The Changing Carbon Cycle: A Terrestrial Focus

Report of the Workshop on the Terrestrial Carbon Cycle

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Introduction

The above Earth scientists participated in a workshop on the Terrestrial Carbon Cycle (TCC), which was held in Washington, D.C. on June 3, 2000. The goal of this meeting was to identify significant research questions and strategies concerning the production, cycling and storage of carbon (and other bioactive elements) at the Earth's surface, with an emphasis on terrestrial settings. The TCC Workshop was organized by Enriqueta Barrera, Director of the National Science Foundation (NSF) Program on Geology and Paleontology. It also was attended by Herman Zimmerman, Director of the (NSF) Division of Earth Sciences; Donald L. Rice, Director of the NSF Program on Chemical Oceanography; and Lisa Dilling from the Office of Global Programs of the National Oceanic and Atmospheric Administration. This report provides a synthesis of written comments and group discussion associated with the TCC Workshop and is not intended to be a comprehensive record of group deliberations.

[1]Participant addresses are appended to this report. Note: ***contributed comments but was not able to attend.

Overriding Issues

Globally important Earth characteristics such as atmospheric CO_2, soil fertility and terrestrial ecosystem stability result from numerous interacting processes. Although often readily measured, these "emergent properties" typically are the product of complexly linked nonlinear relationships that are difficult to unravel and predict, and that span across boundaries of traditional disciplinary investigations. Process networks, similar to those controlling local climates, are intrinsically robust but prone to stability thresholds and abrupt changes in operation. These linked physical and biological systems respond to processes that occur on multiple time scales, from very slow mechanisms such as as continental uplift and weathering, to the buildup of carbon in soils and biomass over centuries, to much faster events and processes such as volcanic eruptions or the turnover of nutrients by soil microbial communities. Thus, the present states of terrestrial ecosystems and the atmosphere that links them reflect not only current conditions, but also a legacy of past events playing out over historic to geologic time. These natural systems must be studied in meaningfully large units and over sufficient time scales to capture both their intrinsic variability and potential responses to change. With the consequences of global change still uncertain, there is a critical need for a more comprehensive understanding of the many components and interlinked process networks that comprise the terrestrial carbon cycle.

The June 3 Workshop on the Terrestrial Carbon Cycle (TCC) proposed the following overriding questions that embody key emergent properties pertinent to present-day concerns about human intervention in the terrestrial cycles of the bioactive elements, including C, N, P, S and O:

A. **What terrestrial processes influence the concentration of carbon dioxide in the atmosphere over time?**

B. **What mechanisms control geographically broad patterns in carbon and nutrient cycles, soil fertility, and stability among terrestrial ecosystems?**

C. **How stable are terrestrial ecosystems, and what are their likely responses to anthropogenic perturbations?**

A well-coordinated program of discovery-based research is needed to probe the complex workings of the terrestrial carbon cycle. This program must bridge the traditional fields of physical, biological, geological and chemical research and respond flexibly to new insights and research opportunities. Conventional scientific divisions focusing on specific environments (limnologists, soil scientists, and oceanographers) and their individual components (forests, lakes and rivers) also must be transcended. The U.S. National Science Foundation is one of the few institutions in the world with sufficient breadth and infrastructure to support a creative research program of this scale and complexity. Through the leadership of NSF, a large integrative study of terrestrial carbon cycling must be guided by clearly defined key questions and research strategies.

Summary of Key Questions

In response to the challenge described above, the TCC Workshop group identified and discussed the following broad questions concerning our present understanding of the changing terrestrial cycles of carbon and other bioactive elements:

1. **How do biota, soils, sediments and climate interact and develop together as a dynamic and evolving system?**
2. **How are atmospheric concentrations of CO_2 influenced by geochemical, biological and climatic processes?**
3. **What are the patterns and controls of terrestrial carbon cycling across geographically broad regions and through time?**
4. **What are the implications of findings concerning the above questions for terrestrial ecosystem responses to human perturbation, locally and globally?**
5. **What are the indicators of change that should be measured to model the contemporary terrestrial carbon cycle, understand its history and predict its future states?**

The central question of dynamic controls on carbon cycling must inherently include interactions of carbon with potentially limiting nutrients (e.g., N, P, or K^+), with water, and with different natural and anthropogenic disturbance agents.

The following text provides a general background on terrestrial element cycling. It is followed by sections that frame each key question and recommend corresponding research directions.

