used to compute probabilistic maps of seawater intrusion in Tunisia's Korba aquifer (Figure 1d) by using a Monte Carlo method. The simulations include flow and density-dependent transport processes in a 3-D heterogeneous coastal aquifer [*Kerrou et al.*, 2007]. In this example, grid computing maintains two key advantages over classical distributed computing. First, a very large number of Monte Carlo simulations, numbering at least in the hundreds, can be run in parallel with substantial gains in time and accuracy. Second, the grid analysis can be controlled simply from a Web browser (e.g., http://www.eumedgrid.org) by collaborating scientists located in Europe and northern Africa.

A Vision for the Future

The above examples show that grid computing can fulfill most of the computing requirements of Earth scientists and offers new ways for efficient collaboration. Grids such as EGEE—consisting of clusters and farms of CPUs—cannot handle massive computations requiring parallel computing, shared memory, and intense communication between the processors. Other grids, such as TeraGrid (http://www.teragrid.org), can fulfill these needs.

Grid computing permits the sharing of resources between institutions and for scaling up the computing power and storage capacity in a way that is impossible for a single institution. Also, grid computing offers a transparent collaborative platform for users, allowing them to access more resources at a given time. This is especially important for the exploitation of large data sets scattered in several locations; for running large statistical jobs; and for sharing data and algorithms, without the need for conversion, among large numbers of partners.

Grid computing is currently available and can meet most of the technical requirements for the Earth sciences. Although some technical gaps still exist, grid developers are aware of them and are working to meet Earth science needs in the next generation of grid development. Significantly more effort will be required before transparent grid usage will be widespread in the Earth sciences. The vision is that the grid infrastructure must provide, within the next 5 years, a dedicated platform for sharing knowledge, algorithms, data, and services over a wide range of time and spatial scales. Such a platform will help provide efficient and timely answers to many fundamental challenges facing mankind.

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References

Foster, I., and C. Kesselman (Eds.) (1998), *The Grid: Blueprint for a New Computing Infrastructure*, 677 pp., Morgan Kaufmann, San Francisco, Calif.

Iapaolo, M., et al. (2007), GOME ozone profiles retrieved by neural network techniques: A global validation with lidar measurements, *J. Quant. Spectrosc. Radiat. Transfer*, *107*, 105–119.

Kerrou, J., G. Lecca, F. Murgia, and P. Renard (2007), Grid-enabled simulation of the impact of exploitation uncertainty on the seawater intrusion of the Korba aquifer (Tunisia), in *IST-Africa 2007 Conference Proceedings*, edited by P. Cunningham and M. Cunningham, Int. Inf. Manage. Corp., Dublin.

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The Hills Are Alive: Earth Science in a Controlled Environment

PAGE 120

The structure of Earth's critical zone, which is the interface between the solid Earth and its fluid envelopes and involves the coevolution of biota, soils, and landforms, is governed by processes important to hydrology, geology, biology, and atmospheric science [*National Research Council*, 2001] (Figure 1). Earth surface scientists have long recognized that temperature, chemical, and gravitational gradients drive energy and water fluxes, thus controlling systems evolution, but understanding the critical zone has been tackled primarily from disciplinary perspectives [*Brantley et al.*, 2006]. Interdisciplinary research is needed, and many such efforts, such as the U.S. National Science Foundation's recent watershed-scale Critical Zone Observatories and the National Ecological Observatory Network, are in formative stages. By and large, these facilities focus on utilizing land surface complexity to elucidate process knowledge. Unfortunately, incorporating such complexity occurs at the expense of the control that characterizes true experimentation.

At the University of Arizona, a science program is being built to bridge the gap between laboratory- and field-scale studies by utilizing the unique infrastructure of the Biosphere 2 project. Biosphere 2 is a large-scale Earth science facility near Tucson that encompasses about 3.15 acres of land and houses five natural biomes. Sealed off to the outside world, Biosphere 2 allows scientists to exert precise climate and mass balance control at large scales [*Osmond et al.*, 2004]. The facility's name stems from the Earth's biosphere (biosphere 1); the goal of Biosphere 2 is to be a microcosm of the interaction between life and landscape seen on Earth, such that critical zone interactions can be studied at large spatial scales.

