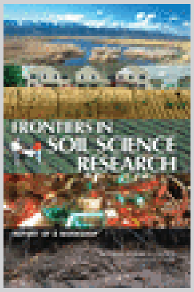

Frontiers in Soil Science Research: Report of a Workshop

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Steering Committee for Frontiers in Soil Science Research; National Research Council

FRONTIERS IN SOIL SCIENCE RESEARCH

REPORT OF A WORKSHOP

Steering Committee for Frontiers in Soil Science Research

Board on International Scientific Organizations

Policy and Global Affairs

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Preface and Acknowledgments

As stated in *Science*, "Soils are the most complicated biomaterials on the planet" (Young and Crawford, 2004[1]). Soils provide support for both natural and human systems. A challenge for soil science is the need for interdisciplinary research involving classical soil science subdisciplines, namely, soil chemistry, soil physics, soil biology, soil mineralogy, and pedology. While basic research provides an understanding of fundamental soil processes, increasing trends in land transformations, environmental challenges, and policy issues require interdisciplinary approaches. To successfully address major research needs, soil scientists must collaborate with each other and with scientists in related disciplines.

In December 2005 the National Academies convened a workshop, Frontiers in Soil Science Research, of experts in soil science and associated disciplines to identify emerging research opportunities and expected advances in soil science, particularly in the integration of biological, geological, chemical, and information technology sciences. The three objectives of the workshop were to

1. identify research priorities and potential breakthroughs within soil science;
2. identify interdisciplinary and cross-disciplinary research opportu-

[1]Young, I. M., and Crawford, J.W. 2004. Interactions and self-organisation in the soil-microbe complex. *Science* 304:1634-1637.

nities in which soil science is involved, particularly in the field of biogeoscience; and

3. identify technological and computational needs to advance soil science.

More than 120 people attended the workshop, with attendees from all around the United States as well as from countries such as New Zealand, the Netherlands, Canada, Italy, Philippines, Germany, and the United Kingdom. The attendees came from several fields, including not only academia but also government and industry. The workshop agenda is included as Appendix A of this report. Funding for this workshop came from the National Science Foundation, the Department of Energy, the U.S. Department of Agriculture–Agricultural Research Service, and the Soil Science Society of America.

The committee would like to thank the speakers and discussants who gave enlightening presentations and comments, providing a basis for the plenary discussions and breakout groups held during the workshop. The speakers and discussants are listed in Appendix B of this report.

One of the exciting aspects of the workshop was the inclusion of a select few graduate students, who not only served as rapporteurs of the breakout sessions but also presented posters of their own research on the second evening of the workshop. Those graduate students, with their affiliations at the time of the workshop, were as follows:

Amy Brock, University of Nevada, Las Vegas
Daniel Clune, Cornell University
Josh Heitman, Iowa State University
DeAnn Ricks Presley, Kansas State University
Matt Ruark, Purdue University

As chair, I would also like to thank the members of the workshop steering committee (listed in Appendix C) and the National Research Council staff who organized the workshop and assisted with the writing of this summary: P. Kofi Kpikpitse, Lois Peterson, and Mariza Silva. We would also like to express thanks to Ester Sztein for her assistance in the completion of this report.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee.

The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this report: Sally Brown, University of Washington; Martin Carter, Agriculture and Agri-Food Canada; Oliver Chadwick, University of California, Santa Barbara; Jon Chorover, University of Arizona; Brent Clothier, Horticultural and Food Research Institute, New Zealand; and Wayne Hudnall, Texas Tech University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the report, nor did they see the final draft before its release. Responsibility for the final content of this report rests entirely with the authors and the institution.

Charles W. Rice
Chair, Steering Committee for
Frontiers in Soil Science Research

Contents

1

Introduction

Soil is a biogeochemically dynamic natural resource that supports all critical components that comprise terrestrial ecosystems. It has been called Earth's living skin. On its June 11, 2004, cover, *Science* declared soils to be "the final frontier." The growing awareness that soil provides a variety of ecosystem services beyond food production has attracted interest in soil from nonsoil scientists. Collectively, soil is known as the pedosphere, and the processes occurring within soil are inextricably linked to ecosystem services such as water quantity and quality, are important in the exchange of atmospheric gases, and are central to the biogeochemical cycles of the nutrients and carbon that sustain life (see Figure 1-1). Soil supports the richest biodiversity on Earth and functions as a filter for, and a buffer of, inorganic and organic contaminants as well as pathogenic microorganisms and viruses. Despite the link between the quality of the soil resource and the rise and fall of world civilizations that has been repeated throughout history, soil remains an undervalued and underappreciated resource.

