, Serreze MC, McFadden JP, Key JR, Lloyd AH, McGuire AD, Rupp TS, Lynch AH, Schimel JP, Beringer J, Chapman WL, Epstein HE, Euskirchen ES, Hinzman LD, Jia G, Ping CL, Tape KD, Thompson CDC, Walker DA, Welker JM (2005) Role of land-surface changes in Arctic summer warming. *Science* 310:657-660.

Chappellaz J, Bluniert T, Raynaud D, Barnola JM, Schwander J, Stauffert B (1993) Synchronous changes in atmospheric CH4 and Greenland climate between 40 and 8 kyr BP. *Nature* 366:443-445.

Chen YH, Prinn RG (2006) Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model. *Journal of Geophysical Research-Atmospheres* 111:D10307, doi:10310.11029/12005JD006058.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr

A, Whetton P (2007) Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 847-940.

Comins, HN, McMurtrie, RE (1993). Long-term biotic response of nutrient-limited forest ecosystems to $CO_2$ enrichment; equilibrium behaviour of integrated plat-soil models. *Ecological Applications* 3:666-681.

Conant RT, Drijber RA, Haddix ML, Parton WJ, Paul EA, Plante AF, Six J, Steinweg JM (2008). Sensitivity of organic matter decomposition to warming varies with its quality. *Global Change Biology* 14:868-877.

Contamin R, Ellison AM (in review) Indicators of regime shifts in ecological systems: what do we need to know and when do we need to know it. *Ecological Applications* (in review).

Coûteaux MM, Bottner P, Anderson JM Berg B, Bolger T, Casals P, Romanya J, Thiery JM, Vallejo VR (2001) Decomposition of C13-labelled standard plant material in a latitudinal transect of European coniferous forests: Differential impact of climate on the decomposition of soil organic matter compartments. *Biogeochemistry* 54:147-170.

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440:165-173.

Day FP,Stover DB, Pagel A, Hungate BA, Dilustro JJ, Herbert BT, Drake BG, Hinkle CR (2006) Rapid root closure after fire limits fine root responses to elevated atmospheric $CO_2$ in a scrub oak ecosystem in central Florida. *Global Change Biology* 12:1047-1053.

Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM, Dickinson RE, Hauglustaine D, Heinze C, Holland E, Jacob D, Lohmann U, Ramachandran U, da Silva Dias PL, Wofsy SC, Zhang X (2007) Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USAEhleringer J, Birdsey R, Ceulemans R, Melillo J, Nösberger J, Oechel W, Trumbore S (2006) Report of the BERAC Subcommittee Reviewing The FACE and OTC Elevated $CO_2$ Projects in DOE. http://www.sc.doe.gov/ober/berac/FACE_2006_report.pdf

Dickinson RE, Meehl GA et al. (2008). *Identifying Outstanding Grand Challenges in Climate Change Research: Guiding DOE's Strategic Planning*. A report of the DOE/BERAC Workshop, 25-27 March 2008, Crystal City, Virginia (in preparation).

Ehleringer J, Birdsey R, Ceulemans R, Melillo J, Nösberger J, Oechel W, Trumbore (2006) *Report of the BERAC Subcommittee Reviewing the FACE and OTC Elevated $CO_2$ Projects in DOE*. White paper report submitted to the United States Deparment of Energy, 16 October 2006, 23 p. http://www.sc.doe.gov/ober/berac/FACE_2006_report.pdf

Fay PA, Carlisle JD, Knapp AK, Blair JM, Collins SL (2000) Altering rainfall timing and quantity in a mesic grassland ecosystem: Design and performance of rainfall manipulation shelters. *Ecosystems* 3:308-319.

Finzi AC, Norby RJ, Calfapietra C, Gallet-Budynek A, Gielen B, Holmes WE, Hoosbeek MR, Iversen CM, Jackson RB, Kubiske ME, Ledford J, Liberloo M, Oren R, Polle A, Pritchard S, Zak DR, Schlesinger WH, Ceulemans R (2007) Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated $CO_2$. *Proceedings of the National Academy of Sciences of the United States of America* 104:14014-14019.

Fletcher SEM, Tans PP, Bruhwiler LM, Miller JB, Heimann M (2004) CH4 sources estimated from atmospheric observations of CH4 and its 13C/12C isotopic ratios: 1. Inverse modeling of source processes. *Global Biogeochemical Cycles* 18:doi:10.1029/2004GB002223.

Forster P, Ramaswamy P, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. Pages 129-234 in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Gill, RA, HW Polley, HB Johnson, LJ Anderson, H Maherali, RB Jackson (2002) Nonlinear grassland responses to past and future atmospheric $CO_2$. *Nature* 417:279-282.

Gill RA, LJ Anderson, HW Polley, HB Johnson, RB Jackson (2006) Potential nitrogen constraints on soil carbon sequestration under low and elevated atmospheric $CO_2$. *Ecology* 87:41-52.

Gillon J, Yakir D (2001) Influence of carbonic anhydrase activity in terrestrial vegetation on the O-18 content of atmospheric $CO_2$. *Science* 291:2584-2587.

Gitlin AR, Sthultz CM, Bowker MA, Stumpf S, Paxton KL, Kennedy K, Munoz A, Bailey JK, Whitham TG (2006) Mortality gradients within and among dominant plant populations as barometers of ecosystem change during extreme drought. *Conservation Biology* 20:1477-1486.

