Quantifying Ecosystem Feedbacks to Climate Change: Observational Needs and Priorities

A report to the
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A contribution to the Strategic Plan for the U.S. Climate Change Science Program milestone:

"Definition of the initial requirements for ecosystem observations to quantify feedbacks to climate and atmospheric composition, to enhance existing observing systems, and to guide development of new observing capabilities."

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SUMMARY

Two-way interactions between climate and ecosystems that amplify or dampen the climate's initial response to elevated greenhouse gas concentrations are known as feedbacks. Ecosystem responses to climatic change may alter biogeochemical processes or biophysical properties, which in turn may alter the ways in which ecosystems influence climate. Although climate-ecosystem feedbacks may be large, it is unknown if they are currently underway or how strong they will be in the future. Observations of processes constituting potential feedbacks are needed both to assess the strength of feedbacks that may be acting today, and to build a predictive understanding for projecting future climate changes. Addressing gaps in current understanding will require a multi-level effort that combines long-term, extensive climate and ecosystem observation with intensive region and ecosystem-specific manipulations targeting ecosystems that cover large areas, that have large leverage on climate, that occur in areas expecting significant climate change, and/or that are sensitive to climatic and CO_2 concentration changes. Critical pathways for ecosystem feedbacks to climate change may vary by ecosystem or region, but in all cases, feedback studies should strive to "close the loop." That is, feedback studies should quantify both likely ecosystem responses to climate change, and net climatic forcings from ecological changes.

A workshop[1] at the 2005 American Geophysical Union Fall Meeting generated community input on observational needs regarding climate-ecosystem feedbacks. Based on this workshop and literature review, specific recommendations for targeted new research are listed in Section 4 of this report.

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1. THE BASICS: WHAT ARE CLIMATE-ECOSYSTEM FEEDBACKS?

The Climate as a Complex System

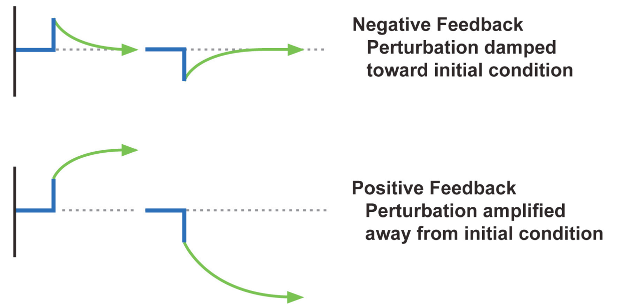

Figure 1. Positive versus negative feedbacks.

Climate is in part determined by a complex web of physical, chemical, and biological interactions— primarily exchanges of greenhouse gases, water and energy— among the atmosphere, oceans, and land. For example, in the 1980s and 1990s only about half of fossil fuel CO_2 emissions accumulated in the atmosphere. The oceans and terrestrial biosphere took up the other half. As a result, human perturbation of climate forcing has been less pronounced that it would have been without these exchanges. As another example, the land surface influences how much incoming solar radiation is reflected versus absorbed. As a result, changes in the surface area of snow and ice cover, or plant distributions, can make globally important changes to earth's energy balance. Further, the fraction of absorbed energy that is released as latent heat (i.e., evaporation), rather than raising surface air temperatures, is dependent on plant transpiration rates. Thus, the oceans, cryosphere, and terrestrial biosphere play active roles in the climate system.

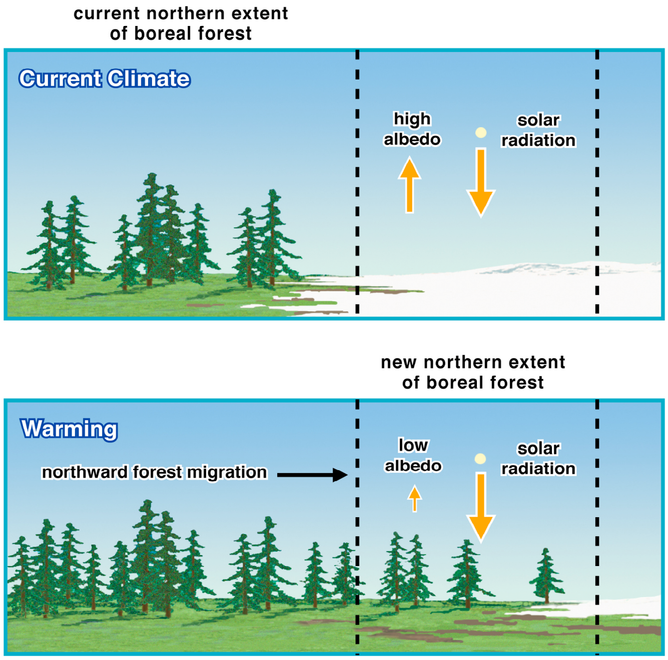

Figure 2. Northward advance of forest vegetation with climate warming reduces land surface albedo, promoting additional warming (a positive climate-ecosystem feedback). Modified from Foley et al. (2003).

Climate-Ecosystem Feedbacks Defined

Two-way interactions between climate and ecosystems that amplify or dampen the climate's initial response to elevated greenhouse gas concentrations (or other external climatic forcings) are known as feedbacks. Interactions that amplify initial perturbations are called *positive* feedbacks, and interactions that dampen them are *negative* feedbacks (Figure 1). An example of a positive feedback is that a warmer climate may favor northward expansion of boreal forest into current tundra (Figure 2). Because boreal forests have a lower albedo (i.e., reflectivity) than the tundra they would replace, the additional energy absorption would lead to higher temperatures, amplifying the initial warming (Levis et al. 1999, Chapin et al. 2005). An example of a negative feedback is that a warmer climate may stimulate photosynthesis and net carbon storage in temperate forests, causing the amount of CO_2 in the atmosphere to decline and thus reversing or reducing the warming.

