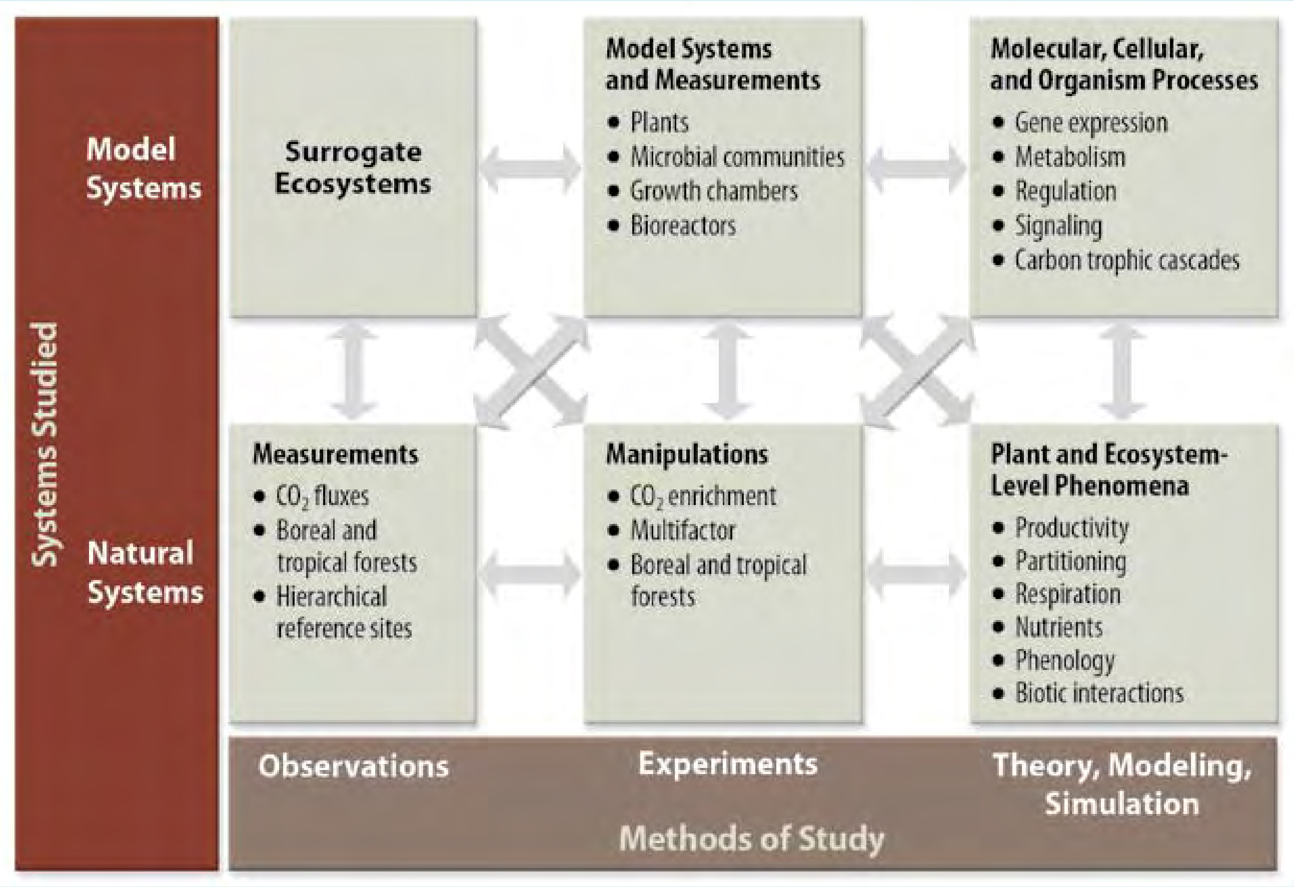
Understanding the Response of Ecosystems and the Global Carbon Cycle to Climate Change: An Integrated Research Approach



- **Using Theory, Modeling, and Simulation (TMS).** The TMS process requires use of data-assimilation techniques to combine (1) varied types and levels of information on natural and model systems, (2) response functions from climate change experiments, and (3) measurements from observatory sites. As descriptive, predictive, and heuristic tools, TMS techniques can explore critical scenarios and variables to provide insight for research strategies, test the adequacy of scientific understanding and models, and develop hypotheses. Theory, Modeling, and Simulation also can create a virtual accelerator of global change to support modeled simulations exploring possible implications of altered carbon management or biosequestration strategies under future climate change. To reflect potential impacts accurately, climate modeling requires that coupled component models be transparently integrated across scales and processes.