To facilitate this study, scientists from the University of Arizona will construct experimental landscape units—hillslopes—within Biosphere 2. They will also build corresponding system models that couple critical zone hydrology, geochemistry, geomorphology, and biology. This program and facility provide a new opportunity to advance understanding of critical zone processes through controlled large-scale experimentation.

Experimental Design

Scientists working on this project are specifically pursuing an interdisciplinary approach to experimental design through cultivating a collaborative group that includes representation from hydrology, geomorphology, soil geochemistry, atmospheric science, ecology, and genomics. Several planning workshops have already occurred (some of which were jointly supported by the Hydrological Synthesis Center; http://cwaces.geog.uiuc.edu/synthesis/index.html), and others are scheduled for the near future (http://www.b2science.org/earth-hillslope.html). A key focus to date has been on understanding spatial variability, temporal dynamics, and interactions (including abiotic-biotic couplings) within hillslopes using modeling assessments.

Three 33-meter × 18-meter environmentally controlled bays will be available to scientists who would like to propose projects for experimentation. The long-term goal is to improve our understanding of the processes that lead to surface and subsurface structure of the critical zone. Workshops have guided design parameters, such as hillslope geometry (slope angle, planar or complex shape), soil composition (mineral assemblage and texture), vegetation type (herbaceous, woody plants), and key details of climate forcing. Focused numerical modeling was also used to inform decision making on design parameters. For example, groups from the University of Arizona; Oregon State University; University of Québec; University of Illinois at Urbana-Champaign; University of California, Riverside; and University of Michigan worked together to investigate hydrological partitioning and chemical weathering rates for different mineral assemblages, surface areas, hillslope configurations, and climate regimes. Hydrological models were used to estimate subsurface saturation and water residence time as a function of soil and geometry.

To relate the project to other existing research infrastructure, scientists sought a design that offered the greatest spatial and temporal soil moisture variability in a climate that contains wet-dry transitions in both warm and cool seasons. These criteria were met with a loamy sand soil distributed within a basin shape that does not vary with time. This basin will be 30 meters long and 12 meters wide with soil 1.0 meter deep (see Figure S1 in the electronic supplement to this *Eos* issue (http://www.agu.org/eos_elec)). The soil will be constructed from granular basalt with loamy sand hydraulic properties, but with sufficient small (clay) particle fraction to enhance chemical weathering and water-holding capacity. The average bedrock slope will be of the order of 8°–12° to enable subsurface throughflow but minimize overland flow and erosion. Soil erosion modeling indicated that these characteristics also will minimize effects of surface runoff on soil loss and rill formation. Detailed hydrogeochemical modeling predicted that within 3 years of treatment, the basalt parent material will develop significant changes in subsurface structure, including pore size and particle size distributions that could potentially affect hydrologic flow paths. Accelerated structural evolution is expected following introduction of vascular plants.