> ***"Two-way interactions between climate and ecosystems that amplify or dampen the climate's initial response to elevated greenhouse gas concentrations are known as feedbacks."***

Biophysical and Biogeochemical Feedbacks

Ecosystems affect climate, and thus can generate feedbacks through *biophysical* and *biogeochemical* pathways (Figure 3). Biophysical pathways involve ecosystem changes that alter energy and water exchange with the atmosphere, directly altering temperature, humidity, precipitation, convection, and wind. Biophysical feedbacks result when climate causes changes in the albedo of vegetation and soil, evapotranspiration rate, and vegetation structure and phenology. Biogeochemical pathways involve changes in carbon and nutrient cycling that affect sources and sinks of greenhouse gases and aerosols. Biogeochemical feedbacks result when climate causes changes to ecosystem uptake and release of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), volatile organic compounds and other ozone precursors, black carbon, and aerosols or aerosol precursors such as dust and marine-produced dimethylsulfide.

Ecosystem responses to climate change, such as altered species composition, productivity, leaf area, vegetation phenology, canopy roughness, rooting depth, and soil water holding capacity, may result in biophysical and/or biogeochemical feedbacks. Some effects of climate change, such as increased fire frequency, may result in both biophysical (altered albedo, reduced evapotranspiration) and biogeochemical (release of CO_2, CH_4, and black carbon) feedbacks. The net feedback resulting from climate-driven changes in fire frequency is not well quantified. Recent research in boreal and tropical forests indicates that biophysical and biogeochemical ecosystem responses can counteract one another (Nepstad et al. 2002, Nepstad et al. 2006, Randerson et al. 2006). In addition, changes in biophysical properties of an ecosystem may lead to changes in biogeochemical processes and vice versa. Therefore, it is critical to evaluate the full suite of responses, on a common timescale, to determine not just the magnitude, but the sign of the net feedback, since the net feedback integrates multiple feedback loops.

Ecological Responses vs. Ecosystem *Feedbacks*

An important distinction should be made between ecological responses to climate change and ecosystem feedbacks, particularly in the context of promoting new research. Ecological responses are the ways that ecosystems change as a result of climatic and atmospheric change, whether or not they result in a change in the way the ecosystem influences climate. For example, climate change may induce responses in species diversity, plant and animal species ranges, nitrogen cycling rates, trophic structures, and trace gas production. Ecosystem feedbacks are created by the subset of ecological responses to climate change that in turn affect the climate. For example, a shift in a species' range affects climate if it results in a change in the albedo of the affected region. In other words, the feedback is generated by both the effect of climate on species range and the effect of species range on climate.

Comprehensive studies of ecosystem feedbacks must quantify the:

(1) climate changes affecting the ecosystem of interest;
(2) ecosystem responses to climate changes;
(3) change in biophysical or biogeochemical properties resulting from ecosystem responses;
(4) net change in climate forcing resulting from these biophysical and biogeochemical changes; and finally, bringing us back to climate,
~~(1)~~(5) regional and global climate consequences of the change in climate forcing (Figure 3).