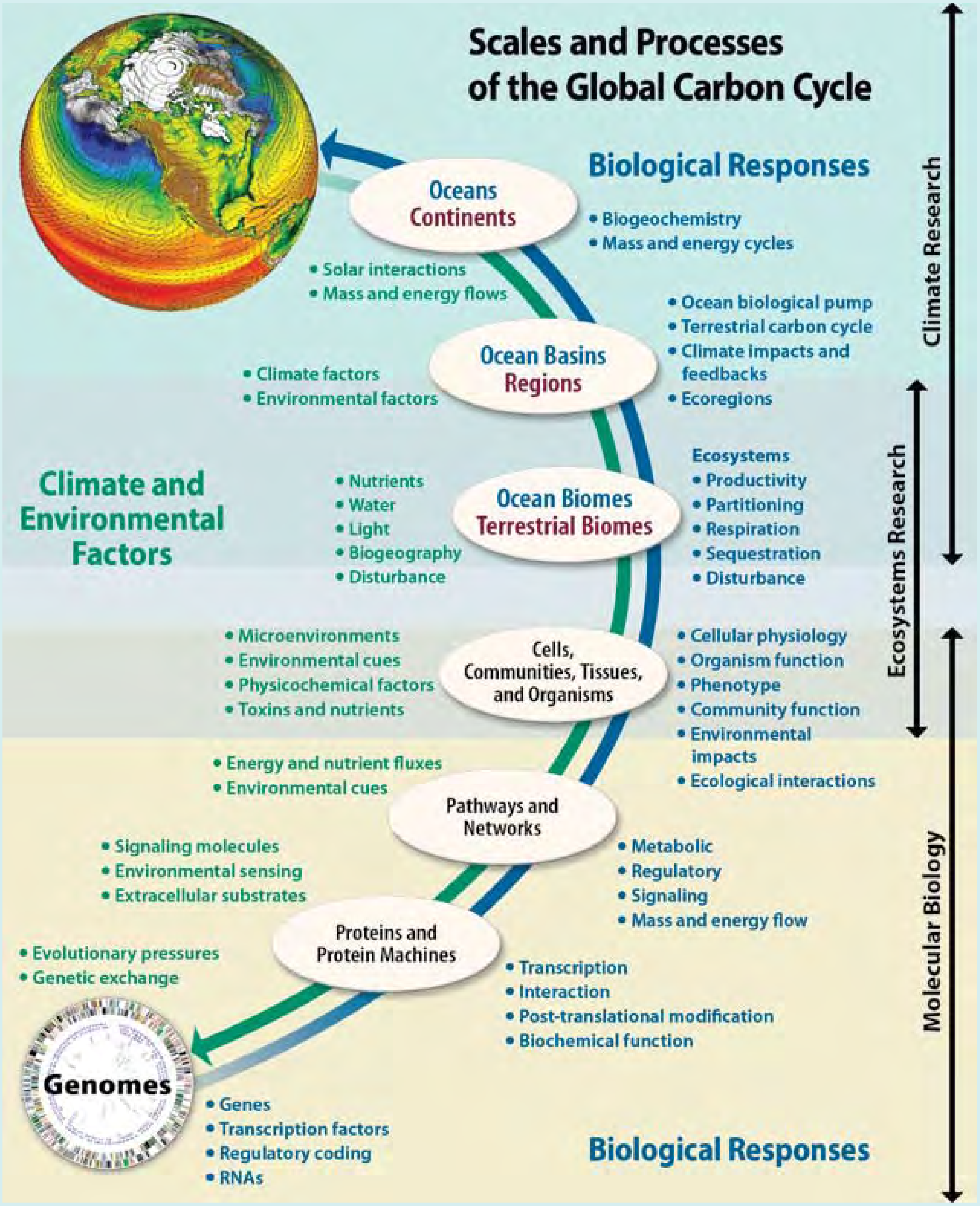


Fig. 2.1. Scales and Processes of the Global Carbon Cycle. The global carbon cycle is determined by the interactions of climate, the environment, and Earth's living systems at many levels, from global to molecular. Relating processes, phenomena, and properties across spatial and temporal scales is critical for deriving a predictive mechanistic understanding of the global carbon cycle to support more precise projections of climate change and its impacts. The domains of climate, ecosystem, and molecular biology research each has a limited reach in scales, constrained by the complexity of these systems and limitations in empirical and modeling capabilities. While linking comprehensively from genomes to global phenomena is intractable, many connections at intermediate scales are viable with integrated application of new systems biology approaches and powerful analytical and modeling techniques at the physiological and ecosystem levels. Biological responses (blue) are to the right of the systems ovals, and climate and environmental factors (green) are to the left of the systems ovals. [Note: Globe portion of figure courtesy of Gary Strand, National Center for Atmospheric Research, with funding from the National Science Foundation and the Department of Energy.]

Opportunities from Genomics and Systems Biology

Carbon cycling research and understanding can be greatly advanced by capitalizing on new and emerging insights from genomic and systems biology studies. Genome sequencing has ushered in a new generation of high-throughput or "omics" methods (e.g., transcriptomics, proteomics, and metabolomics) enabling systematic investigation of comprehensive networks of genes, proteins, and metabolites within cells. This systems biology approach—through modeling and simulation coupled with experiment and theory—aims to define organizing principles, emergent properties, and the resulting detailed organization that control the functions of organisms. Ecosystems carry out common, core functions and likely have a common set of principles and concepts encoded in their collective genomes. Even though specific functions vary from one system to another, the common fundamental principles allow the accumulated knowledge of regulatory, physiological, and metabolic functions developed for one biological system to accelerate knowledge discovery for other systems. Systems biology capabilities enable scaling to higher levels of biological organization, such as multispecies consortia, multicellular organisms, and even complex biological communities. Genomics and systems biology are hallmarks of DOE's Genomics:GTL program, whose ultimate scientific goal is achieving "a predictive, systems-level understanding of microbes, plants, and biological communities."

Box 2.1

Metagenomics: Extending Genomics to Natural Systems

Historically, biology has been confined to the study of individual organisms. New technologies such as metagenomics, metatranscriptomics, and metaproteomics offer a window into the metabolisms and lifestyles of vastly diverse microbes, including uncultivated organisms from environmental samples. Developing and pursuing metagenomic (or other "omic") research techniques not only will help capture the functional potential encoded in genomes, but also will enable new approaches for qualitative and quantitative measurements of active metabolic processes in the environment that then can be applied to mechanistic and predictive models.