There has been renewed interest in soil and soil science in recent years as the recognition that biogeochemical processes that occur at the Earth's surface influence global climate change, land degradation and remediation, the fate and transport of nutrients and contaminants, soil and water conservation, soil and water quality, food sufficiency and safety, global carrying capacity, wetlands function, and many other issues pertinent to the stewardship and conservation of land and water resources (special issue of *Science*, 2004). Population pressure and associated changes in land use

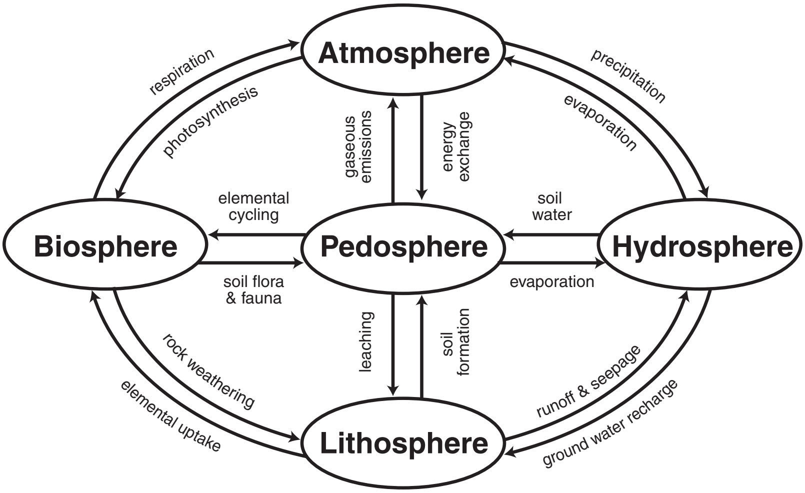

FIGURE 1-1 Interactive processes linking pedosphere with atmosphere, biosphere, hydrosphere, and lithosphere.
SOURCE: Lal, Kimble, and Follett, 1997, 4. Reproduced with permission of Taylor & Francis Group LLC.

place an increasingly high burden on the global soil resource. In some areas of the Earth we have approached irreversible soil conditions that threaten the existence of future generations. Understanding the long-term implications of decreased soil quality and addressing the aforementioned challenges will require new information based on advances and breakthroughs in soil science research that need to be effectively communicated to stakeholders, policy makers, and the general public.

Soil science is an intrinsically interdisciplinary science that integrates knowledge of physical, chemical, and biological processes that interact across a large range of spatial and temporal scales. Soil scientists employ a multiscale approach—from the molecular to the landscape levels—to address issues related to biogeochemical reactions and processes in the environment, land use and degradation, regional and global climate change, food security, and water quality. There have been several National Research Council studies that identify areas in which opportunities for basic research in soil science are especially compelling. A report on the bioavailability of contaminants in soils and sediments noted the need for further research on how physical, chemical, and biological processes in soil influence the bioavailability of chemicals (National Research Council, 2003). The report also noted the uncertainty related to variations in soil at various spatial scales, something that was discussed at this workshop. A Board on Agriculture report described the inherent link between soil and water quality, noting that soil productivity is not the only reason to protect soil resources (National Research Council, 1993). This report stated the need for research leading to the development of new technologies that protect soil and water quality. A report on metagenomics noted that this new science will draw on expertise from several disciplines, including soil science (National Research Council, 2007).

Another report discussed the integrative studies of the "Critical Zone," which encompasses the soil, rock, air, water, and ice at the Earth's surface (National Research Council, 2001). The soil, or pedosphere, is *the* interface among the other components of the Critical Zone—the biosphere, hydrosphere, atmosphere, cryosphere, and lithosphere. As such, it is a major determinant of the global water, carbon, and geochemical cycles. Since soil represents a natural body covering essentially the entire nonaqueous surface of planet Earth, it is intimately involved in absorption, storage, transfer, and release of heat, water, gases, and chemical constituents; serves as a reservoir for biological and microbial diversity; and, as such, has a profound influence on all living organisms.