Gorham E (1991) Northern peatlands - role in the carbon-cycle and probable responses to climatic warming. *Ecological Applications* 1:182-195.

Hall RD (2006) Plant metabolomics: from holistic hope, to hype, to hot topic. *New Phytologist* 169: 453-468.

Hanson PJ (2000) Large-scale Water Manipulations. Chapter 23 in Sala OE, Jackson RB, Mooney HA, Howarth RW (Eds.) *Methods in Ecosystem Science*, Springer-Verlag, New York. pp. 341-352.

Hanson PJ, Todd DE, Amthor JS (2001) A six year study of sapling and large-tree growth and mortality responses to natural and induced variability in precipitation and throughfall. *Tree Physiology* 21:345-358.

Hanson PJ, Wullschleger SD, Editors (2003) *North American Temperate Deciduous Forest Responses to Changing Precipitation Regimes.* Springer, New York, 421 p.

Happell JD, Chanton JP, Whiting GJ, Showers WJ (1993) Stable isotopes as tracers of methane dynamics in Everglades marshes with and without active populations of methane oxidizing bacteria. *Journal of Geophysical Research* 98:14771-14782.

Harper CW, Blair JM, Fay PA, Knapp AK, Carlisle JD (2005) Increased rainfall variability and reduced rainfall amount decreases soil $CO_2$ flux in a grassland ecosystem. *Global Change Biology* 11:322-334.

Hickler T, Smith B, I. Prentice C, Mjöfors K, MILLER P, Arneth A, Sykes MT (2008) $CO_2$ fertilization in temperate FACE experiments not representative of boreal and tropical forests. *Global Change Biology* (in press).

Hijmans RJ, Grahm CH (2006) The ability of climate envelope models to predict the effect of climate change on species distributions. *Global Change Biology* 12:2272-2281.

Houghton RA, Goodale CL (2004) Effects of land-use change on the carbon balance of terrestrial ecosystems. In *Ecosystems and Land Use Change*. Geophysical Monograph Series 153:85-98.

Jackson RB, Linder CR, Lynch M, Purugganan M, Somerville S, Thayer SS (2002) Linking molecular insight and ecological research. *Trends in Ecology and Evolution* 17: 409-414.

Jasoni RL, Smith SD, Arnone JA (2005) Net ecosystem $CO_2$ exchange in Mojave Desert shrublands during the eighth year of exposure to elevated $CO_2$. *Global Change Biology* 11:749-756.

Johnson DW, Hungate BA, Dijkstra P, Hymus GJ, Hinkle CR, Stiling P, Drake BG (2003) The Effects of elevated $CO_2$ on nutrient distribution in a fire adapted scrub oak forest. *Ecological Applications* 13:1388-1399

Kimball BA (2005) Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* 11:2041–2056.

Kimball BA, Conley MM, Wang S, Lin X, Luo C, Morgan J, Smith D (2008) Infrared heater arrays for warming ecosystem field plots. *Global Change Biology* 14, 309–320.

King JS, Kubiske ME, Pregitzer KS, Hendrey GR, McDonald EP, Giardina CP, Quinn VS, Karnosky DF (2005) Tropospheric O3 compromises net primary production in young stands of trembling aspen, paper birch and sugar maple in response to elevated atmospheric $CO_2$. *New Phytologist* 168:623-636.

King JY, Reeburgh WS, Thieler KK, Kling GW, Loya WM, Johnson LC, Nadelhoffer KJ (2002) Pulse-labeling studies of carbon cycling in Arctic tundra ecosystems: The contribution of photosynthates to methane emission. *Global Biogeochemical Cycles* 16:1062, doi:10.1029/2001GB001456.

Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition and the effect of global warming on soil organic carbon storage. *Soil Biology and Biochemistry* 27:753-760.

Kirschbaum MUF (2000). Will changes in soil organic matter act as a positive or negative feedback on global warming? *Biogeochemistry* 48:21-51.

Kirschbaum MUF, King DA, Comins HN, McMurtrie RE, Medlyn BE, Pongracic S, Murty D, Keith H, Raison RJ, Khanna PK, Sheriff DW (1994). Modelling forest response to increasing $CO_2$ concentration under nutrient-limited conditions. *Plant, Cell and Environment* 17:1081-1099.

Kirschbaum MUF, Medlyn BE, King DA, Pongracic S, Murty D, Keith H, Khanna PK, Snowdon P, Raison JR (1998) Modelling forest-growth response to increasing $CO_2$ concentration in relation to various factors affecting nutrient supply. *Global Change Biology* 4:23-42.

Knapp AK, Fay PA, Blair JM, Collins SL, Smith MD, Carlisle JD, Harper CW, Danner BT, Lett MS, McCarron JK (2002) Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland *Science* 298:2202-2205

Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L (2008) Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452:987-990.

Leakey ADB, Bernacchi CJ, Dohleman FG, Ort DR, Long SP (2004) Will photosynthesis of maize (*Zea mays*) in the US Corn Belt increase in future $CO_2$ rich atmospheres? An analysis of diurnal courses of $CO_2$ uptake under free-air concentration enrichment (FACE). *Global Change Biology* 10:951-962.

Leakey ADB, Uribelarrea M, Ainsworth EA, Naidu SL, Rogers A, Ort DR, Long SP (2006) Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of $CO_2$ concentration in the absence of drought. Plant Physiology 140:779-790.