Background

Carbon is one of the most abundant elements in the solar system and provides the structural basis for life on Earth. Inorganic forms of carbon (carbon dioxide, bicarbonate and carbonate) strongly affect the acidity of soils and natural waters, the heat insulating capability of the atmosphere, and the rates of such key natural processes as photosynthesis, weathering and biomineralization. In reduced form, carbon provides the elemental backbone for myriad organic molecules that comprise living organisms, soil humus, and fossil fuels.

Table 1. Earth's Carbon Reservoirs

Reservoir Type	Mass*
Sedimentary rocks	
Inorganic	
Carbonates	60,000
Organic	
Kerogen, coal, etc.	15,000
Active (surficial) pools	
Inorganic	
Seawater DIC	38
Soil carbonates†	1.1
Atmospheric CO_2	0.66
Organic	
Soil organic matter†	1.6
Land plant tissues	0.95
Seawater DOC	0.60
Surface marine sediment	1.0

*Units = 10^{18} grams C, †within the upper meter, From Hedges and Keil, (1995), *Mar. Chem.* 49: 81-115.

Only ~ 40 x 10^{18} grams of carbon are present at the Earth's surface (Table 1). Of this "mobile" carbon, the major pool occurs in inorganic substances (largely bicarbonate) dissolved in seawater; each of the other active reservoirs contains approximately 1 x 10^{18} grams C. Carbon in these active pools affects climate and is involved in atmosphere-biosphere-lithosphere interactions. It is continuously cycled between land and sea, in inorganic and organic form. Most of the carbon stored in organic matter is nonliving, occurring either in soil humus or dissolved organic carbon (DOC) in seawater. The atmosphere, in addition to comprising a major carbon reservoir, plays a critical role as a medium for rapid global exchange of CO_2 and other bioactive elements.

Over short time periods (up to years), the dynamics of atmospheric CO_2 is primarily controlled by the biotic processes of photosynthesis, respiration, and decomposition. At longer time scales, however, these processes are embedded within slower fluxes of carbon in and out of the deep ocean dissolved inorganic carbon (DIC) pool, and in the very-long-term context of cycling through the immense sedimentary rock reservoir (Table 1). The long-term sinks for atmospheric CO_2 are weathering of silicate rocks and sequestration of organic matter in marine sediments. Weathering rates of silicate rocks are greatly accelerated by land plants, which physically break up the substrate and increase chemical weathering rates by injecting CO_2 and organic acids via root respiration and exudation. Burial of organic matter in marine sediments is compensated for by continental weathering and oxidation of kerogen in exposed shales and coal deposits, a process which ties together the fates of atmospheric CO_2 and O_2 over geologic time.

The mechanisms controlling atmospheric CO_2 generate small net differences between huge simultaneous exchanges of carbon and other bioactive elements among the active reservoirs in Table 1 (for a detailed discussion see "A U.S. Carbon Cycle Science Plan," 1999). For example, during the 1980s, atmospheric CO_2 increased at an average rate of 3.3 billion metric tons (gigatons or 10^{15} grams of C) per year, which corresponds to roughly 60% of total fossil fuel emissions of that decade (5.5 Gt/yr). (Fossil fuel emissions represent human-accelerated oxidative "weathering" of ancient sedimentary organic matter). Models and measurements indicate the ocean absorbed roughly 2.0 Gt/yr of C, and thus that the net terrestrial carbon sink is small. However, the average loss of carbon from the terrestrial biosphere due solely to deforestation is estimated at 1.6 Gt/yr, necessitating terrestrial uptake of CO_2 at a comparably large rate. Isotopic evidence suggests an even greater terrestrial carbon sink was in effect in the 1990's; recent research suggests that the compensatory terrestrial carbon sink may reside in the Northern Hemisphere. Most of the previously discussed net fluxes correspond roughly to 0.1% or less of the carbon stored in individual active surface pools (Table 1) and to 1% or less of the carbon that these reservoirs exchange annually.

Carbon cycling on land is as quantitatively important as in the ocean, and at least as difficult to study. A major factor contributing to this complexity is the inherent heterogeneity of the landscape at spatial scales ranging from microns to thousands of kilometers. The Earth's solid surface is poorly insulated, weakly mixed and deeply penetrated by air and water, making fluxes extremely difficult to measure. Weathering and physical erosion selectively displace and rearrange the land surface, so that materials of very different ages are commixed and chronological records are rapidly erased. Finally, the modern global landscape has been so impacted by a legacy of deforestation, cultivation, desertification, nitrogen-loading, erosion, burning, dam building and other human activities, that unaltered landscapes and ecosystems are now exceptions, rather than the rule.