A report emanating from a National Science Foundation-sponsored workshop on the Critical Zone (Brantley et al., 2006) reiterated the importance of applying fundamental knowledge of soils to understanding the complex coupled hydrobiogeochemical processes occurring in the Critical Zone. Because of the central role of the pedosphere, it is clear that progress in understanding key processes in the Critical Zone is predicated on breakthroughs in soil science research. An understanding of critical soil processes and the ability to measure them is also central to other emerging research initiatives, such as the National Ecological Observatory Network. Soil science is at a critical threshold in identifying new areas for research. Emerging topics—such as climate change, carbon sequestration, water quality, vadose zone transport of nutrients and contaminants, biofuels, and food security—need strategic research on soil processes. New and emerging technologies and sensors are providing unprecedented opportunities for revolutionary advances and breakthroughs in fundamental soil science research. These opportunities enhance problem-solving abilities and integrate knowledge from associated disciplines (i.e., microbiology, hydrology, ecology, environmental science, geochemistry, geology, atmospheric sciences) to further unravel the mystery of soils and soil processes. As was noted in *Science*, "Interest in soil is booming, spurred in part by technical advances of the past decade" (Sugden, Stone, and Ash, 2004, 1613).

On December 12-14, 2005, the National Academies convened the Frontiers in Soil Science Research Workshop to identify emerging areas for research in soil science by addressing the interaction of soil science subdisciplines, collaborative research with other disciplines, and the use of new technologies in research. The organizing committee for the workshop identified seven key questions that addressed research frontiers for the individual soil science disciplines, but also addressed the need for integration across soil science and with other disciplines.

The seven questions addressed by the speakers and discussants were as follows:

1. How well do we understand the physical, chemical, and biological processes in soils that impact the atmosphere, vegetation, and the hydrogeosphere?
2. What are the chemical interactions at the molecular level that define the fate of ions, chemicals, and microbes as they are transported through soil systems?
3. What controls biodiversity belowground? How does this biodiversity affect the function of the soil system?
4. What is the effect of in situ soil architecture on soil physical, chemical, and biological processes? How does it vary from one soil system to another? What are the controlling factors?
5. How does landscape architecture (topography, vegetation, land use) affect the upscaling of soil processes to a regional level?
6. What are the new tools for making in situ and laboratory measurements of soil biological and physicochemical properties and processes?
7. From a systems analysis standpoint, what are the key indicators for detecting the resilience and stability of the soil system? What are the critical factors that control its resilience and stability?

The committee then proceeded to identify potential speakers and discussants for each of these seven questions, which addressed chemical, biological, and physical processes, and their interactions. In choosing speakers and discussants, the committee looked for individuals who would be able to address the questions from both a disciplinary and an interdisciplinary viewpoint. A particular strength of the workshop, as described by many attendees, was that the presentations cut across and integrated traditional subdisciplinary areas of soil science. The organizing committee purposely selected speakers for their abilities to cut across these lines and examine coupled hydrobiogeochemical processes. The workshop was not designed to identify specific issues within a subdiscipline.

As part of the overall goal of the workshop to identify frontiers in soil science research, speakers, discussants, and attendees (the workshop was open to all interested individuals) were asked to consider overarching issues:

- Main challenges and priorities within basic soil science research
- Opportunities for inter- and cross-disciplinary research
- Technological and computational opportunities to advance soil science research
- Student and early career training issues

At first glance, it may appear that the workshop did not explore particularly "new frontiers" in soil science research. However, several attendees at the workshop commented that they were learning new ways to approach their own research. In many cases, the "frontier" may not be a specific technology or technique new to the field, but expanded use of existing technologies (i.e., tracers, spectroscopy, "omics") within the soil science community. Many readers may find a new approach or technique with which they are not familiar or which they have yet to explore themselves.

Although the original intent had been to also address the role of federal funding for research in soil science, the committee decided to not specifically address funding issues to avoid discussion that would devolve into a plea for more funding from sponsors present at the workshop. However, there were discussions during the workshop that identified a lack of an effective primary sponsor or steward of the soil science discipline and how this is problematic for maintaining strength in the discipline that could be leveraged in the interdisciplinary activities and opportunities in other funding agencies. To many people, including many in the federal funding agencies, soil science is still identified as a part of agricultural science only. Soil science is much more than this, integrating and drawing on many basic sciences as well as addressing societal issues beyond agriculture. Much of the discussion on the value of soil science research described in Chapter 2 arose because of the perceived lack of funding that many attendees believed was caused by a misunderstanding of how soil science research can contribute to other research areas, for example, environmental science, ecosystem services, and climate change science.