Li Y, Chen DL, Zhang YM, Edis R, Ding H (2005) Comparison of three modeling approaches for simulating denitrification and nitrous oxide emissions from loam-textured soils. Global Biogeochemical Cycles 19:GB3002, doi:10.1029/2004GB002392.

Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR (2006) Food for thought: lower than expected crop yield stimulation with rising carbon dioxide concentrations. *Science* 312:1918-1921.

Long SP, Ainsworth EA, Rogers A, Ort DR (2004) Rising atmospheric carbon dioxide: Plants face the future. *Annual Review of Plant Biology* 55:591-628.

Luo Y, Su B, Currie WS, Dukes JS, Finzi A, Hartwig U, Hungate B, McMurtrie RE, Oren R, Parton WJ, Pataki DE, Shaw MR, Zak DR, Field CB (2004) Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. *BioScience* 54:731-739.

Mack MC, Schuur EAG, Bret-Harte MS, Shaver GR, Chapin FS (2004) Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. *Nature* 431:440-443.

McCarthy HR, Oren R, Finzi AC, Johnsen KH (2006a) Canopy leaf area constrains $CO_2$-induced enhancement of productivity and partitioning among aboveground carbon pools. *Proceedings of the National Academy of Sciences of the United States of America* 103:19356-19361.

McCarthy HR, Oren R, Johnsen KH, Pritchard SG, Davis MA, Maier C, Kim H-S (2006b) Ice storms and management practices interact to affect current carbon sequestration in forests with potential mitigation under future $CO_2$ atmosphere. *Journal of Geophysical Research-Atmospheres* 111:D15103, doi:10.1029/2005JD006428.

McDowell NG, Pockman W, Allen C, Breshears D, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams D, Yepez E (2008) Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb? *New Phytologist* 178: (in press; doi: 10.1111/j.1469-8137.2008.02436)

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007) Global climate projections. Pages 747-845 in Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Megonigal JP, Whalen SC, Tissue DT, Bovard BD, Albert DB, Allen AS (1999) Radiocarbon cycling from photosynthesis through methanogenesis in a wetland plant-soil-atmosphere microcosm. *Soil Science Society of America Journal* 63:665-671.

Melillo JM, Steudler PA, Aber JD, Newkirk K, Lux H, Bowles FP, Catricala C, Magill A, Ahrens T, Morrisseau1 S (2002) Soil warming and carbon-cycle feedbacks to the climate system. *Science* 298:2173-2176.

Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR (2002) Responses of coastal wetlands to rising sea level. *Ecology* 83:2869-2877.

National Research Council of the National Academies (NRC) (2007) *Understanding Multiple Environmental Stresses: Report of a Workshop*. Committee on Earth-Atmosphere Interactions: Understanding and Responding to Multiple Environmental Stresses, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, The National Academies Press, Washington, D.C., 142 p.

Norby RJ, DeLucia EH, Gielen B, Calfapietra C, Giardina CP, King JS, Ledford J, McCarthy HR, Moore DJP, Ceulemans R, De Angelis P, Finzi AC, Karnosky DF, Kubiske ME, Lukac M, Pregitzer KS, Scarascia-Mugnozza GE, Schlesinger WH, Oren R (2005) Forest response to elevated $CO_2$ is conserved across a broad range of productivity. Proceedings of the National Academy of Sciences of the United States of America 102:18052-18056.

Oren R, Ellsworth DE, Johnsen KH, Phillips N, Ewers BE, Maier C, Schäfer KVR, McCarthy H, Hendrey G, McNulty SG, Katul GG (2001) Soil fertility limits carbon sequestration by forest ecosystems in a $CO_2$-enriched atmosphere. *Nature* 411:469-472.

Osmond B (2002) *Earth Systems Questions in Experimental Climate Change Science: Pressing Questions and Necessary Facilities.* DOE-Columbia University Earth Institute workshop held at Biosphere 2 Center, 14-18 December 2001, a white paper report (unpublished).

Ottman MJ, Kimball BA, Pinter PJ, Wall GW, Vanderlip RL, Leavitt SW, LaMorte RL, Matthias AD, Brooks TJ (2001) Elevated $CO_2$ increases sorghum biomass under drought conditions. *New Phytologist* 150:261-273.

Palmroth S, Oren R, McCarthy HR, Johnsen KH, Finzi AC, Butnor JR, Ryan MG, Schlesinger WH (2006) Aboveground sink strength in forests controls the allocation of carbon belowground and its $CO_2$-induced enhancement. *Proceedings of the National Academy of Sciences of the United States of America* 103:19362-19367.

Parton WJ, Morgan JA, Wang GM, Del Grosso S (2007) Projected ecosystem impact of the Prairie Heating and $CO_2$ Enrichment experiment. *New Phytologist* 174:823-834.

Penuelas J, Gordon C, Llorens L, Nielsen T, Tietema A, Beier C, Bruna P, Emmett B, Estiarte M, Gorissen A (2004) Nonintrusive field experiments show different plant responses to warming and drought among sites, seasons, and species in a north-south European gradient. *Ecosystems* 7:598-612.

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pepin L, Ritz C, Saltzman E, Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399:429-436.

Rahmstorf S (2006) A semi-empirical approach to projecting future sea-level rise. *Science* 315:368-370.