Linking genomic-based information to function requires both genome-scale data generation and systems biology tool development. Extending genomic understanding from model to nonmodel systems will be critical for identifying potentially useful organismal functions previously eluding study (for example, see Box 2.1, Metagenomics: Extending Genomics to Natural Systems, this page). Such efforts should be guided by larger-scale coupled models to acquire specific classes of data needed to populate component models. This data specificity, as opposed to indiscriminate accumulation of large volumes of information, will increase models' predictive capability and drive development of new theory.

Emphasis must be placed on developing and using genomic and systems biology approaches to model, for example, the regulatory networks controlling carbon processing (e.g., from assimilation by phototrophs to decomposition of organic matter by heterotrophs). Mechanistic (versus phenomenological) representations of such networks are critical for extrapolating ecosystems' properties and behaviors to a wide range of variables ideal for climate-simulation scenarios but historically outside the scope of observations. These representations are now tractable with the advent of genomic technologies that can supply a sufficient volume of information at many levels of organization and can couple that data with, for example, isotopic techniques that trace carbon flow through ecosystems.

The entire progression of data processing—from genome sequencing to determination of biogeochemical function—may be viewed as a unified (or potentially unifiable) information-sciences challenge. New instrumentation and methods for both biology and geochemistry, coupled with various visualization tools, are excellent catalysts for discovery and communication across disciplines and at multiple scales. The visualization aspect of data analysis is underappreciated but can be an important impetus for cutting-edge research. Furthermore, applying new tools and methods can improve the use of models to assimilate data, test understanding, and serve as heuristic and predictive tools.

Models: Predicting Carbon Cycle Behavior on Multiple Levels

A numerical model is a mathematical representation used in computer simulations to calculate the evolving state of dynamic, real-world systems. Models and simulations enable scientists to study complex phenomena difficult or impossible to examine under natural or laboratory conditions. Researchers also use models to represent and test current knowledge of a given system.

Models historically have been developed to address the needs of specialized, individual research communities. Improving the accuracy of climate projections, achieving a predictive understanding of biological carbon cycling, and assessing the feasibility of carbon biosequestration strategies require coordinated, multidisciplinary development of multiscale models and experiments that must inform and relate to one another. Three general scales of modeling—global, ecosystem, and organismal—are important to carbon cycling research. The array of models comprising each category helps expand and refine current knowledge as well as define areas requiring experimentation at multiple scales of biology.

Global Climate Models

Among all scientific computational challenges, global climate modeling is one of the most complex and computer intensive, requiring collective contributions from teams of modelers focused on different parts of the climate system. The most advanced global climate models currently available—Atmosphere Ocean General Circulation Models (AOGCM)—use mathematics and high-performance computing to couple component models for atmosphere, ocean, land, and ice. Extraordinarily sophisticated, AOGCMs incorporate phenomena ranging from volcanic eruptions' effect on temperature patterns to the impact of shifting sea ice on reflectance of atmospheric sunlight. The behavior of atmosphere, ocean, land, and ice is represented by a system of mathematical algorithms based on parameterized component systems' behaviors and the fundamental laws of physics and chemistry. However, as climate impacts become more pronounced and human presence and activities expand, model complexity must evolve to the next level: Earth System Models (ESM).

Earth System Models

As extensions of general circulation models, ESMs include biogeochemical processes, vegetation changes, and human influences to more completely simulate the multitude of factors influencing climate in all its complexity (see Fig. 2.2a. Terrestrial Ecosystem Parameters Important to Earth System Models, p. 19). Accurately predicting future CO_2 feedbacks and concentrations is a key objective driving development of ESMs. Central to meeting this goal is a detailed understanding of the global carbon cycle, including how its sources and sinks behave and respond to climatic and atmospheric change.

Connecting the Scales of Climate

Applying experimental results and observations across process, spatial, and temporal scales is the primary challenge of global carbon cycle research. Environmental scientists can measure ecosystem functions and phenomena (see Fig. 2.1. Scales and Processes of the Global Carbon Cycle, p. 16) but have difficulty relating results to higher and lower scales and extrapolating behavior outside the range of observations.

Fortunately however, scientific research is addressing these challenges. A new generation of ecosystem-level analyses and emerging genomic information hold promise for improving our mechanistic understanding of and, ultimately, ability to scale important carbon cycle and climate change processes. Key crosscutting areas of interest are new multifactor ecosystem manipulations that analyze climate change effects on carbon cycling at the ecosystem level and the potential of genomic data to inform representations of critical biological processes and parameters (e.g., mechanisms, rate constants, and submodels of metabolism and regulation). Such genomics-enabled advances are necessary for removing the "black box" of understanding surrounding the biology element of ecosystems. For example, research must fill significant knowledge gaps in the complex processes controlling