The geologic record provides a unique means for comparing the contemporary cycle of carbon to those that have prevailed over our planet's surface for billions of years. This profound sedimentary perspective reveals that change has been the rule over Earth history and that the range and abruptness of variability can be immense. In particular, it becomes clear that our present circumstance, within one of numerous historically brief warm stages of a glacial epoch, is not a firm basis for predicting future climate conditions. The geological record offers challenging extremes that predictive models of climate and biogeochemistry must be able to encompass, as well as a reminder of how different our world can be. This big picture, written in rock, sediments and ice, is an appropriate backdrop for present-day concerns because carbon cycling is inherently historical. The present reservoir sizes and exchange rates reflect the cumulative influences of landscape and life through past time, and set the modern environment’s potential to respond to perturbations that may resonate for thousands of years into the future.

Key Questions

The following sections individually discuss key questions, presented above, and indicate research directions by which each might be addressed.

1. How do biota, soils, sediments and climate interact and develop together as a dynamic and evolving system?

This broad question is the fundamental basis for all that follows. Terrestrial ecosystems develop in myriad forms as individual living organisms respond over time to each other, nutrients, climate, and their geological substrates. Biota and soils develop in response to their natural settings with characteristic patterns that have been recognized (if not always understood) by botanists, agronomists and ecologists. For example, recent work has shown that forest carbon balances can be sensitive to external inputs of nutrients such as nitrogen (e.g., most temperate forests), or phosphorus (e.g., old tropical forests), yet, in some cases they can remain insensitive to increases in nutrient supply rates (e.g., some temperate forests in polluted regions). While such geographically broad variations in the effects of nutrient limitation on carbon sequestration are of fundamental concern, the underlying mechanisms depend on poorly understood feedbacks between biota, soils, climate, and geological substrates. The level of mechanistic understanding necessary to explain such broad patterns and to predict their potential response to change is immense, and presently incomplete. This complexity results in part from the nonlinear interactions of numerous processes that exhibit varying sensitivities, linkages and response times. The whole system is considerably more than the simple sum of its components and may rest disproportionately on unknown or under-appreciated key processes.

Of central importance is to integrate geochemical, biological, and physical processes into unified dynamic models of how terrestrial ecosystems function. For example, the influence of nutrients on the biological process of "net carbon sequestration" depends on relative supply rates of potentially limiting nutrients. The supply of these nutrients, in turn, depends on geochemical and physical processes linked to weathering and atmospheric deposition, which vary at scales of decades to millennia, and across large geographic regions. In contrast, supplies of nitrogen are (in the absence of anthropogenic inputs) largely controlled by biological processes of nitrogen fixation, and shorter-term cycling by plants and soil microbial communities. Thus, while it may be relatively straightforward to measure net carbon balances in ecosystems, it is a significantly greater challenge to untangle the complex interaction of processes and time scales that define the dynamic control of these carbon balances. Current models display considerable weakness, or even complete absence, of such broad-scale efforts of integration.

A second key issue is whether studies of areas that have experienced various modern human influences (e.g., accelerated nitrogen cycling, or forest cutting) provide an adequate representation for questions about how unimpacted ecosystems function. Throughout large regions of the world, human impacts have grown so strong that it is difficult to ask questions about processes that might control the natural patterns of carbon and nutrient cycling in unimpacted environments. While there is much to be learned from studies of human-impacted ecosystems, there is an equally strong need to understand how ecosystems function in the absence of human effects. Baseline studies from relatively unimpacted regions of the Earth can not only help to discern mechanisms and magnitudes of modern human impacts but, perhaps more importantly, can help examine factors that influenced carbon and nutrient dynamics in pre-industrial environments.