Rastetter EB, McKane RB, Shaver GR, Melillo JM (1992) Changes in C storage by terrestrial ecosystems: how C:N interactions restrict responses to $CO_2$ and temperature. *Water Air, and Soil Pollution* 64:327-344.

Raupach MR, Marland G, Ciais P, Le Quere C, Canadell JG, Klepper G, Field CB (2007) Global and regional drivers of accelerating $CO_2$ emissions. Proceedings of the National Academy of Sciences of the United States of America 104:10288-10293.

Rustad LE (2008) The responses of terrestrial ecosystems to global climate change: towards an integrated approach. *Science of the Total Environment* 404:222-235.

Rustad LE, Campbell JL, Marion GM, Norby RJ, Mitchell MJ, Hartley AE, Cornelissen JHC, Gurevitch J (2001) A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* 126:543-562.

Sabine CL, Feely RA, Gruber N, Key RM, Lee K, Bullister JL, Wanninkhof R, Wong CS, Wallace DWR, Tilbrook B, Millero FJ, Peng T-H, Kozyr A, Ono T, Rios AF (2004) The oceanic sink for anthropogenic $CO_2$. *Science* 305:367-371.

Schütz H, Schroder P, Rennenberg H (1991) Role of plants in regulating the methane flux to the atmosphere. Pages 29-64 in T. Sharkey, E. Holland, and H. Mooney, editors. *Trace Gas Emissions from Plants*. Academic, San Diego, CA.

Seager R, Ting M, Held I, Kushnir Y, Lu J, Vecchi G, Huang H-P, Harnik N, Leetmaa A, Lau N-C, Li C, Velez J, Naik N (2007) Model projections of an imminent transition to a more arid climate in Southwestern North America. *Science*, 316:1181-1184.

Shaver GR, Bret-Harte SM, Jones MH, Johnstone J, Gough L, Laundre J, Chapin FS (2001) Species composition interacts with fertilizer to control long-term change in tundra productivity. *Ecology* 82:3163-3181.

Smith RA, Alexander RB, Wolman MG (1987) Water-quality trends in the Nation's rivers. *Science* 235:1607-1615.

Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA, Wratt D (2007) Technical Summary In Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, eds. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA.

Spahni R, Chappellaz J, Stocker TF, Loulergue L, Hausammann G, Kawamura K, Fluckiger J, Schwander J, Raynaud D, Masson-Delmotte V, Jouzel J (2005) Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* 310:1317-1321.

Thornley JHM, Cannell MGR (2001) Soil carbon storage response to temperature: an hypothesis. *Annals of Botany* 87:591-598.

Thornton PE, Lamarque J-F, Rosenbloom NA, Mahowald NM (2007) Influence of carbon-nitrogen cycle coupling on land model response to $CO_2$ fertilization and climate variability. *Global Biogeochemical Cycles* 21:GB4018, doi:10.1029/2006GB002868.

Updegraff K, Bridgham SD, Pastor J, Weishampel P, Harth C (2001) Response of $CO_2$ and CH4 emissions in peatlands to warming and water-table manipulation. *Ecological Applications* 11:311-326.

Vann CD, Megonigal JP (2003) Elevated $CO_2$ and water depth regulation of methane emissions: comparison of woody and non-woody wetland plant species. *Biogeochemistry* 63:117-134.

Wall GW, Brooks TJ, Adam R, Cousins AB, Kimball BA, Pinter PJ, LaMorte RL, Triggs L, Ottman MJ, Leavitt SW, Matthias AD, Williams DG, Webber AN (2001) Elevated atmospheric $CO_2$ improved Sorghum plant water status by ameliorating the adverse effects of drought. *New Phytologist* 152:231-248.

Walter KM, Zimov SA, Chanton JP, Verbyla D, Chapin FS (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* 443:71-75.

Wang JS, Logan JA, McElroy MB, Duncan BN, Megretskaia IA, Yantosca RM (2004) A 3-D model analysis of the slowdown and interannual variability in the methane growth rate from 1988 to 1997. *Global Biogeochemical Cycles* 18:GB3011, doi:101029/102003GB002180.

Whiting GJ, Chanton JP (1993) Primary production control of methane emissions from wetlands. *Nature* 364:794-795.

Wohlfahrt G, Hammerle A, Haslwanter A, Bahn M, Tappeiner U, Cernusca A (2008) Seasonal and inter-annual variability of the net ecosystem $CO_2$ exchange of a temperate mountain grassland: Effects of weather and management. Journal of Geophysical Research – Atmospheres 113(D8) D08110.

Zhuang Q, Melillo JM, Kicklighter DW, Prin RG, McGuire AD, Steudler PA, Felzer BS, Hu S (2004) Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model. *Global Biogeochemical Cycles* 18:GB3010, doi:3010.1029/2004GB002239.