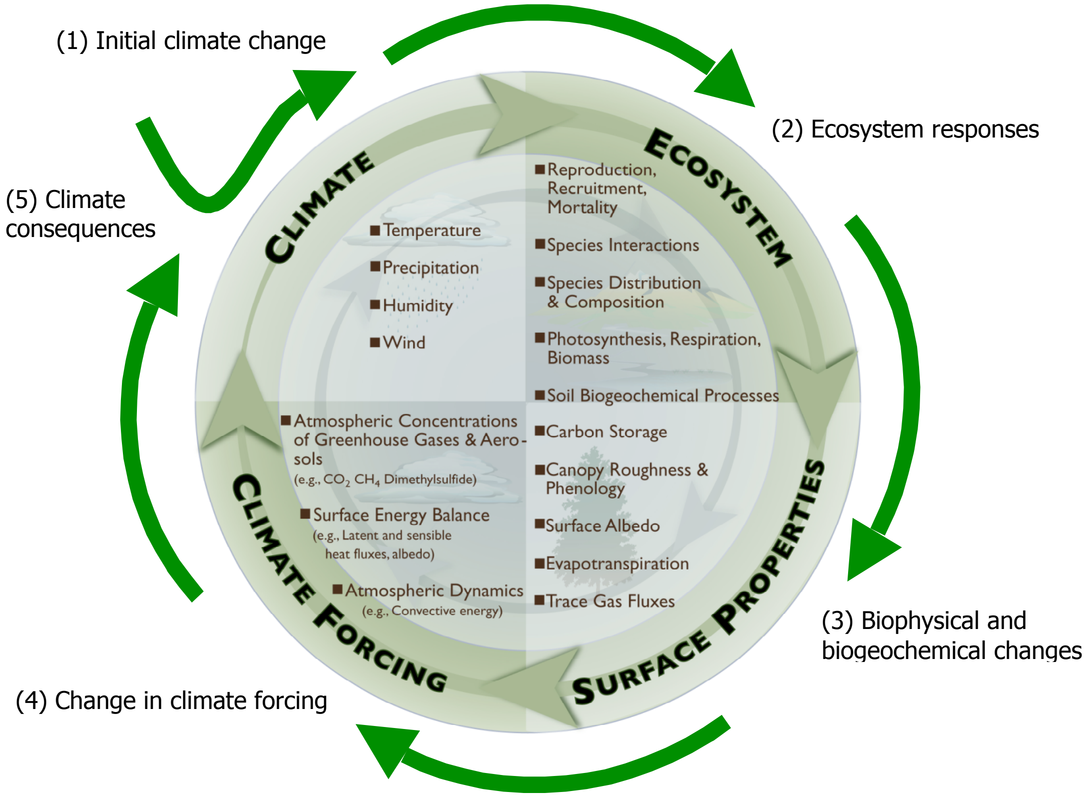

Figure 3. Elements required for quantifying and predicting climate-ecosystem feedbacks. Numbers refer to steps in text.

As ecosystems respond to ongoing climate changes (i.e., with multiple passes around a feedback loop), effects may saturate or reach thresholds such that an initial (i.e., short-term) response to initial climate changes may differ from long-term responses.

No observational studies to date have quantified all elements of a climate-ecosystem feedback system for any particular region, ecosystem, or time period.

2. WHY ARE CLIMATE-ECOSYSTEM FEEDBACKS IMPORTANT?

Feedback Contribution to Global Climate Change

Feedbacks are important to the climate system. In fact, most of the warming projected by coupled atmosphere-ocean general circulation models (AOGCMs; our primary tool for projecting future climate change) under anthropogenically increasing greenhouse gas concentrations is not due to the direct effect of those greenhouse gas increases, but rather is due to feedbacks involving water vapor, clouds, and ice that amplify the initial response. Without these feedbacks, the radiative forcing from an equivalent doubling of atmospheric CO_2 concentrations would be expected to warm global climate by 1.2°C. When water vapor, cloud, and ice-albedo feedbacks are included, the predicted climate sensitivity to a CO_2 doubling rises to 2.0-4.5°C (IPCC 2007). This range of AOGCM estimates does not include biophysical (e.g., geographic ecosystem shifts or changes in plant phenology) or biogeochemical (e.g., carbon cycle) feedbacks. Although climate models to date have had very limited representation of ecosystem processes, ecosystem feedbacks can also be quite large.

Recent estimates from paleo-records of the strength of global feedbacks between temperature and CO_2, and temperature and CH_4, indicate that the above AOGCM estimates of anthropogenic climate change are too low, because they do not include positive carbon cycle feedbacks (Scheffer et al. 2006, Torn and Harte 2006). Torn and Harte report that a warming of 1.5-4.5°C could be amplified to 1.6-6.0°C if the greenhouse gas feedbacks that operated across multiple ice age cycles also occur in the future with anthropogenic climate change. These feedbacks involve not only geochemical processes, such as ocean carbonate dissolution, but also ecological processes.

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3. APPROACHES TO QUANTIFYING CLIMATE-ECOSYSTEM FEEDBACKS

Although climate-ecosystem feedbacks may be large, we do not know if they are currently underway or how strong they will be in the future. We need observations both to assess the strength of feedback processes that are acting today, and to build a predictive understanding for projecting future climate change.

Modeling Climate-Ecosystem Feedbacks

As stated above, AOGCMs still have relatively rudimentary representations of biophysical and biogeochemical interactions between ecosystems and climate. For example, few AOGCM experiments have allowed vegetation to migrate with changing climate and those that do assume perfect dispersal and migration (e.g., Cox et al. 2000, Levis et al. 2000), even though ecosystem feedback strength is highly sensitive to this assumption (Higgins and Harte 2006). Regardless, current models have limited ability to predict a realistic, non-equilibrium ecosystem response. Moreover, no AOGCM includes dynamic representation of trace gases other than CO_2; there is no CH_4 or N_2O production or consumption by ecosystems in state-of-the-art AOGCMs. Only a few model experiments have included a rough ecosystem carbon cycle (Cox et al. 2000, Friedlingstein et al. 2001, Thompson et al. 2004, Fung et al. 2005, Friedlingstein et al. 2006). In these coupled climate-carbon cycle experiments, all models project that climate-carbon cycle feedbacks are positive. Specifically, warming results in a decrease in the carbon sink, and consequently leads to higher CO_2 concentrations and 0.1–1.5 ºC more warming in 2100 than was predicted in simulations without active land and ocean biology (Figure 4; Friedlingstein et al. 2006). In the AOGCMs, factors controlling the modeled terrestrial climate-carbon feedback include if and how CO_2 fertilization of photosynthesis saturates (Thompson et al. 2004), the response of net primary production to climate changes (Friedlingstein et al. 2006), and the response of soil carbon storage to temperature and moisture changes (Jones et al. 2005).

> ***"In coupled climate-carbon cycle experiments, all models project that climate-carbon cycle feedbacks are positive."***

Even state-of-the-science AOGCMs with interactive vegetation shifts and ecosystem carbon cycles still do not fully integrate current understanding of climate-relevant ecosystem responses to climate variability and change. For example, AOGCMs have not (or have rarely) included nutrient limitation to plant growth, wildfire, prognostic phenology, or trace gas emissions by wetlands. There is much to be gained by improving existing models with existing ecological knowledge. However, there are also many areas where new empirical work is needed to improve basic understanding of potential feedbacks and where observations are needed to test models.