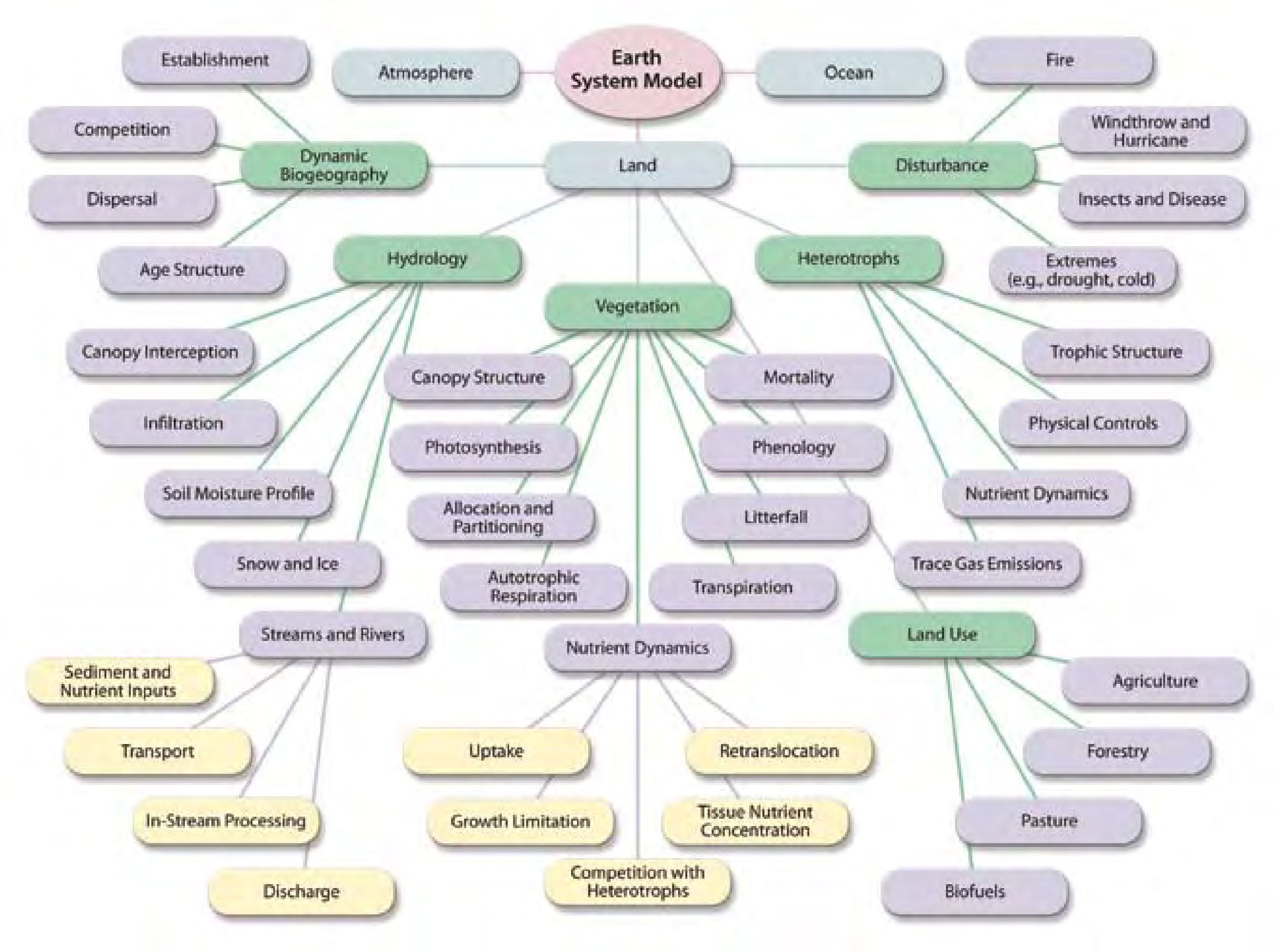


Fig. 2.2a. Terrestrial Ecosystem Parameters Important to Earth System Models.