## APPENDIX A: WORKSHOP AGENDA

Monday, 14 April 2008

1900 to 2100 Steering Committee Meeting with Speakers, Discussion leaders, and Rapporteurs

Tuesday, 15 April 2008

0730 to 0830 Welcome Session and Introductions

0830 to 0835 Official Welcome,
Dr. Anna Palmisano, Associate Director of Science for Biological and Environmental Research, Office of Science, US Department of Energy

0835 to 0855 Presentation of the Workshop Charge
Dr. Jerry Elwood, Director, Climate Change Research Division, Office of Biological and Environmental Research, Office of Science, US Department of Energy

0855 to 0915 Workshop Details, Science Questions and Survey Results (Paul Hanson)

0915 to 1200 Context Presentations (Paul Hanson presiding)
Key Scientific and Impact Results from the IPCC's Fourth Assessment —And What Has Emerged Since; Michael MacCracken

Can Models Inform Experimental Design?; Todd Ringler,

Science needs: Next-generation climate change/elevated-$CO_2$ experiments western/dryland ecosystems; Christopher Field

Single-factor and Multifactor Experiments: Multiple Issues, Multiple Approaches; Richard J. Norby

Warming of Open-Field Plots with Infrared Heater Arrays; Bruce Kimball

~1200 to 1400 Lunch break

1400 to 1415 Breakout Group Charge (Jeffrey Dukes presiding)

1415 to 1800 Breakout Groups (L = leader; R = rapporteur)
A. Terrestrial ecosystem feedbacks affecting climate and atmosphere (L: Peter Thornton; R: Alistair Rogers)
B. Ecosystem Response: Long-term (L: Robert Jackson R: Lara Kueppers)
C. Ecosystem Response: Thresholds and Nonlinearities (L: Alan Knapp R: Aimee Classen)
D. Managed Ecosystem Responses as a Special Case (L: Reinhart Ceulemans R: Yiqi Luo)

Wednesday, 16 April 2008

0830 to 0930 Breakout-Group reports in plenary session (James Morris presiding)

0930 to 1015 Contextual presentation continued from Day 1
Elevated-$CO_2$-Exposure Technologies: Current Options, Future Possibilities; Keith Lewin

1015 to 1200 Brief Reports on Related Discussions and Research Methods (James Morris presiding)

- European Science Foundation FACE workshop Summary; Reinhart Ceulemans
- Smithsonian elevated-$CO_2$ working group summary; Jack Morgan
- NEON climate change experiments; Alan Knapp
- A Facility for Carbon Enrichment and Sequestration Research; John Aber
- Air-Capture of Carbon Dioxide; Allen B. Wright
- Designing forest warming experiments etc. ; Rob Jackson

1200 to 1400 Lunch break

1400 to 1730 Breakout group -- targeted writing activities

Thursday, 17 April 2008

0800 to 1100 Breakout-Group sessions
Reading, group discussion give-and-take, PowerPoint summary generation and revision.

1100 to ~1300 Lunch break

~1300 to 1500 Final Plenary Reports from the Breakout Groups
Group A: Peter Thornton
Group B: Lara Kueppers
Group C: Michael Goulden
Group D: Yiqi Luo

1900 to 2100 PM: Working Dinner for Post-Meeting Discussions among the Steering Committee/ Discussion Leaders/ and Rapporteurs

Friday, 18 April 2008

0800 to 1200 Morning session for the Steering Committee and Discussion Leaders to finalize the strategy and plans for the workshop report.

# APPENDIX B
# ALPHABETICAL LISTING OF WORKSHOP PARTICIPANTS

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# APPENDIX C

# KEY SCIENTIFIC AND IMPACT RESULTS FROM THE IPCC'S FOURTH ASSESSMENT — AND WHAT HAS EMERGED SINCE

Michael MacCracken
Chief Scientist for Climate Change Programs
Climate Institute, Washington DC

The Intergovernmental Panel on Climate Change (IPCC) completed its Fourth Assessment Report (AR4) in 2007. Overall, the results from IPCC's Working Group I (WG I) on climate change science indicated that there was increasing confidence in the findings. Among the key findings from the WG I Summary for Policymakers (quoting, sometimes with minor deletions and reordering of points) are the following:

- Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed preindustrial values determined from ice cores spanning many thousands of years. The global increases in carbon dioxide concentration are caused primarily by fossil fuel use and land-use change (Houghton and Goodale 2004), while those of methane and nitrous oxide are primarily caused by agriculture.
- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Most of the observed increase in global average temperatures since the mid-20th century is very likely caused by the observed increase in anthropogenic greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns.
- For the next two decades, a warming of about 0.2 °C per decade is projected for a range of SRES [Special Report on Emissions Scenarios] emission scenarios. For 2100, the best estimate for the low scenario (B1) is 1.8 °C (likely range is 1.1 °C to 2.9 °C), and the best estimate for the high scenario (A1FI) is 4.0 °C (likely range is 2.4 °C to 6.4 °C). Extratropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns, continuing the broad pattern of observed trends over the last half century.
- It is very likely that hot extremes, heat waves and heavy precipitation events will continue to become more frequent. Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures.
- Anthropogenic warming and sea level rise would continue for centuries because of the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized. [For 2090 to 2099, and omitting the contribution from future rapid dynamical changes in ice flow that could add 0.1 to 0.2 m, the estimated range for the B1 scenario is 0.18 to 0.38 m, and the estimated range for the A1FI scenario is 0.26 to 0.59 m.] The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago during the

Eemian interglacial), reductions in polar ice volume led to 4 to 6 m of sea level rise.

- Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1 °C per decade would be expected.