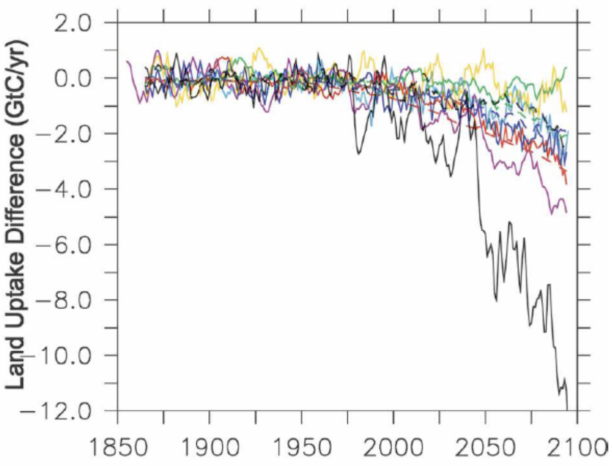

Figure 4. Difference in land carbon uptake with and without climate-carbon cycle feedbacks. Carbon uptake is consistently reduced when the climate is allowed to respond to changes in the carbon cycle, relative to the case with CO_2 increases and climate determined only by emissions and no climate-carbon cycle feedback, across multiple coupled climate-carbon cycle models (Figure 1d from Friedlingstein et al. 2006). The different colors represent the different models: HadCM3LC (solid black), IPSL-CM2C (solid red), IPSL-CM4-LOOP (solid yellow), CSM-1 (solid green), MPI (solid dark blue), LLNL (solid light blue), FRCGC (solid purple), UMD (dash black), UVic-2.7 (dash red), CLIMBER (dash green), and BERN-CC (dash blue).

Empirical Studies of Climate-Ecosystem Feedbacks

There are three categories of scientific unknowns with respect to climate-ecosystem feedbacks, all of which require new empirical work. First, are the processes that are *already included in models, but which are not well tested or quantitatively understood*. For example, geographic shifts in the ranges of biomes and plant functional types are currently modeled as though vegetation can track climate change on a year-by-year basis. This is almost certainly not the case, but we have little empirical basis for alternative schemes (Higgins and Harte 2006). Nor do we have AOGCM configurations that can adequately represent species level differences – the level at which ecologists would typically pursue these questions. Second, *are the processes that are not included in models, but for which we have a basic understanding*. For example, AOGCMs have begun to include an ecosystem carbon cycle, with plant growth increasing with atmospheric CO_2 concentration ("CO_2 fertilization"). From empirical work, we know that other resource limitations may constrain the magnitude and duration of the fertilization effect (Norby et al. 2005, van Groenigen et al. 2006); but these resource limitations are not yet included in AOGCMs. And third, *are the processes not included in models, and for which we have insufficient understanding*. For example, non-CO_2 greenhouse gases have been observed to vary roughly in tandem with CO_2 over glacial-interglacial cycles (Spahni et al. 2005). Ecosystem fluxes of CH_4, N_2O, VOCs and other gas species are likely sensitive to climate change, but the details of how, why, and where are big unknowns. Until robust relationships can be developed at an appropriate spatial scale, these potentially important pieces of the puzzle cannot be incorporated into AOGCMs. In the meantime, sensitivity analyses could indicate whether they are likely to be important and which pathways, gases, or regions deserve the most immediate and thorough study.

Diverse empirical approaches have been used to study ecosystem responses to climate variability and change (step 2 in Figure 3), and to some degree have been adopted to study how ecosystem responses alter biogeochemical and biophysical properties relevant to climate (step 3 in Figure 3). Relatively little empirical work has focused on quantifying the climate forcing resulting from changes in biophysical and biogeochemical properties of ecosystems (step 4 in Figure 3), or the climate changes resulting from a change in climate forcing by ecosystems (step 5 in Figure 3). There are also few published studies to date that explicitly consider the incongruities between experiments that follow ecosystem responses to step changes in climate on the one hand, and the ongoing, transient nature of real climate change on the other (Chapin et al. 1995, Harte et al. 2006). Similarly, there has been little study of the distinction between transient climate-ecosystem feedbacks important over years and decades, versus those that are important over centuries or longer.

SPECIES, FUNCTIONAL GROUPS AND FUNCTIONAL TYPES

Species have responded individually to past climate fluctuations (Davis and Shaw 2001), which also has had a range of effects on ecosystem function (Chapin et al. 2000). However, with millions of species in the world (and hundreds of thousands of plant species), there will never be enough information to comprehensively incorporate species into ecosystem models, let alone into dynamically coupled atmosphere-ocean general circulation models (AOGCMs). As result, species are often grouped according to a functional trait that is dominant for the question at hand. Plant functional type (PFT) has thus become the fundamental biological unit for ecosystem and carbon cycle modeling in global change research (Bonan et al. 2002). We conclude, however, that the response to and effect on climate are two such different plant functions that much more work is needed to create PFTs that capture both aspects (functions) of plants and ecosystems.

In the context of research on climate-ecosystem feedbacks, there are two important aspects of species (or categories of species): (1) their ecological response to climate change and (2) their role in climate forcing, either via effects on biophysical properties or on biogeochemical processes of the ecosystem. Ecologists have developed the conceptual distinction between 'functional response groups' and 'functional effects groups' (Hooper et al. 2005), which may not overlap. In contrast, the current generation of dynamic vegetation models utilized in AOGCMs does not reflect these distinctions. One exception is the differentiation of C_3 and C_4 grass functional types, which have similar climate effects in terms of albedo and carbon cycling, but respond quite differently to increased CO_2 concentrations and climate due to the different photosynthetic pathways they employ.