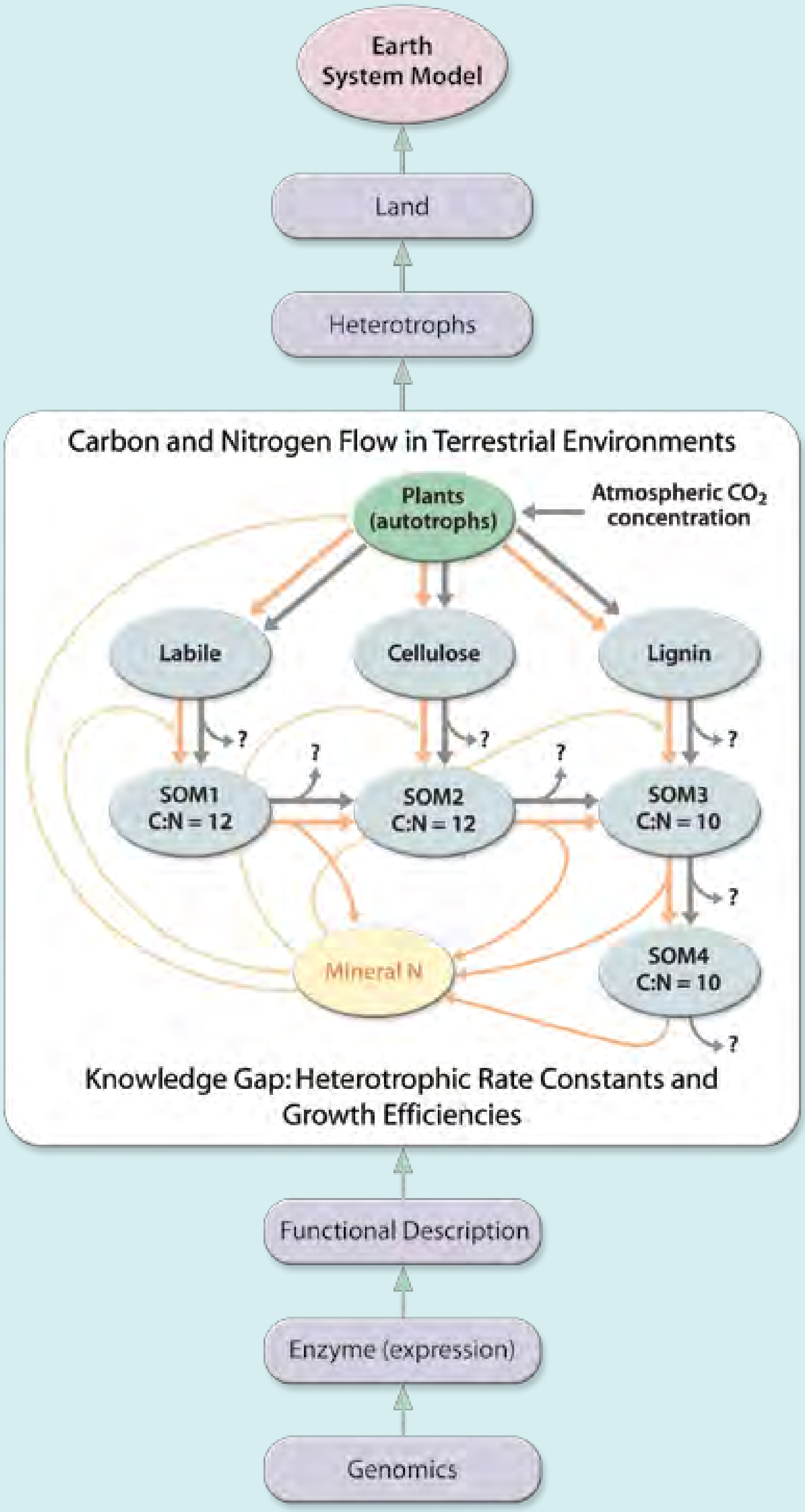


Fig 2.2b. Knowledge Integration and Synthesis.

soil carbon dynamics. Particularly needed are the rate constants and detailed mechanistic knowledge of the processing of plant litter to long-lived soil organic matter by soil mesofauna and heterotrophic microorganisms (see Fig. 2.2b. Knowledge Integration and Synthesis, this page). Current model representations of these processes are highly parameterized using rate constants from radiolabeled (^{14}C) from biomass-decomposition experiments in microcosms that lack mechanistic detail and links to actual environmental conditions.

The dynamic interplay between the functional potential encoded in a biological community's collective metagenome and the physicochemical conditions of the surrounding environment governs molecular processes controlling cellular, organismal, ecosystem, and ultimately global phenomena (i.e., phenotypic traits are the product of genome-environment interactions; phenotype = G × E). However, connecting mechanistic understanding at the molecular level to the physiological changes observed in organisms, ecosystems, and global climate represents a major challenge for these difficult-to-reconcile approaches (see Fig. 2.1. Scales and Processes of the Global Carbon Cycle, p. 16).

As computational capabilities become more powerful, models are able to incorporate greater detail about climate processes, yet including all real-world details is impossible. Thus, approximations—often based on insights from laboratory and field experimentation—or parameters derived from process calculations of more complex components are used to represent processes too small in scale or too complex to be resolved in large-scale models. Many assumptions in current global models about carbon fate in a changing climate may not be valid considering the limited understanding of the biogeochemical cycling of carbon. (For example, see the broad range of modeling parameters in Fig. 2.2a. Terrestrial Ecosystem Parameters Important to Earth System Models, p. 19.) However, larger-scale models can be enriched by more detailed, smaller-scale research to provide hypothesis-driven experiments, measurements, and observations needed to validate and refine assumptions and parameters. For instance, research on the genetic regulation and molecular mechanisms controlling root proliferation could inform root-turnover rates used in terrestrial ecosystem models. Further model refinement will require greater insight into biogeochemical processes, particularly those yielding the largest potential feedbacks—either positive or negative—of atmospheric greenhouse gases. Thus, research strategies targeting these processes and quantifying their feedbacks are high priorities.

Ecosystem Models

Ecosystem models—categorized as either biogeographical or biogeochemical—represent interactions between biotic and abiotic components of a particular environment. Biogeographical models represent how populations in a particular region change over long time scales. Biogeochemical models represent biologically mediated transformations and flows of carbon and other materials within an environment.

Biogeographical Models. One type of biogeographical model is the Dynamic Global Vegetation Model (DGVM), which is used to study how general categories of plant functional types are established and respond to competition, disturbances, and other factors. DGVMs coupled to global climate models play a key role in projecting changes in land surface and terrestrial carbon storage. Improving DGVMs and carbon cycle models requires refining representations of response functions that link alterations in community structure to global change factors at different time scales. For example, rising atmospheric CO_2 concentration, climate warming, altered precipitation, and nitrogen deposition likely will alter the amount of organic matter transferred from plant to litter to soil (see Fig. 2.2b, p. 20). This could lead to concomitant shifts in the balance and structure of plant and microbial communities. Advancing our understanding of these responses and incorporating resultant insight into DGVMs will improve predictions of climate effects on terrestrial carbon flow.

Biogeochemical Models. These models are developed independently for ocean and terrestrial systems, and those produced by global climate–modeling communities are coupled to larger general circulation models (sometimes called global circulation models) for atmosphere and ocean.