Since the publication of the papers on which the IPCC WG I assessment was based (roughly mid-2006), the observed changes tend to indicate that the situation is significantly worse than the IPCC concluded. Specifically, with respect to each of the indicated points:

1. The atmospheric $CO_2$ concentration is climbing more rapidly than projected, which is a result of the rapidly increasing emissions in China and India from new coal-fired electric plants and only limited actions by others to constrain their emissions, or even the rate of growth of their emissions. Despite initial steps being taken under the Kyoto Protocol, the world appears to be on a path that is, at present, above the highest SRES emissions scenario (A1FI).
2. Global average temperature has continued to be very warm, although not consistently setting new records for global warmth. Other indications of warming are, however, showing accelerating change, including the melting back of Arctic sea ice (which is much more rapid than models have projected and is significantly delaying onset of very cold conditions), retreat of mountain glaciers, and increased loss of ice from the Greenland and Antarctic ice sheets.
3. The increasing emissions of $SO_2$ from China and India may well result in a negative contribution to forcing as a result of increasing sulfate concentrations, especially if efforts are made to limit local air pollution by increasingly going to tall stacks and filters for ash and soot. Just as apparently happened during the mid-20th century when tall stacks were introduced in the United States and Europe, increasing sulfate lifetimes and loadings have the potential to slow the pace of warming over a few-decade period. However, the counterbalancing effects of sulfates will rapidly be overcome toward the mid- to latter parts of the century.
4. Extreme conditions continue to occur, mostly of the type projected to occur from global warming. An interesting blog about such events is now maintained by Stu Ostro, senior meteorologist for The Weather Channel (see http://climate.weather.com/blog/9_15153.html).

5A. Whereas the IPCC AR4 projects that the net effect of changes in the Greenland and West Antarctic ice sheets will be near zero through the 21st century, the most recent results from NASA's GRACE satellites show both continents are currently losing mass, and there is little prospect for the pace doing anything but accelerating. The primary mechanism is just the dynamic movement term that IPCC's estimates do not explicitly treat and that were likely the cause of the rapid loss during the Eemian interglacial. In that the average rate of loss from the peak of the last glacial until sea level stabilized was about a meter per century, it would seem quite plausible that the rapid warming that is projected could lead to even higher rates, especially in that most of the Greenland ice sheet is, as it turns out, grounded below sea level and there are fjords that penetrate to the interior.

5B. Analysis of ocean temperature records has clarified that the apparent natural variability in the heat content record is primarily caused by the changing mix of observations using different methods. With the present rate now nearing 4 mm/yr, up from about 3 mm/yr from 1993-2003 and about 1.8 mm/yr over the 20th century, there is strong evidence emerging that the rate of global sea level rise is accelerating. The observed rate of sea level rise is now exceeding the upper bound rate of rise projected for this period in IPCC's Third Assessment Report.

6A. IPCC's projection of warming in the case of stabilization of atmospheric composition made the very misleading assumption that the aerosol loading would stay the same as well as the concentrations of greenhouse gases. To stabilize greenhouse gas concentrations would require very sharp cutbacks in their emissions (averaging perhaps 80%), which would surely lead to sharply reduced $SO_2$ emissions and sulfate loading, canceling out the counterbalancing cooling influence. As a result, stabilization would likely lead to continued warming at a rate perhaps double the rate suggested in AR4, so it does seem that, at least for several decades, reducing emissions is unlikely to slow the pace of global warming.

6B. It is recognition of this that is spurring increased attention to both very strong mitigation measures and even to consideration of the potential for geoengineering to limit realized warming for at least the several decades it would take to get greenhouse gas concentrations coming back down from their projected peaks. Increasingly, it is being recognized that the notion of going up to some concentration and stabilizing, which is the objective of the UN Framework Convention on Climate Change, needs to be changed because we may well have already passed the stabilization level that would preserve the Greenland and Antarctic ice sheets. Clearly, the impacts of both sheets melting over even many centuries would be catastrophic.

In contrast to the WG I results, IPCC's Working Group II on impacts and adaptation made clear, although often in the muted language of scientists talking among themselves, that the impacts of climate change were occurring more rapidly and intensely than had been indicated in their preceding assessments. In addition, very serious concern was expressed over the effects on ocean chemistry of the rising $CO_2$ concentration itself. For the North America, the key findings on future changes, all with high confidence and none since disputed, were:

1. Warming in western mountains is projected to cause decreased snowpack, more winter flooding, and reduced summer flows, exacerbating competition for over-allocated water resources.
2. Disturbances from pests, diseases and fire are projected to have increasing impacts on forests, with an extended period of high fire risk and large increases in area burned.
3. Moderate climate change in the early decades of the century is projected to increase aggregate yields of rain-fed agriculture by 5 to 20% but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or that depend on highly utilized water resources.
4. Cities that currently experience heat waves are expected to be further challenged by an increased number, intensity and duration of heat waves during the course of the century, with potential for adverse health impacts. Elderly populations are most at risk.
5. Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Population growth and the

rising value of infrastructure in coastal areas increase vulnerability to climate variability and future climate change, with losses projected to increase if the intensity of tropical storms increases. Current adaptation is uneven, and readiness for increased exposure is low

# APPENDIX D
# CAN MODELS INFORM EXPERIMENTAL DESIGN?

Todd Ringler,
Theoretical Division, Los Alamos National Laboratory

Climate system models are the primary tool used to quantify the evolving form of anthropogenic climate change. While these models are clearly deficient in many respects, climate system models have proven to be exceptionally powerful in aiding the interpretation of observations and theories. But what value, if any, do these models add to the design of experiments meant to quantify the relationship between atmospheric $CO_2$ concentration and ecological change? The pathways between $CO_2$ concentration and possible ecological change are complex and not necessarily linear. In their simplest form, these pathways might look like the following:

*$CO_2$ concentration→ ecological response*
*$CO_2$ concentration→changes in temperature→ecological response*
*$CO_2$ concentration→changes in precipitation→ecological response*
*$CO_2$ concentration→changes in extreme events→ecological response*

This document will provide a brief overview of what climate system models have to say about these four precursors to ecological change: $CO_2$ concentration, changes in temperature, changes in precipitation, and changes in extreme events. The geographic region of focus will be North America, with a particular emphasis on the contiguous United States. Finally, except where specifically referenced, all finding are taken from the IPCC 4th Assessment Report (4AR).