Although it may be necessary to aggregate species together to make observation, data analysis or modeling more tractable, there is not currently adequate information to assign species to groups. Pursuit of new species-level research is critical until we have a sufficient understanding of the most important response and effect categories for predicting ecosystem feedbacks to climate change. In addition, efforts to identify the suite of possible responses to climate change and better elucidation of the many dimensions of climate effects (both biophysical properties and biogeochemical) need to be initiated. The functional types currently used by dynamic vegetation models need to be refined, but without an empirical basis for a new framework, progress will be limited.

Ideal Observational Approaches

Figuring out how to make observations to quantify climate-ecosystem feedbacks is one of the major challenges in ecological research today. No perfect, or even sufficient, approach currently exists to capture both ecosystem responses to climate change and the influence of those responses on climate. The ideal observational approach would have these qualities: the scale of observations would be large enough to allow measurable changes in biophysical properties, to enable reasonable disturbance regime, and to capture important trophic processes, yet tractable enough to allow for manipulation of multiple global change factors. The approach would allow study of the key processes giving rise to species range shifts, such as pollination and seed dispersal, as well as observation of plants at all stages in their life cycle, from germinants to mature individuals of long-lived species. Finally, the ideal approach would last long enough to distinguish transient ecosystem responses from more persistent ones.

Below we briefly review the strengths and weaknesses of five empirical approaches and then recommend priorities for new research based on gaps in the research portfolio.

Observations of Climate and Ecosystem Variability

Long-term monitoring of climate and ecosystems has yielded important insights into how seasonal and interannual variability in climate affects ecosystem phenology and carbon exchange with the atmosphere (Myeni et al. 1997, Barford et al. 2001, Dunn et al. 2007). To be most fruitful, this approach requires long-term commitments by researchers and funding agencies, as well as some luck in capturing episodic or extreme climatic events (e.g. El Nino cycles or multi-year droughts). Changes in ecosystems that track multi-year trends in climate reveal transient, real-time ecosystem responses to climate (Harte et al. 2006). What they can reveal about long term responses to longer trends in these forcing factors is less clear, because transient responses can continue, reverse or otherwise change as they system develops towards long-term, more stable conditions (Dunne et al. 2004).

Strengths of Observations of Climate and Ecosystem Variability

Ecosystems are observed *in situ*, under natural conditions; Eddy flux methods allow high temporal resolution of observation, and site footprint is large relative to most experimental plots in ecology; Biophysical feedbacks fairly well captured by eddy flux methods or combinations of remote sensing and eddy flux; Satellite-based remote sensing of interannual variation in ecosystem phenology is spatially complete at regional and even global scales; Investigator-based observations of individual or stand level phenology can catch unexpected phenomena (e.g., importance of frost damage for plant reproductive success); Transient changes in carbon uptake, water flux, and phenology can be observed and differentiated from long-term trends

Weaknesses of Observations of Climate and Ecosystem Variability

Difficulty of using eddy flux in certain kinds of sites such as those with patchy land cover, complex topography, or very still air leads to biases in site selection with this technique; the large footprint of eddy flux measurements makes it difficult to combine with climate manipulation experiments; Long-term commitment of personnel and funds required for best results; Uncertain funding of Earth observing satellite missions jeopardizes value of existing remotely sensed datasets; Long-term “monitoring” accrues scientific value with time, making it difficult for program managers to evaluate and support on typical program funding cycle time frames; Long-term observations of biogeochemical feedbacks not common; Long-term changes not captured without decades of observation, making such studies historical and not predictive enough to help science and society anticipate and mitigate climate change.

Spatial Gradient Analysis

Analysis of spatial gradients in climate, for example elevational or latitudinal temperature gradients, provides information on how ecosystem properties vary with mean climate. For example, changes in leaf area, evapotranspiration rates, ecosystem carbon cycling, and rates of trace gas production often track spatial variation in climate (Gholz 1982, Trumbore et al. 1996, Schuur et al. 2001). Systematic quantification of these relationships began in the 19th century for soils and early in the 20th century for plants. As with observations of interannual variability, spatial associations between climate and ecosystem properties can establish correlations, but causality is harder to determine.

Strengths of Spatial Gradient Analysis

Ecosystems are observed *in situ*, under natural conditions; Inexpensive compared to artificially manipulating climate (cost of observations is the same); Multiple sites along a gradient provide quasi-continuous equations relating ecosystem properties to climate; Range of available sites defines range of climate conditions that can be considered; Defines long-term ecosystem states under relatively stable climate conditions; Large trees and older plants, as well as trophic interactions and disturbance regimes are included; Can directly investigate how a certain ecosystem configuration influences climate through its energy and gas exchanges.

Weaknesses of Spatial Gradient Analysis

Statistical relationships along spatial gradients may (e.g., for plant phenology) or may not (e.g., for soil carbon) directly predict ecosystem responses to rapid climate change (Saleska et al. 2002, Dunne et al. 2003, Dunne et al. 2004); Site selection is critical for minimizing confounding factors; Causation can not be definitively established; Does not address potential transient feedbacks to climate change; Does not account for relevant time scales of ecosystem responses to climate change (e.g., dispersal, propagation, soil formation).

Experimental Climate and CO_2 Manipulation

Experimental manipulations of CO_2 concentrations and climate variables are used to investigate ecosystem responses under relatively controlled conditions (Körner 2000, Shaver et al. 2000). Experiments that manipulate climate variables and CO_2 concentration vary considerably, both in applied treatments and in measured response variables. Net primary productivity is one relatively common response variable; with the addition of soil respiration measurements, the net effect of climate/CO_2 change on carbon cycling, and a climate forcing could be estimated. Additional measurements of albedo, leaf area index, rooting depth, and trace gas production would improve our understanding of how specific biophysical and biogeochemical properties respond to climate change.