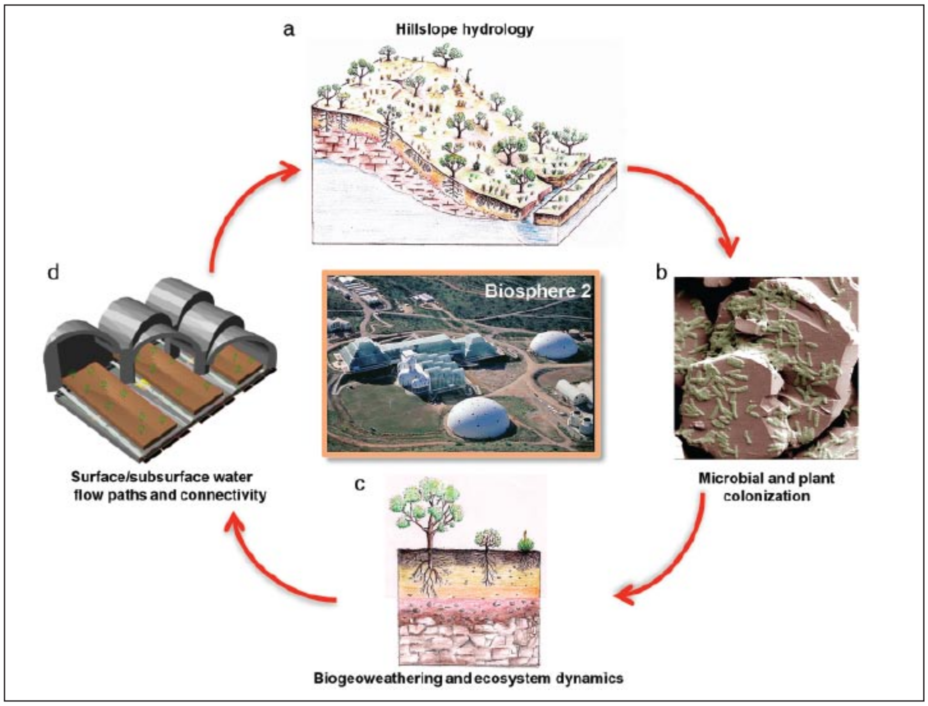

Fig. 1. Interactions and feedbacks among critical zone processes leading to structural evolution. The controlled "hillslope" experiments planned at Biosphere 2 intend to improve scientific understanding of the coevolution of landscapes and ecosystems, the integrated mechanisms of land-atmosphere-hydrosphere exchange, and the role of vegetation in catchment hydrologic response. The evolution of landscape structure includes coupled processes at different scales: (a) Hydrologic partitioning at the hillslope scale is affected by bedrock type and slope, soil type and profile, topographic convergence, vegetation, and surface-subsurface water interactions. (b) Microbial and plant colonization leads to spatial differences in carbon and nitrogen fixation, biomass decay, mineral weathering, and the creation of hot spots and hot moments of more active interactions. (c) Biogeoweathering and ecosystem dynamics results in redistribution of carbon pools and fluxes, net ecosystem exchange, and soil formation by combined action of acids, water, rock, and biota. (d) Surface and subsurface water flow paths change, and new connectivity structures emerge with feedbacks to Figures 1a–1c that can be studied within the constructed hillslopes of Biosphere 2. Micrograph courtesy of A. Dohnalkova, Pacific Northwest National Laboratory.

Toward a Greater Understanding of the Critical Zone

A main goal of the experiments conducted on these hills will be to address effectively the topics that integrate physical and biological processes. These include (1) understanding how the environment in general and the water cycle in particular affect assembly of biological communities; (2) determining whether simple versus diverse communities arise as a consequence of differing climate regimes; and (3) assessing if different communities affect ecosystem function (e.g., the cycling of water through ecosystems) differently. A classic example of these problems in ecosystem ecology is the "two-layer" vegetation community in which shallow-rooted herbaceous plants stably coexist with more deeply rooted woody plants. By accessing different resource pools, this functionally diverse community is both ecologically robust and hydrologically important, using the water resource much more effectively than the simpler single-layer community.

Coupled-system modeling will help scientists refine the experimental and instrumental design and generate cross-disciplinary hypotheses that can be tested in the experiment. Modeling can be used to infer aspects of the system that are difficult to measure by mass and energy balance, and will be critical to improving the accuracy of forecasts of landscape change in the real world. It will be used in the experiment as part of a "learning cycle" approach in which models are used to predict system response before the experiment is run, and then the subsequent experiments on a specific topic will be used to improve the model accuracy. Developing a process-based, coupled-system model is a formidable task. The approach will be to use existing models to the greatest extent possible and focus on model coupling (e.g., Common Component Architecture; http://www.cca-forum.org/).

While key elements of the design are emerging, several factors require additional consideration and development for which program scientists are seeking input from the research community. An issue important to experimental design relates to the trade-offs between replication and treatment. Three identical hillslopes offer opportunities to increase statistical significance through replication. Conversely, the experiment may be limited in its power to elucidate how biology controls hydrological partitioning and subsurface structure if it does not allow for separate treatments in each bay (e.g., nonvascular, herbaceous, woody plants). Specifically, the Biosphere 2 researchers are soliciting comments on the extent to which the experimental facilities should be prioritized for replication of the same treatments to enable stronger inference or prioritized to maximize different treatments to provide a wider range of responses. Feedback on the overall design or on the replication versus treatment issue can be sent to the authors.

References

Brantley, S. L., et al (2006), Frontiers in exploration of the critical zone: An NSF sponsored workshop, report, 30 pp., Natl. Sci. Found., Arlington, Va.

National Research Council (2001), *Basic Research Opportunities in Earth Sciences*, Natl. Acad. Press, Washington, D. C.

Osmond, B., et al. (2004), Changing the way we think about global change research: Scaling up in experimental ecosystem science, *Global Change Biol.*, *10*, 393–407.

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