Table D1. $CO_2$ concentration (ppmv) for various scenarios as a function of time.

| IPCC Scenario | $CO_2$ 2025 | $CO_2$ 2050 | $CO_2$ 2075 | $CO_2$ 2100 |
|---|---|---|---|---|
| B1 | 424 | 488 | 531 | 549 |
| A1B | 437 | 532 | 630 | 717 |
| A2 | 434 | 532 | 668 | 810 |
| A1FI | 436 | 567 | 758 | 970 |

Changes in $CO_2$ Concentrations: The evolution of atmospheric $CO_2$ concentration is primarily dependent upon the global carbon cycle and the amount of fossil fuel energy production. The former is not included in climate system models used in AR4 and the latter is subject to such societal uncertainty that it is assumed to be external to the climate modeling framework. We accommodate the uncertainty in future emission profiles by assuming various $CO_2$ concentration curves in our simulations (see Table D1) that are intended to elucidate the relationship between $CO_2$ and climate change. Fig. D1 shows the global temperature response for multiple models (different lines) as a function of scenario (B1, A1B, and A2) and as a function of time (2020–2029 and 2090–2099). The spread in the late 21st century response is determined primarily by the scenario. *So while climate system models add no value in determining the target $CO_2$ concentration for ecological change experiments, the results make* *it clear that the choice of $CO_2$ scenario is much more important than the choice of climate model when quantifying the basic characteristics of anthropogenic climate change.* During the last several years, actual emissions have exceeded even the most fossil-fuel-intensive scenario (A1FI), so the use of these scenarios to "bracket" uncertainty is questionable (Raupach 2007).

Changes in Temperature: The primary pathway through which $CO_2$ alters the climate system is through modification of long-wave radiation leading, subsequently, to changes in\ temperature. The models are in strong agreement that warming will be most pronounced over land. A rough guide is to multiply the values in Fig. E1 by 1.5 to obtain estimates of warming over land. *Thus, the expected increase in mean land temperature at year 2100 ranges between 1.5 °C and 6.0 °C for the contiguous United States relative to the 1980–1999 reference period.* A warming of 8 to10 °C by year 2100 for latitudes above 60 °N can not be ruled out. Rough estimates of warming in the 2020–2029 time frame can be obtained by dividing the year 2100 values by 4. In the context of ecological change, it is critical to note that this anticipated warming will be accompanied by a commensurate increase in specific humidity, leading to little, if any, change in relative humidity from present-day climate. (Held and Soden,2000).

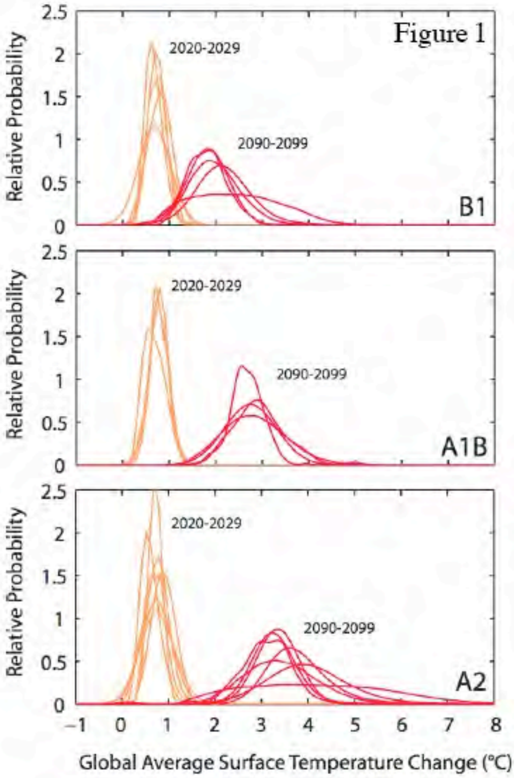

Figure E1. Extracted from Figure TS.28 Solomon et al. (2007): Projected surface temperature changes for the early and late 21st century relative to the period 1980 to 1999. Panels show the AOGCM multimodel average projections (°C) for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over the decades 2020 to 2029 (centre) and 2090 to 2099 (right). Each panel shows corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and EMIC studies for the same periods.