The workshop consisted of an opening session with a keynote speaker, seven sessions focusing on the above questions with a presenter and discussants followed by general discussion, five breakout group discussions, and a final plenary discussion. Another key element of the workshop was the involvement of five graduate students who served as breakout rapporteurs and also presented posters on their own research. More than 120 people from various disciplines and from around the world attended the workshop. The president of the National Academy of Sciences, Ralph Cicerone, welcomed the participants, noting the complexity of soils and the challenges facing soil science research. He noted that soil science was important to atmospheric scientists and other Earth scientists. This volume is a summary of the presentations and discussions at the workshop.

The second chapter of this report addresses the need to place an economic value on soil science research. Although this was not one of the specific questions asked by the steering committee, it became clear during the workshop that this was a critical element to obtaining funding for soil science research, as noted above. The third chapter is a synopsis of the presentations, in the order they were made at the workshop. The fourth chapter details the research frontiers discussed at the workshop in the following categories: (1) Overarching Challenges, (2) Research Needs and Opportunities (divided into six subcategories), (3) Tools, Techniques, and Current Opportunities, (4) Interdisciplinary Collaborations and Emerging Research Opportunities, and (5) Student and Training Issues. The report concludes with a brief epilogue, followed by three appendixes: the workshop agenda, brief biographies of the speakers, and brief biographies of the steering committee.

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2

Placing a Value on Soil Science Research

An underlying starting point for discussion of the directions that soil science research should take is the need to place a value on soil and its contribution to ecosystem services. Soils play an important role in ecosystem services and environmental quality, but in comparison to water and air, they receive neither the same attention nor funding. More is known about water and air where effects of certain actions are directly visible, but relatively little is known about soil, where the actions may be invisible to the layman's eye and in which processes occur at a much slower rate. The need for funding for soil science research was mentioned throughout the workshop in both plenary discussions and breakout periods. Brent Clothier, HortResearch, New Zealand, in his opening presentation, gave workshop participants an example from New Zealand of how soil science researchers might work with those for whom the research is intended (the end users) to define the research that is needed and thereby secure funding for research of important aspects of both basic and applied soil science.

Clothier described how the New Zealand soil science research community regrouped after almost disappearing in 2003 to become a sustained research program funded by the central government. The media called for support of soil science, noting that research into soil was one of the most productive uses of science for the country and that constant requirements for fertilizer and soil erosion were reasons enough to continue research for improving soil quality and stability. The soil science community responded by identifying the "why" and the "for whom" the research is being conducted, and in turn identifying "what" research needed to be done. Clothier defined four steps to a healthy research climate in New Zealand:

1. Participation–identifying end users and clarifying their needs and expectations
2. Policy–developing a framework for delivering research and development needed to meet those expectations
3. Purchase–an institutional framework for investing in that research
4. Progress–the enhanced development of soil science research in New Zealand

How do we apply the lessons learned in New Zealand to a broader approach for expanding the frontiers of soil science research?

One aspect that was drawn out by workshop participants during the discussion that followed Clothier's presentation was the importance of placing economic and environmental values on the soils' natural capital stocks and the ecosystem services associated with soils. The imperatives are to ensure that the inventory value of the soils' stocks does not decline, and that their ecosystem services are sustained. Our ultimate goal is sustainable development that encompasses not only environmental concerns but also economic and social concerns. Indeed, Clothier noted that New Zealand has seen new land uses develop in the last 20 years, even as agricultural productivity has increased. Greater emphasis has focused on the need to address the impact of land use on managed ecosystems—both agricultural and nonagricultural. Clothier mentioned the greater appreciation in New Zealand for the value of ecosystem services such as maintenance and regeneration of habitat, provision of shade and shelter, pest control, maintenance of soil health, maintenance of healthy waterways, water filtration by soil and control of soil erosion, sustaining the productive capacity of soil, regulation of greenhouse gas emissions, and moderation of climate change. The role of soil and soil function in these ecosystem services is beginning to be recognized, and new knowledge is needed to support these services.