Strengths of Experimental Climate and CO_2 Manipulation

Direct causation can be established; Treatments can push systems outside the range of current natural climate variability; Many ecosystem properties can be followed simultaneously; Can isolate or cross factors of change according to gaps in understanding.

Weaknesses of Experimental Climate and CO_2 Manipulation

Difficult to manipulate forest ecosystems, which have large leverage on climate; Relatively large step changes in experiments probably cause different responses than would be caused by gradual changes such as those occurring in the real world (Klironomos et al. 2005), so manipulation experiments might be best for testing models rather than for developing predictions; Most experiments do not measure, or are not large enough to measure, changes in biophysical properties such as albedo or latent heat flux; Few experiments are designed with multiple treatment levels, making it difficult to use results for creating ecosystem response functions; Feedbacks cannot be measured directly because the size of plots is too small (e.g., an experimental plot treated with elevated CO_2 will not affect regional water vapor concentration, but a global increase in CO_2 can); By nature, experimental manipulations are conducted for just a few years, or under exceptional conditions a couple of decades, limiting their utility for estimating long-term (e.g., century-scale) responses.

Experimental Manipulation of Ecosystem Structure

Changes in species diversity and composition affect ecosystem properties (see Hooper et al. 2005 for a comprehensive review). Experiments set up to study ecological consequences of species loss, biotic invasions, and management regimes have not typically measured effects on biophysical and biogeochemical properties, but could be harnessed for this purpose. As it is for climate/CO_2 change experiments, net primary productivity is often a primary response variable in studies that manipulate ecosystem structure (Tilman et al. 1996, Hector et al. 1999). By adding concurrent measurements of soil respiration, the net effect of species change on carbon cycling, and thus one important climate forcing, could be estimated. Additional measurements, on existing or new experiments, such as of albedo, leaf area index, rooting depth, and trace gas production would help fill gaps in our understanding of how species loss or shifts in species ranges might affect climate. Coupled with information about how climate change may drive species losses/gains and shifts (Harte and Shaw 1995, Walker et al. 2006), we could then begin to quantify and predict feedbacks involving species or functional group changes (Cross and Harte 2007).

Strengths of Experimental Manipulation of Ecosystem Structure

Direct causation can be relatively well established; Treatments can create model systems that have no modern analogs; Many ecosystem properties can be followed simultaneously; Can isolate or cross ecosystem structure manipulations with manipulation of climate variables or CO_2 concentrations to separate the direct climate effects on biogeochemical and biophysical properties from indirect effects due to changes in species composition and relative abundance.

Weaknesses of Experimental Manipulation of Ecosystem Structure

To identify the experiments relevant to realistic scenarios of change, gaps in understanding the effects of climate and CO_2 concentration on species and functional group abundance and distribution must first be quantified; Spatial scale of manipulation experiments is often quite small and manipulating tree species diversity and composition is difficult; Step changes in plant community composition probably cause different responses than would be caused by gradual changes such as those occurring in the real world with sequential species gain or loss, so manipulation experiments might be best for testing models rather than for developing predictions; Present experiments not measuring response variables that are of primary importance for quantifying feedbacks, such as net ecosystem production or albedo; By nature, experimental manipulations are conducted for just a few years, or under exceptional conditions a couple of decades, limiting their utility for estimating long-term (e.g., century-scale) responses.

Combination of Methods and Meta-Analysis

Ultimately a combination of methods such as those described above will yield the most comprehensive understanding of ecosystem feedbacks. A few studies have integrated several methods to determine robust results (i.e. responses that are consistent across methods) or to estimate net feedback strength resulting from multiple biophysical and/or biogeochemical changes (Chapin et al. 2005, Harte et al. 2006, Randerson et al. 2006). Such intensive studies, by necessity, have an ecosystem-specific focus due to the need for comprehensive data on a wide range of climate and ecosystem variables, often collected over many years. However, due to interactions across ecosystem boundaries and the scale required for some biophysical changes to yield a detectable feedback, regional to global scale integration is ultimately required. For example, changes in evapotranspiration rates in forest ecosystems can affect temperature, precipitation and water availability for downwind or downslope ecosystems (e.g., grasslands). To estimate a regional-scale feedback it would be important to integrate forest feedbacks, grassland feedbacks and feedbacks resulting from the interaction of the two systems. A multi-layer observational infrastructure that includes satellite imagery and low intensity, but widely dispersed, observations (e.g., engaging the members of the public as ‘citizen scientists’) may help increase the number of regions with baseline observational data onto which more intensive investigator-driven research can be built. For example, prior observation can aid in strategically locating intensively instrumented transects or intensively studied manipulation experiments (American Institute of Biological Sciences 2004). NEON should create or complement such opportunities.

A complementary and useful tool for identifying consistent relationships between climate change and changes in ecosystem properties is meta-analysis. For example, a recent meta-analysis of four studies found that CO_2 enrichment raises net primary productivity (NPP) by a median of 23% in young temperate forest plantation ecosystems, with variable allocation of this additional carbon to fast and slow turnover pools (Norby et al. 2005). Across multiple studies of tundra, experimental ecosystem warming has yielded shifts in plant community composition (Walker et al. 2006), increases in nitrogen mineralization, and increases in carbon cycling (both plant productivity and soil respiration) (Rustad et al. 2001). However, to date, no meta-analysis has attempted to assess individual studies of climate-ecosystem feedbacks.