Changes In Precipitation: Changes in patterns of large-scale precipitation are driven primarily by changes in the general circulation as the atmosphere adjusts to a substantially weaker equator-to-pole temperature difference. The tendency of warming to increase precipitation gradients is a robust model result that is gaining theoretical support (Lu et al. 2007). *Thus, as $CO_2$ concentrations rise, relatively wet areas tend to get wetter, and relatively* *dry areas tend to get drier.* The line separating the "wetter regions" from the "drier regions" runs roughly east-west from Southern California across the United States. This intensification of precipitation patterns is accompanied by a poleward expansion of subtropical highs leading to a marked decrease of precipitation in regions that presently reside on the poleward edge of subtropical highs. Models suggest that semi-arid and arid regions, such as the Southwest United States, should expect decreases in annual mean precipitation of up to 25% under the A1B scenario (Seager 2007). In contrast, regions that remain poleward of the east-west dividing line as it extends further north should expect increases in annual mean precipitation of about 15%. In terms of Western U.S. snowpack, it appears that the warming overwhelms the increase in precipitation leading to significantly reduced springtime snowpack and a shift toward earlier streamflow peaks. Climate system models tend to better represent wintertime, baroclinic-eddy driven precipitation than summertime, mesoscale precipitation. In particular, monsoonal flows, such as the North American Monsoon, still pose a significant challenge to the climate models. Statements regarding model predicted changes in summertime precipitation patterns are not as strong as statements regarding changes in wintertime precipitation.

Changes in Extreme Events: Since many ecological systems are strongly controlled by extreme events, a robust, comprehensive description of greenhouse gas driven changes of extreme events will be required to appropriately characterize many ecological responses. Accurate representation of heat waves, extreme precipitation events, and even episodic drought still challenges climate system models because of the models' relatively coarse resolution. In order to characterize the influence of greenhouse gases on extreme events, high-resolution regional climate models are utilized. While this modeling approach is relatively young compared to its global modeling counterpart, initial model results suggest increases in both extreme warm temperature and extreme precipitation events throughout the contiguous United States with increasing $CO_2$ concentration. Increases in heat wave activity (>95th percentile of present-day temperature PDF) are widespread by year 2100 (A2), with the most pronounced increases in the interior Western United States where the T95 threshold is exceeded between 50-100 days per year (Diffenbaugh 2005). Increases in extreme precipitation events were also found to be widespread, even in regions where mean precipitation was decreasing. Analysis of 20th century station data provide support to these findings (DeGaetano 2002, Kunkel 2004).

## Summary

An analysis of climate system model results for the contiguous United States allow us to draw the following conclusions:

1. The choice of a specific $CO_2$ emissions scenario is much more important than the choice of a specific climate system model in assessing changes to temperature, precipitation, and extreme events.
2. When we try to account for both scenario uncertainty and inter-model variability, anticipated ranges of temperature increase for the contiguous United States are 1.5 °C to 6.0 °C in year 2100 relative to the 1980-1999 reference period.
3. The changes in precipitation are expected to be less uniform than the changes in temperature for the contiguous United States, with increases in annual mean precipitation of up to 15% toward the north and deceases of up to 25% toward the south.

4. While the characterization of greenhouse gas driven changes in extreme events by climate system models is still not certain, the tendency for more heat waves and for a greater fraction of precipitation to occur in high amplitude events has been found.

So can models inform experimental design? Yes. Given an emissions scenario, the models largely agree on basic characteristics of change. Incorporating this knowledge into the design of ecological change experiments should certainly add value. ***Given the importance of identifying ecological thresholds and abrupt events that may, in aggregate, have global impacts sufficient to alter the above findings, a full description of the ecological response to the "high-end" estimates appears to be an appropriate path forward.*** New experimental data have the potential to dramatically improve the land surface process models (such as eco-hydrology and vegetation mortality/succession) used in our climate model simulations. Designing ecological change experiments such that the results are applicable to a modeling framework would provide a great service to the modeling community.

### References

DeGaetano AT, Allen RJ (2002) Trends in 20th century temperature extremes across the United States. *Journal of Climate* 15:3188-3205.

Diffenbaugh NS, Pal JS, Trapp RJ, and Giorgi F (2005) Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences, U.S.* 102:15774-15778.

Held IM, Soden BJ (2000) Water vapor feedback and global warming. *Annual Review of Energy and the Environment* 25:441-475.

Kunkel KE, Easterling DR, Hubbard K, Redmond K (2004) Temporal variations in frost-free season in the United States: 1895-2000. *Geophysical Research Letters* 31:L03201.

Lu J, Vecchi GA, Thomas Reichler T (2007) Expansion of the Hadley cell under global warming. *Geophysical Research Letters* 34:L06805.

Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG, Klepper G, Field CB (2007) Global and regional drivers of accelerating $CO_2$ emissions. *Proceedings of the National Academy of Sciences, U.S.* 104:10288-10293.

Seager R, Ting M, Held I, Kushnir Y, Lu J, Vecchi G, Huang H-P, Harnik N, Leetmaa A, Lau N-L, Li C, Velez J, Naik N (2007) Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science* 316:1181-1184.

Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA, Wratt D (2007) Technical Summary In Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, eds. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA.

## Back Cover:

Priority ecosystems from the top and left (designed by David Cottrell)

- Boreal black-spruce forest in Manitoba (Photo credit – Paul J. Hanson)
- High-altitude eastern spruce-fir forests (Photo credit – Paul J. Hanson, ORNL photo 10311-88)
- Midlatitude temperate forests (Photo credit – Paul J. Hanson, ORNL photo 11821-91)
- Wet tropical forest in Brazil (Photo credit – FLUXNET photo gallery)
- Switchgrass biomass plantation in Tennessee (Photo credit – Charles T. Garten Jr.)
- Arid or dryland ecosystems (public domain photograph)
- Coastal salt marsh at North Inlet, South Carolina (Photo credit – Paul J. Hanson)

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