It has become clear from experience that no single experimental approach to elucidating terrestrial carbon cycling is sufficient to predict responses on all time and space scales. Broad geographic gradients (e.g., in climate, biota, weathering, geologic parent material, and human disturbance) provide valuable "natural laboratories" to examine controls on emergent ecosystem properties. Disciplinary approaches that rely entirely on empirical relationships within isolated subsets of terrestrial systems, however, can be incomplete or subject to misinterpretation. The following strategies that integrate scientific approaches for addressing the functions of terrestrial ecosystems over time are recommended:

- **Observational and experimental studies across broad natural gradients provide unique opportunities to delineate controls on the co-development of biota, soils, sediments, and nutrient cycles.**
- **Studies should emphasize links between biological, geochemical, and climatic processes that control cycles of potentially limiting nutrients, water, fertility and stability within ecosystems. While these processes are manifested across widely different temporal and spatial scales, the goal should be to produce integrated conceptual and numerical models of such causal networks.**
- **Studies must incorporate the tightly coupled cycles of carbon and the other major (N, P, S, and O) and minor (K, Ca, Si, Fe, Mn, Co, Ni, etc.) bioactive elements.**
- **Effective investigations of element cycling must transcend traditional boundaries of disciplines (biology, chemistry, physics, geology) and geographic setting (uplands, lowlands, rivers, lakes and the ocean) and cover a range of timescales.**
- **Research should encompass both pristine and highly altered landscapes of different types, where in the latter case the history of land use is taken systematically into account.**

2. How are atmospheric concentrations of CO_2 influenced by geochemical, biological and climatic processes?

Atmospheric carbon dioxide concentration is a useful indicator of short-term and cumulative environmental change. Varying distributions of this extremely dynamic gas reflect net differences in carbon flux over a broad span of time and space scale, ranging from hourly changes in the local balance of photosynthesis and respiration, to shifting rates of carbon sedimentation and weathering over geologic time. Although natural processes modulate CO_2 (and O_2) cycling over time, the balance of sources and sinks is not perfect. Geologic evidence suggests that both gases have been subject to substantial fluctuations in atmospheric concentration, although CO_2 typically responds much more quickly and with larger variations than for O_2. Study of past environments via the geologic record can thus provide extremely useful information about the sensitivity of climate to integrated effects of large and small variations in atmospheric CO_2 concentration.

Appreciable effects of weathering on carbon cycling are not necessarily limited to past environments. Deforestation, cultivation, and over-grazing have greatly accelerated erosion rates on the continents, as reflected in part by the greatly elevated turbidities of many of the world's major rivers. This global-scale dislocation of surface material may have a major effect on weathering rates, which can be expected to rise with average global temperature. The released minerals may both lose (shales) or adsorb (igneous weathering products) organic matter, which in the latter case can be stored in the large volumes of river sediments now accumulating beneath artificial reservoirs. Thus, weathering/deposition cycles may now be going through a substantial anthropogenic perturbation, which in transition may not exhibit the steady-state balances that are often associated with these processes in the longer term.

Because atmospheric CO_2 mixes rapidly between the hemispheres, it reflects net carbon fluxes on a global basis for timescales longer than a few years. Atmospheric CO_2 gradients thus point to regional carbon imbalances, such as the large Northern Hemisphere terrestrial sink inferred in recent years from inversion models. Radiocarbon, with a half-life of ~5,700 years, adds an internal clock by which atmospheric CO_2 can be traced in various chemical forms through the biosphere and geosphere over time scales especially pertinent to anthropogenic effects. The pulse of ^{14}C released by atmospheric testing of thermonuclear devices in the middle 20th century has facilitated studies of carbon cycling on decadal time scales. The $^{13}C/^{12}C$ abundance ratios of carbonaceous materials provide robust signatures of natural sources, fates and transport pathways, as well as a useful constraint in mass balance calculations over long and short time scales.

To understand how atmospheric CO_2 concentrations respond to climatic and biogeochemical forcing, it is necessary to delineate the underlying processes, their sensitivities, interdependencies and characteristic dynamics. This is especially true for processes involving terrestrial carbon reservoirs in vascular plant biomass, soil organic matter and soil carbonates (Table 1). The biggest of these reservoirs, soil organic matter (largely amorphous humus), comprises a complex mixture of nonliving organic substances of largely uncharacterized composition that is associated intimately with both its plant source and mineral matrix. Cultivation generally leads to net loss of soil organic matter (which has C/N ≈10-15) and the concomitant release of nitrogen, phosphorus and other elements. Nutrients released by humus degradation can lead to production of plant biomass (C/N ≈ 20-500) and short-term sequestration of carbon on the landscape. Nitrogen and phosphorus introduced by fertilization can have similar effects.