The value of soil as an ecosystem service was a theme that echoed throughout the workshop. A later speaker, Iain Young, Scottish Informatics, Mathematics, Biology, and Statistics (SIMBIOS) Centre, University of Abertay, Scotland, quoted the following values (in trillions of dollars) of the following ecosystem services: soil 20, clean water 2.3, food 0.8, and genetic resources 0.8 (Boumans et al., 2002). He stated that the total of ecosystem services (approximately 24 trillion pounds sterling) is twice the global gross national product. Kate Scow, University of California, Davis, also noted the need to place a value on soil and the ecosystem services it provides. She stated a need to bring in and engage stakeholders, as well as the need to inspire the public.

Another key point made by Clothier was that the understanding of soil function, that is, the knowledge and understanding of basic soil science processes, is of utmost importance. Clothier noted that it underpinned the other research areas in which their end users and stakeholders were interested. The example he gave was that improvements in our ability to measure and model the flow and transport of water and solutes through soil are required to enable developments in better managing contemporary land use, in the understanding of the resilience of soils under land-use change or global change, as well as in providing measures of the value of the ecosystem services provided by soil as a filter.

Throughout the workshop, many participants identified issues of funding and the undervaluation of soil both as a resource and as a topic of scientific study as problems facing the discipline. The rapporteur's summary of one of the breakout groups, in discussing soil science as part of the public conscience, noted: "Soil science is an undervalued science and soil is an undervalued resource. It is important to raise public awareness of what we do and how soil science can solve regional and world problems." The examples provided by the New Zealand revitalization of soil science can serve as a model. The summary of the breakout group went on to say, "We need to demonstrate the interaction of soil science with socioeconomic problems facing the world. In America, soil is seen as part of agriculture, and as long as we maintain crop yields, there will be little concern. Soil functions beyond crop production need to be related to the public, especially how soil functions in water quality and availability."

This last comment was echoed in Kate Scow's presentation at the end of the workshop. She quoted Tilman et al. (2002) on soil valuation and the lack of information on why soils are important to society beyond agricultural needs. Scow stated that a "fundamental institutional shift [is] required to quantify and derive societal value from remaining natural soils and ecosystems and to provide the scientific basis to argue for their preservation." As a framework for valuing ecosystem goods and services, Scow noted a 2004 National Research Council report on *Valuing Ecosystem Services,* which gives a conceptual framework for understanding, shown in Figure 2-1. This total economic value framework for ecosystem services includes not only value derived from using a service or resource, but also "nonuse" values that may

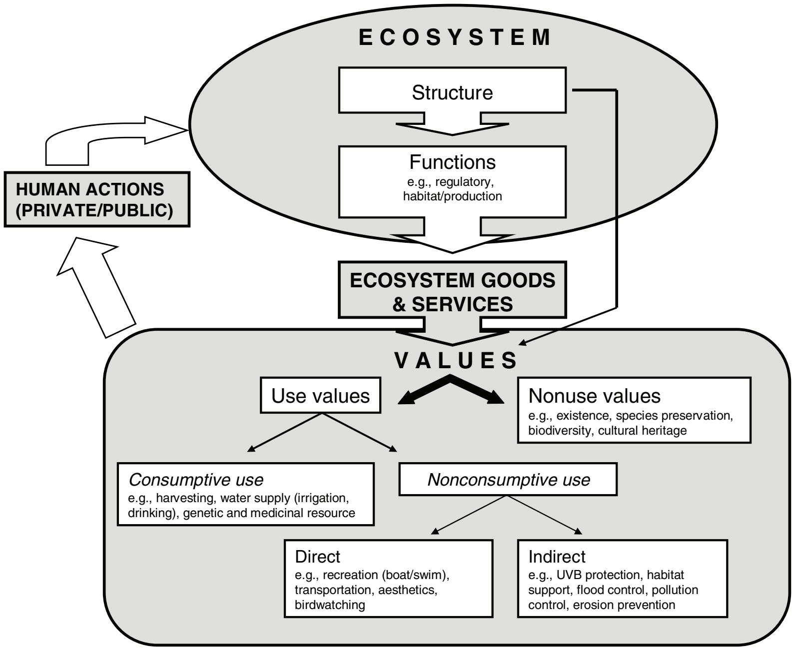

FIGURE 2-1 Connections between ecosystem structure and function, services, policies, and values.
SOURCE: National Research Council, 2004, 241.

be derived from a service's existence. A social value, as well as environmental and economic, determines the value of an ecosystem service. "The fundamental challenge of valuing ecosystem services lies in providing an explicit description and adequate assessment of the links between the structures and functions of natural systems, the benefits (i.e., goods and services) derived by humanity, and their subsequent values" (National Research Council, 2004, 2). Another method of identifying the value of ecosystem services, also mentioned by Scow in her presentation, is the approach adopted by the Millennium Ecosystem Assessment (2005), which is based on function: provisioning, regulating, cultural, and supporting. Scow noted that the soil resource fits into all of these functions.