Strengths of Combination of Methods and Meta-Analysis

Addressing the same question from multiple angles can identify robust results, as well as where short-term, transient feedbacks differ from long-term feedbacks; Can better utilize long-term observational networks when paired with intensive investigator-driven experimental research; increasing familiarity with statistical tools and institutional support for meta-analysis has spurred this approach.

Weaknesses of Combination of Methods and Meta-Analysis

Requires skill sets from multiple disciplines and funding for diverse approaches; Intensive data requirements will limit the number of ecosystems or regions that can be carefully characterized; May require a new level of collaboration and cooperation beyond that commonly found in the scientific community (and which might require sociological change, appropriate funding, and new job-performance evaluation metrics).

4. PRIORITIES FOR FUTURE RESEARCH ON CLIMATE-ECOSYSTEM FEEDBACKS

There are many ways to prioritize new research on climate-ecosystem feedbacks, but ultimately priorities should reflect a combination of concerns, including

(1) ecosystems that cover large areas globally (e.g., boreal forest),
(2) ecosystems that are likely to be sensitive to climate and CO_2 changes (e.g., shallow-rooted ecosystems),
(3) ecosystems whose response could have a large climate impact (e.g., ecosystems with large carbon stocks or with particularly high or low albedo),
(4) ecosystems in geographic areas expecting relatively large climate changes (e.g., arctic and Central American ecosystems; Figure 5), and
(5) poorly understood climate-ecosystem feedback pathways (e.g., species range shifts, human role in feedback loops).

Modeling studies should be helpful for planning field research that focuses on poorly understood pathways with potentially large consequences.

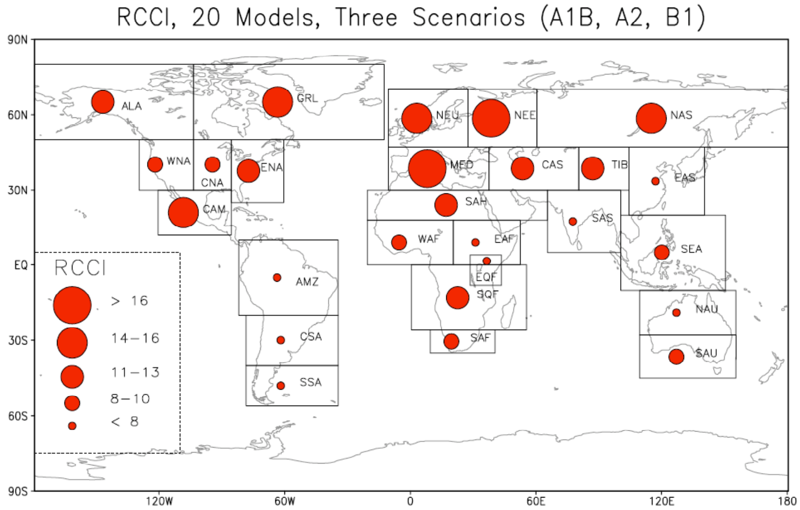

Figure 5. A regional climate change index (RCCI) shows regional variation in the relative magnitude of projected future climate changes. The RCCI is calculated from the (equally weighted) changes in mean wet and dry season temperature and precipitation, as well as from changes in temperature and precipitation variability between the end of the 21st century and near middle of the 20th century, as projected by twenty AOGCMs for three standard greenhouse gas emission scenarios (B1, A1B and A2) (Giorgi 2006). Regions with high RCCI's are projected to experience greater climate change relative to the global mean than regions with low RCCI's (all land regions have above average RCCI's).

To collect input on observational needs and research priorities from a broad spectrum of scientists working on components of climate-ecosystem feedbacks, we held a Workshop at the 2005 Fall Meeting of the American Geophysical Union (Dec 5-9, 2005, San Francisco, CA). The following lists of priorities for new or additional research and of promising observational approaches are based on ideas expressed at the workshop.

Priorities for Climate-Ecosystem Feedback Research

1. Need ecosystem feedback studies that make more comprehensive measurements so that net sign and strength of the feedback can be estimated
    - Many experimental manipulations look at only half the carbon cycle (net primary production) and few measure energy fluxes, albedo, or trace gas fluxes
2. Need a better understanding of tropical ecosystem sensitivity to CO_2 increases and to climate change since these regions have significant leverage in coupled climate-carbon cycle models.
    - Few manipulations of CO_2 concentration in tropical ecosystems
    - Few manipulations of climate variables in tropical ecosystems
3. Need a better understanding of potential feedbacks in understudied regions that expect relatively large future climate change, including North Eastern Europe, Northern Asia, and Central America among others (Figure 5).
4. Need a better understanding of how species ranges could be altered by and feedback to climate change
    - How fast can species migrate? Will all populations respond in the same manner?
    - By what mechanisms will ranges change (local extinctions, long-range "leaps" to habitat "islands", gradual movement at edges of current ranges, insect/fire/pathogen mediated changes)
    - Which species or vegetation types are able to move, which aren't?
5. Need to know whether species are important.
    - Should focus of study be on species, functional types and/or systems (communities)?
6. Need more knowledge regarding non-CO_2 trace-greenhouse-gas responses to climate change.
    - N_2O budget and its sensitivity to climate variability and change still poorly constrained
    - CH_4 budget and climate sensitivity is similarly unconstrained
    - Dust, black carbon, and volatile organic compounds all affect radiative forcing and potential changes in their abundance and distribution with climate change are not known
7. Need to characterize the role of trophic interactions in controlling ecosystem-climate feedbacks
    - Insect herbivores are damaging vast areas of forest in boreal and temperate zones, perhaps in response to warming. What are the consequences for feedbacks, and how can such interactions be predicted?
8. Need strategies for scaling across space, time, and levels of ecological organization
    - Individuals and ecosystems respond to fine-scale local and regional climate variation, but to quantitatively represent feedbacks in climate model predictions we need to understand ecosystem responses regionally or globally.
    - An approach is needed to understand lags, episodic events, and ecosystem responses to extreme conditions, but there are few continuous, long-term experiments or observations that can capture infrequent or delayed events.