Growing evidence suggests land plants can photosynthesize more efficiently at higher concentrations of atmospheric carbon dioxide. Such "CO_2 fertilization" is of great interest as a possible negative feedback control on increasing atmospheric CO_2 concentrations, especially in regions where biomass increases result from the return of agricultural and grazing lands to natural vegetation. Elevated concentrations of CO_2 also accelerate removal by rock weathering, especially when augmented by the effects of increasing temperatures and the release of carbonic and organic acids from plant roots. In turn, silts and clays formed by physical and chemical weathering become intimately associated with organic substances, which they can physically protect from leaching and biodegradation. Unfortunately, most models for the turnover of soil organic matter are based on broad kinetic characterizations (e.g. fast, slow or passive) that are often determined by nonspecific analyses (e.g. solubility characteristics or elemental composition) and do not take mineral association into account. In addition, these models generally do not discriminate among various types of sparingly reactive organic matter such as charcoal, soot, and incompletely weathered kerogens and coals, which nevertheless have different origins, dynamics and long-term fates. Erosion and leaching of dissolved organic matter from soil horizons also are largely ignored.

With these many considerations in mind, the following guidelines for specifically assessing terrestrial carbon cycling effects on atmospheric CO_2 concentrations are recommended:

- **The quantitative effects and mechanisms of both CO_2 fertilization and nutrient loading on atmospheric carbon dioxide concentrations should be assessed as a high priority.**
- **The effects of nutrient limitation on carbon cycling should be addressed in detail, especially via field and laboratory experiments to determine whether the degradation of soil organic matter leads to <u>net</u> carbon sequestration by supporting enhanced biomass production.**
- **Processes affecting production and turnover of soil organic matter and ancient kerogen should be studied to elucidate important microbial activities (production and mineralization), organic structural characteristics, mineral associations and climatic controls.**
- **Research should be encouraged on biogeochemical interactions between vascular plants and microorganisms, including such processes as nitrogen fixation and nutrient exchange in mycorhizal communities.**
- **Improved methods for determining atmospheric CO_2 concentrations and fluxes are needed. Emphasis should be placed on methods that are amenable to automation, applicable over broad spatial scales and can provide complementary information on a range of other trace gases and their isotopic compositions.**
- **Relationships between atmospheric CO_2 levels and climate/ecosystem interactions should be pursued throughout the geologic record, especially for periods characterized by extreme CO_2 concentrations (e.g. Mesozoic highs and Permo-Carboniferous lows) and rapid change (e.g. glacial/interglacial transitions).**

3. What are the patterns and controls of terrestrial carbon cycling across geographically broad regions and through time?

The spatial and temporal scale over which terrestrial carbon cycling might be most practically studied to address issues of changing atmospheric CO_2, soil fertility and system stability are overarching concerns. Focusing on a single spatial scale is an incomplete approach. This derives in large part from the extreme heterogeneity of the landscape, within which functional units are closely nested, from the scale of microorganisms to regional life zones. A key consideration in such assessments is that terrestrial processes do not necessarily scale up or down in a smooth, continuous manner. For example, a property or behavior that may be typical of an individual plant type may not hold for a population of the same species. Changes in plant communities may have important effects on the carbon cycle, yet the rate and nature of changes may be difficult to predict. Lag times and hysteresis effects may contribute to difficulty in understanding community-environment feed backs. Additionally, the reactivities of soil organic components are known to change greatly with size, both because size is related to ultimate source (e.g. coarse woody debris versus fine microbial remains) and because degradation typically decreases substrate size.

The existence of geographical variations in nutrient cycles, fertility, and terrestrial ecosystem dynamics requires us to recognize that controlling mechanisms vary broadly across the Earth's surface. It thus becomes critical to understand not only processes within localized study sites, but also how these processes scale across terrestrial ecosystem gradients. Thus, we must examine essential mechanisms and emergent properties across ranges of physical scales and within regional gradients of chemical, hydrologic or climatic conditions. Manipulation experiments can be included at different locations within the matrix of such gradients, to probe specific processes or system responses. In all field and laboratory studies, the scaling of landscape processes over space and time should be critically evaluated.

Any analysis of carbon cycling across the landscape must consider hydrology. In addition to supplying water necessary for plant production and microbial activity, precipitation can be an important source of nutrients to many terrestrial ecosystems. Water runoff transfers dissolved and particulate components of plants and soils to aquifers and rivers. Streams and rivers serve both as processors and pipelines for the continental weathering products they transport, and continuously reflect in their chemistry the results of process interactions within discrete areas of drainage basins.