Terrestrial biogeochemical models are based on current knowledge of carbon-transfer processes that partition photosynthetically fixed carbon into several pools. However, partitioning among plant parts and soil pools versus plant respiration is poorly understood and thus requires further research for improved model representations. Another limiting factor in biogeochemical modeling is inadequate understanding of nitrogen-climate interactions. Nitrogen availability is a key regulator of CO_2 assimilation, and although more models are incorporating nitrogen processes, insight into how nitrogen availability shifts in response to atmospheric and climate change is very limited and warrants further study. Another need is identifying—as a function of soil depth—more dynamic linkages between root deployment and soil responses, including nutrient and water uptake, decomposition, and biosequestration of carbon and nitrogen. Further progress can be made by expanding information on nitrogen fixation in natural ecosystems under steady state and in response to elevated CO_2, climate change,

Key Research Questions

1. **What is the carbon-handling capacity of global ecosystems, and how will it be affected by climate change and human activities?**
2. **Where and in what form is the carbon in global ecosystems?**
3. **What are the mechanisms at molecular, ecosystem, and global scales by which carbon is cycled into and out of ecosystems?**
4. **How long will carbon reside in various pools, and why?**
5. **What are the potential factors controlling ecosystem carbon flow (e.g., nutrients, soil physics and chemistry, soil microbial processes, temperature, and moisture)? To what extent do such factors influence carbon cycling?**
6. **How are global ocean and terrestrial carbon cycling linked to each other and climate via atmospheric processes?**
7. **What are the atmospheric factors in ecosystem productivity and carbon biosequestration, and how do such factors affect the integrated carbon-nutrient-water cycles?**
8. **How will carbon pools and biosequestration mechanisms respond to the full range of climate change variables, including CO_2, temperature, modified water regimes, nutrients, and radiation?**
9. **What opportunities are available to optimize carbon biosequestration and extend pool lifetimes?**

and disturbances. Equally important is advancing our understanding of how denitrification, leachage, volatilization, and other nitrogen-loss processes respond to elevated CO_2 and climate change. Critical to effective biogeochemical models is incorporation of several key regulatory mechanisms underlying ecosystem response to warming (e.g., adaptation of photosynthesis and respiration and nutrient dynamics). However, most models are incapable of including such information, a limitation that must be overcome for better predictive capabilities.

Oceanic biogeochemical models currently have relatively simple structures. These models may incorporate active cycling of nitrogen, phosphorus, and oxygen and are based on numerous variables such as dissolved oxygen; nutrients, including nitrate and phosphate; detritus particles; and a few general categories of organisms (e.g., phytoplankton and zooplankton). Given a particular scenario for anthropogenic CO_2 emissions, ocean ecosystem models can be used to project changes in surface-water partial pressure of CO_2, planktonic biomass, the concentration of biologically available nitrogen in the water column, or subsurface oxygen concentrations. In many cases, however, these models are based on parameter fitting to empirical data rather than mechanistic modeling and thus are less reliable in predicting dynamic responses to climate change.

Biological Models

Although powerful systems biology approaches have achieved some success in predicting gene regulatory networks that control bacterial response to genetic and environmental perturbations (Bonneau et al. 2007), modeling of cellular systems is still in its infancy. In fact, no comprehensive model of an organism or even a bacterial cell yet exists. Cells and the molecular processes driving life are so complex, building a complete model of even a single cell requires a combination of multiple modeling approaches. Examples of strategies for modeling different cellular processes and networks are (1) metabolic models using differential equations to describe enzymatic reactions and associated reaction rates, (2) gene regulatory network models characterizing gene expression and interactions between transcription factors and the genes they regulate, and (3) signal-transduction models describing information flow in cells via a cascade of chemical transformations in response to a few critical biomolecules. A key challenge for systems biology research is integrating data and information from these diverse cellular processes to create a predictive model for the behavior of whole cells and ultimately larger-scale biological systems.

Summary of Research Requirements for Biological Carbon Cycling and Biosequestration

Several consistent themes have emerged that together frame and set the requirements for the next generation of carbon cycling research. This research must aim to (1) understand and predict the behavior of the global carbon cycle and its interactions with climate, (2) improve climate change projections, and (3) create the foundations of carbon biosequestration strategies. Every element of this approach applies to each of the specific research examples outlined in this report, which integrates molecular biology, ecology, and climate modeling to address the molecular- to global-scale processes directing the carbon cycle. Specific research objectives follow.

- **Apply Diverse Scientific Approaches to Natural and Model Systems, Observations and Experimentation, and Modeling.** Using molecular and genomic approaches to investigate model systems (e.g., experimentally tractable organisms, artificially constructed communities, microcosms, mesocosms, and managed ecosystems) will generate methods and hypotheses that can drive experimentation on natural systems. Such hypotheses also can be used to determine whether model-system results can be translated to other systems. The mechanistic understanding resulting from these experiments will be used to create predictive models—at the process, ecosystem, and climate levels—that will stimulate a new generation of model-driven research. Conversely, direct observation of natural systems can generate hypotheses that can be tested more easily and rigorously in model systems (e.g., individual organisms, low-diversity constructed communities, microcosms, and mesocosms). Taken together, these activities lead to iterative refinements of experimental approaches, models, and theories.
- **Obtain a More Detailed Understanding of Major Carbon Pools.** Elucidating global carbon-carrying capacity and understanding the dynamics and response of the global carbon cycle require research that focuses on the world's major carbon pools and areas of primary productivity. These areas include boreal regions with massive stores of carbon in peat (see Fig. 2.3a. Global Carbon Storage in Vegetation and Fig. 2.3b. Global Carbon Storage in Soils, p. 24), tropical rainforests, and oceans, all of which dominate global primary productivity. Identifying and characterizing major carbon pools for particular regions within the United States can help define national strategies for mitigation and adaptation and could provide insight into global pools.
- **Characterize and Ultimately Predict Biological Response to Climate Change with Genomics and Systems Biology.** Biological structure and function at all scales are determined by the collective genome (or metagenome) of a system and its interactions with the environment. High-throughput, genomic-based tools (e.g., transcriptomics, proteomics, metabolomics, and interactomics) will be used to characterize the functions of biological systems and develop a predictive, mechanistic understanding of various systems across required spatial and temporal scales.
- **Design Experiments Addressing Multiple Climate Factors.** Research has demonstrated that the effects of multiple climate factors are not always additive combinations of the same factors taken individually but are nonlinear, complex results of shifting variables acting in concert. Research on ecosystem response