  - Climate models that include changes in the distribution of vegetation types currently use broad biome-level categorizations of ecosystems or plant functional type generalizations, but we know from paleoecological studies and modern field experiments that species (and populations) respond individualistically to climate change to create non-analog communities, with potentially unique functional consequences. How can we scale from species to ecosystem and beyond with incomplete information at each level?

9. Need to design studies based on regionally specific climate changes and that incorporate uncertainties in the magnitude (and sign) of climate changes
   - In some regions the sign of precipitation change is highly uncertain.
   - Some regions expect greater changes than others (Figure 5)
10. Need a consideration of human responses to climate/ecosystem change in observational approaches. Humans may alter ecosystems and therefore modify feedbacks to climate change, either purposefully (to mitigate climate change) or inadvertently.
    - Humans respond to stochasticity in climate with potential consequences for carbon emissions, albedo change, and so on.
    - Climate change mitigation options include strategies for intentionally modifying surface albedo and carbon cycling that would feedback to climate.

Additional bottlenecks and knowledge gaps limiting our ability to quantify and predict ecosystem feedbacks to climate change that were raised at the workshop include, the role of extreme events in triggering threshold responses by ecosystems, genetic context and constraints to ecosystem response, non-linear dynamics in ecosystem-climate interactions, model – observation integration, the relationship between mineral dust and vegetation productivity/biomass.

Promising Observational Approaches for Climate-Ecosystem Feedback Research

1. Large coordinated experiments targeted to under-studied regions (tropics, Asia, Africa).
   - Such experiments should use lessons from past large projects (e.g., BOREAS) and include a mix of intra-and cross-site scientists
   - Large international experiments should train local scientists
2. Pursue ‘citizen science’ efforts to monitor climate and ecosystem conditions extensively, and over the long-term to build datasets useful for interpolation and extrapolation.
   - Citizen observations must be simple, repeatable observations – suggestions: precipitation, soil moisture, water table depth, phenology, herbivory, leaf decomposition, mushrooms
   - Citizen experiments could be considered – suggestions: temperature x moisture effects on above- and belowground, observations along gradients in climate or land use
   - Information exchange can take place via a web portal with forms, protocols, maps etc.
   - Use of qualitative observations by citizens
3. Need a commitment to long-term, continuous, perhaps international, remote sensing program.
   - What will replace Landsat?

  - How do we really invest in long-term monitoring given reality of funding/political cycles?
  - Validation of remotely sensed data is critical
  - We need new ideas for space-based measurements.

4. Make use of commercial aircraft for repeat 'down-looking' and atmospheric measurements on standard transects.
   - Suggested instruments/observations on airplanes/trains – profiling technology, trace gases, albedo, hyperspectral observations, H_2O concentration, dust, lidar
5. Promote work at species and functional group levels, acknowledging that sensible functional categories cannot always be determined *a priori*
   - Consider species dominance
   - Plant trait approach – root area, root distribution, herbivore susceptibility, dispersal/colonization ability (fecundity, seed viability), flammability, role of extreme events, coevolution of traits
   - Sub-functional type albedo measurements important
6. Collaboration with social scientists to understand (and predict) human responses to climate and ecosystem change.
   - "Surprises" in human responses may be critical – how to scope out unknown unknowns?
   - How sensitive are land uses and land management practices to mean climate and to climate variability
   - Can/will humans 'manage' feedbacks?

Additional approaches to quantifying and predicting ecosystem feedbacks to climate change that were discussed at the workshop include, development of common protocols to facilitate comparisons across sites, opportunistic experiments for understanding transient feedbacks, long-term manipulations, synthesis of ecosystem sensitivities from multiple experimental methods and multiple interacting factors, data-assimilation or "model-data fusion" as an approach to scaling in space and time, use of non-traditional information/observations (e.g. local records of farm productivity, river ice melt, etc.) to build long-term datasets, continental trace gas observations, and alternatives to eddy covariance.

5. CONCLUSIONS

Climate-ecosystem feedbacks are a major source of uncertainty in predictions of future climate change. Some improvements to coupled climate-biosphere models can be made based on current understanding of ecosystem responses to climate change. However, there are still major outstanding questions regarding ecosystem responses to climate change and resulting climate forcings, and these require new empirical research. Addressing gaps in current understanding will require a multi-level effort that combines long-term, extensive climate and ecosystem observation with intensive region and ecosystem-specific manipulations targeting ecosystems that cover large areas, that have large leverage on climate, that occur in areas expecting significant climate change, and/or that are sensitive to climatic and CO_2 concentration changes. Critical pathways for climate-ecosystem feedbacks may vary by ecosystem or region, but in all cases, climate-ecosystem feedback studies should strive to "close the loop."

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