Streams and rivers provide a convenient way of quantifying nutrient and water fluxes from spatially explicit areas of landscapes. Thus, watershed-scale studies provide a scale of integration above local physiological and biogeochemical processes, but below scales of regional and global processes. Rivers and small streams offer an important complement to airborne or satellite survey methods, because water chemistry and fluxes reflect subsurface processes, such as weathering, that cannot be observed by conventional remote sensing techniques. Climatic information stored in eroded soils and plant debris is integrated over drainage basins through confluent river networks and eventually transcribed to continental margin sediments. These buried sediment sequences comprise an enduring chronology of ecosystem processes on the ephemeral surfaces of adjacent continents, and constitute a major source of carbon passing into long-term geologic storage. In regions with accelerated erosion due to land clearing and cultivation, sediments on floodplains and collecting behind dams may be quantitatively important contemporary sinks for bioactive elements.

It is paradoxical that, while short-term and local-scale processes dominate the proximate turnover of carbon and nutrients, many of the ecosystem-scale properties that we are ultimately interested in (e.g., long-term balances of carbon and other nutrients) develop over much longer time scales - decades, millennia, or more. This means that entirely different processes and questions can emerge at longer time scales: for example, processes of weathering, atmospheric deposition, immobilization of secondary minerals, and mechanisms by which nutrients are lost in hydrologic outputs. These processes influence how ecosystems respond over long periods to variations in climate, atmospheric dust deposition, and weathering rates and thus ultimately influence concentrations and isotopic signatures of atmospheric carbon dioxide, methane, and oxygen.

Although all time scales are relevant, a scientific emphasis on periods of decades to thousands of years may be advantageous. This time dimension is sufficiently long to largely average out weather fluctuations, seasonality, and some patterns of interannual variability (e.g. El Niño). This temporal framework also complements shorter-term agricultural studies and covers the average turnover times of terrestrial biomass and soil organic matter. This period also corresponds to the history of most pronounced human perturbation of natural systems and the length of time into the future that meaningful projections can be made. Given, however, that terrestrial ecosystems and climate interact via a complex network of processes that are sometimes unknown and often nonlinear or abrupt, a temporal focus on dynamics of 10^1-10^3 years must be framed with parallel studies of faster and slower phenomena. For example, seasonal and interannual fluctuations can provide valuable insights regarding the influences of such variables as temperature and rainfall have on terrestrial ecosystems and their carbon exchanges. At the other extreme, sedimentary deposits uniquely record such gradual processes as changing solar luminosity, planetary oxidation, and the co-evolution of the global ocean, atmosphere and biosphere. The geologic record also is sufficiently extensive to capture rare catastrophic events such as earthquakes, volcanic eruptions, and bolide impacts that can constitute (or trigger) major long-term effects.

The following questions and guidelines are recommended for distributional investigations of terrestrial carbon cycling:

- ♦ **What factors and processes control geographically broad natural patterns of carbon cycling across terrestrial ecosystems?**
- ♦ **Field studies along natural gradients of climate, altitude and age are advised to capture ecosystem properties on sufficiently large scales to represent processes with potential global impacts. These investigations can be augmented with field manipulations and laboratory simulations to single out important components.**
- ♦ **What are the processes and mechanisms that influence how terrestrial ecosystems respond to long-term changes in climate, atmospheric wet and dry deposition, and weathering rates? How do these processes and responses link to signals written in the long-term proxy records of isotopic and concentration variations of atmospheric gases, pollen records, and sediment chemistry?**
- ♦ **Studies of carbon cycling should be carried out over a broad range of time scales ranging from essentially instantaneous biological responses to gradual processes that are uniquely recorded in ancient sedimentary records.**
- ♦ **The spatial scope of carbon cycle investigations should also be broad, ranging from cell/substrate/mineral interactions at the micron scale to regional patterns of climate, lithology, tectonic processes, vegetation and land use.**

- **Rivers and streams merit emphasis as integrators of biogeochemical processes (and attending chemical fluxes) across the landscape.**
- **Sedimentary deposits on land and along continental margins should be investigated as components of the carbon cycle and as convenient records of plant sources, climate and cycling mechanisms on adjacent continental areas.**

4. What are the implications of findings concerning the above questions for terrestrial ecosystem responses to human perturbation, locally and globally?