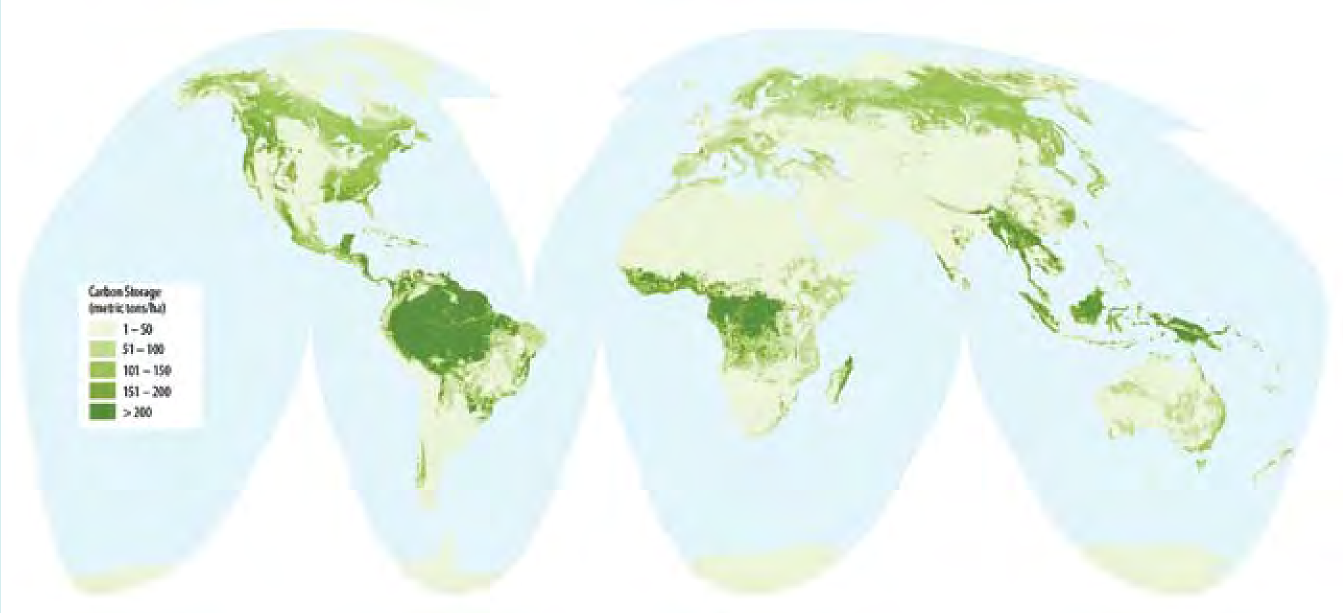


Fig. 2.3a. Global Carbon Storage in Vegetation. Estimates of carbon storage in the world's above- and belowground live vegetation are shown at a 10-km resolution. This live vegetation includes woody tissue, leaves, fruits, flowers, and root systems. The greatest carbon stores in live vegetation are observed in tropical and boreal forests. Temperate forests and tropical savannas also store significant quantities of carbon in their vegetation. [Source: World Resources Institute. 2000. EarthTrends: Environmental Information. Available at http://earthtrends.wri.org/text/climate-atmosphere/map-225.html. Washington, D.C.: World Resources Institute.]

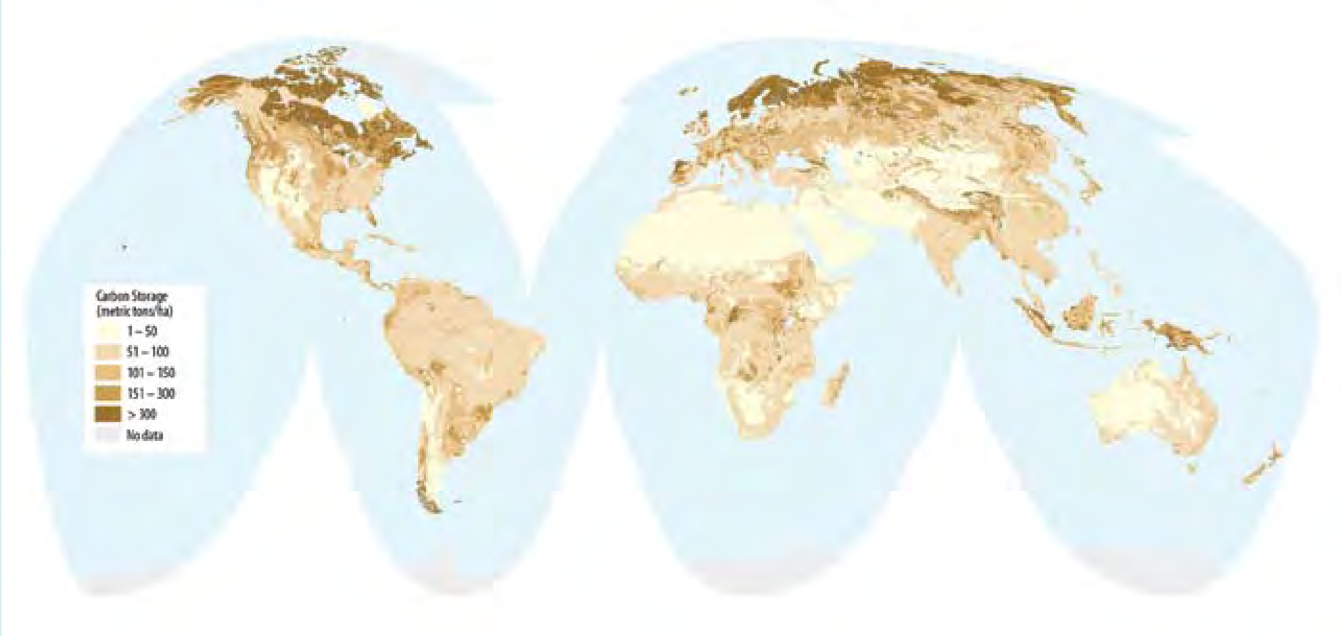


Fig. 2.3b. Global Carbon Storage in Soils. The greatest soil carbon stores are found in high latitudes (e.g., boreal forests and tundra), with other important stores located in tropical forests, tropical savannas, and temperate grasslands. [Source: World Resources Institute. 2000. EarthTrends: Environmental Information. Available at http://earthtrends.wri.org/text/climate-atmosphere/map-226.html. Washington, D.C.: World Resources Institute.]

must therefore employ a balanced scheme of observations and experiments incorporating the full range of climate factors (e.g., CO_2, temperature, precipitation, nutrients, ozone, and cloudiness) critical for predicting scenarios of future climate change.

- **Link Carbon, Nutrient, and Water Cycles.** Carbon cycling cannot be studied in isolation. Photosynthetic productivity and respiration are limited by water and nutrient availability, thus research must integrate carbon, nutrient, and water cycles. For example, the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC 2007) characterized the CO_2-fertilization effect as a negative climate–carbon cycle feedback and regarded this conclusion as robust, even though the studies on which this result was based used coupled climate–carbon cycle models that excluded nutrient cycles. Several studies have suggested that incorporating nutrient cycles can change the magnitude and even sign of this feedback.
- **Address Multiple Scales of Time and Space for Processes Underlying Climate Change.** A major challenge in climate research is integrating information about processes occurring at various spatial scales—from molecular (nanometer scale) to ecosystem (meter to kilometer scale) to global levels. Time scales for these processes extend from picoseconds to centuries. Along with empirical and theoretical methods, modeling and simulation techniques must transparently bridge these vast spans of space and time.
- **Apply Advanced Instrumentation and Methods.** Critical for carbon cycling research are new generations of tools for investigating biological mechanisms and measuring the flux of carbon and other materials at molecular, cellular, organismal, and ecosystem scales. Needed tools include suites of sensors and techniques for field-scale, in situ, and remote-sensing observations as well as those enabling laboratory- and facility-based measurements.
- **Understand the Interactive Genomic, Environmental, and Climatic Influences on Plant Productivity.** The mechanistic bases underlying ecosystem productivity are the consequences of interactions between global genomic potential (biological capabilities) and environmental and climate factors. (Phenotypic traits are the product of genome-by-environment interactions.) Research must elucidate the effects of all such factors on the underlying biological metabolic, regulatory, and physiological processes of plant productivity. For example, greater insight is needed into carbon partitioning, community composition, and how different community members are affected by climate change. A mechanistic understanding of these and other relevant processes is necessary for better representation of them in models. Environmental variables defining agroecosystems and biomes are important to plant productivity, such as soil mineralogy, physiology and chemistry, topography, hydrology, latitude, length of season, and length of day. Significant climate factors include temperature, precipitation, radiation, cloudiness, humidity, CO_2 and other gases, and nutrient inputs. Because interactions between these variables and a community's collective genome can affect productivity profoundly, rigorous investigation is required.
- **Determine the Role of Disturbance in Ecosystem Dynamics.** Ecosystems' carbon-carrying capacity and dynamics are influenced greatly by their disturbance history. Thus, global ecosystem inventories must be calibrated in terms of such histories, and the effects of climate change and human activity on

disturbance frequency and severity must be more precisely understood and predicted (see Box 1.1, Types of Ecosystem Disturbances, p. 10).

Interdisciplinary Projects and Training

Addressing current and future challenges in climate change science requires cross-disciplinary interactions and training as well as integration of modeling and experimentation. Particularly essential is incorporating classical ecosystem science and biology into climate and biogeochemical modeling in a synergistic manner. Solving complex problems in carbon cycling requires interdisciplinary teams focused on a common set of questions and working toward a shared goal (a grand challenge concept). Effective collaboration comprises the appropriate mix of skills and capabilities to facilitate linkage of different disciplines, theory, experiments, and models at various scales. A shared vision of producing more-predictive models should be developed, with specific needs depending on the particular ecosystem aspect under investigation. For example, climate modelers, biogeochemists, soil scientists, microbial ecologists, and molecular biologists and bioinformaticians together could address the problem of connecting climate-modeling needs with soil biology to provide critical kinetic mechanisms and parameters for processing of soil organic matter (see Fig. 2.2b. Knowledge Integration and Synthesis, p. 20).

Systems biology and modeling in general require cooperative, cross-disciplinary efforts performed in close collaboration with experts in, for example, computer science, engineering, statistics, physics, and information visualization. Moreover, collaborations among groups studying various organisms and across multiple scales (from molecules to ecosystems) should enable development of approaches agnostic to the source of the data. Specific workshops and cross-disciplinary projects, programs, and training should be developed to foster interactions among groups using systems approaches. Such opportunities would promote modeling and data integration across platforms and scales, including genomic, organismal, environmental, ecosystem, and climate.