The Earth's terrestrial surface is poorly buffered against the effects of various modern human activities, ranging from nitrogen deposition, to shifting land use, to global climate change. The prospect of continued widespread change across the land surface points to necessitates a better understanding of how carbon interacts with nutrients, water, and other controlling factors across widely different terrestrial ecosystems. However, delineating anthropogenic offsets from natural variations in fluxes among massive carbon and nutrient pools is a difficult challenge. It is equally challenging to delineate the processes that control the long-term emergent responses of terrestrial ecosystems to variations in climate and to the stresses imposed by modern human activities.

How well answers to the previous three questions can be applied to issues regarding human perturbations will depend upon which characteristics are measured, what functional relationships can be observed and how that information is eventually used. Direct measurements should emphasize system components that are diagnostic and or potentially causative (e.g. carbon dioxide, methane, soil humus) of major climate and ecosystem shifts. An overriding concern should be the stability of natural and altered ecosystems to abrupt changes in modes of bioactive element cycling. Examples of potentially harmful events include loss of crucial biotic components due to stress or disease, destruction of wetlands by fire, and large-scale soil erosion resulting from sodium loading or loss of binding organic matter. Thus:

- **Studies of carbon cycling on land should seek to improve understanding of the mechanisms that underpin agricultural systems and be directed toward regions of concentrated human impacts.**
- **Sensitive landscapes (e.g. tropical forests, dry plains, and tundra) in regions undergoing rapid development or environmental changes provide useful large-scale examples of ecosystem alteration.**
- **Where possible, measurement and modeling efforts should seek to understand thresholds for abrupt changes in ecosystem state and function.**
- **Geological and historical sedimentary records should be collected and compared to search for repeating patterns of landscape stress and response over periods of decades to millennia. Examples from past interglacial periods, epochs of high atmospheric CO_2 and widespread vegetation change may be especially informative.**

5. What indicators of change should be measured to model the contemporary carbon cycle, understand its past, and predict its future states?

This question addresses the issue of how observations, experimental measurements and modeling efforts could be combined effectively to assemble predictive simulations of terrestrial carbon cycles. This broad focus gave rise to the following general recommendations:

- ♦ **Strategies for measuring and modeling bioactive element dynamics should co-evolve so that key processes and system components are directly characterized and accounted for adequately in numeric representations.**
- ♦ **Models should be mechanistically based, rather than empirical, with emphasis on the capability to guide ongoing research as well as predict the future.**
- ♦ **New chemical and isotopic tracers need to be developed that reflect and record critical aspects (e.g. temperature, hydrology, weathering processes, atmospheric composition, and species distribution) of present and past environments. Such proxies should be applied in consort to sediments and soils, with emphasis given to high-resolution, broadly integrative records.**
- ♦ **Concerted effort should be made to "mine" and combine the huge amounts of quality data on landscape properties and their historical use that are presently dispersed in the literature and institutional records.**
- ♦ **These assembled data should be combined into geographic information systems (GIS) and other integrative treatments, especially those capable of quantitatively routing materials through the landscape.**

Strategies for organizing the scientific approach

In the course of group discussion it became evident that the mechanisms by which the questions posed above might be most effectively addressed constitute an important crosscutting concern. The unprecedented scope and complexity of the proposed scientific studies will require strategies and facilities beyond those that are now commonly available. A variety of pertinent governmental program implementations and critical partnerships for carbon cycling studies are outlined in Chapter 6 of the US Carbon Cycle Science Plan. In addition, the following actions are recommended:

Highly interdisciplinary programs of advanced scientific education that focus on both experimental and numeric analysis of nonlinear interactions within complex natural systems should be emphasized and supported.

Increased collaboration across traditional guilds of earth scientists should be encouraged by workshops, conferences, and research programs that stress complex system interactions across broad temporal and spatial scales.

Reference materials for comparing analytical results among different laboratories, and within individual laboratories over time, should be made widely available to earth scientists.

Stronger partnerships of developing countries with scientifically more advanced counterparts are necessary to monitor ongoing effects of environmental change as they are occurring.

Although many of the previous recommendations are in the direction of increased collaboration and organization, support and encouragement must be retained for individual scientists and small research groups, who continue to produce a wealth of useful new experimental methods, data and concepts.

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