One of the research gaps in soil science that was noted in the workshop is the understanding of soil functions in relation to these ecosystem services, and how these functions are affected by such factors as degraded conditions, management techniques, and inherent soil properties. New monitoring and measurement methods, as well as dynamic simulation models that reflect real field conditions, are needed to better place a value on soil functions as they relate to ecosystem services.

Perhaps the broader soil science research community can learn from the New Zealand experience. We need to find ways to work with the funding community to raise awareness of the value of the ecosystem services that soils in both managed and natural settings provide, as did the scientific community in New Zealand.

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3

Summary of Presentations

Each of the seven presentations focused on various questions specifically, and also addressed the overarching questions raised at the workshop. Except for Session 6, each session consisted of a presentation of a key speaker followed by two discussants. Session 6 consisted of two speakers. The seven sessions are briefly summarized below. Chapter 4 summarizes the key points that were made during the workshop.

SESSION 1: USING TRACERS TO UNDERSTAND SOIL PROCESSES

Susan Trumbore, University of California, Irvine, discussed the use of transient isotopic tracers on land to quantify and better understand soil processes and how they interact. Soils are a complex of physical, chemical, and biological processes that interact across a range of spatial and temporal scales. It is critical to have tools that quantify and serve as indicators of (1) physical rates, (2) isotopic or elemental "fingerprints," and (3) time involved in the transformations. Trumbore's paper and presentation described the intersection of geochemistry and soil science through the increasing use of isotopes and tracers as tools for separating physical, chemical, and biological processes that operate simultaneously in soils. She noted that tracers are in the "toolbox of soil science," but they are not always used to their maximum advantage.

The tools are available to quantify indicators that address the state factors at work in soil, that is, climate, vegetation, parent material, and time. These state factors interact with human activity to provide quantitative understanding of additional soil responses that can be used to determine the potential long-term impact of soil management decisions (intentional and unintentional) on the soil resource.

Tracers are available from natural and human-made (i.e., from atomic weapons testing) isotopes; however, the number of these tracers is decreasing because of the elapsed time since those tracers were introduced into the atmosphere. The analytical tools exist to use these tracers as reliable measures of the indicators. Some of the reasons that tracers are not more widely used include a lack of understanding in the scientific community of the potential use of tracers to address soil science questions, a perceived expense of isotope measurements, and the need for geochemists familiar with tracer methods to work with soil scientists in defining questions that the use of tracers can answer. Trumbore suggested that a combination of recent methodological advances and framing of critical questions makes this an appropriate time for a more systematic application of a suite of tracers to study problems in soil science.

Trumbore presented three examples of how tracers can be applied to soil science research: (1) use of inert or biologically unreactive tracers to separate physical from biological and chemical processes, (2) the use of time-sensitive tracers to determine the rates of soil processes on several timescales, and (3) the use of isotopic or elemental fingerprints to determine the relative importance of different processes or sources of elements in soil and soil solution. She discussed these in the context of important soil geochemistry research topics.

Tracers can be applied to identify nutrient supply to plants through separation of weathering, recycling, and dust inputs into soil nutrient pools. These applications provide insights into the dynamics of nutrients in different soils. Tracers can also be used to evaluate trace gas emission from soils. Soils serve as sinks and sources of greenhouse gases; however, tracers can serve as indicators of the interacting processes occurring within the soil volume. Quantification of erosion rates, deposition within the landscape, and restoring soil is a complex set of processes. Tracers have been applied to the question of soil restoration, addressing the question of time required for restoration. Tracers have been used as tools to fingerprint sources of soil-derived materials that move from the landscape into nearby water bodies, providing quantification of the source and movement of soil materials for environmental quality assessments.

Although applying tracers to soil science research will require some innovative approaches to develop the appropriate questions and techniques, there are several areas of soil science research that can benefit from the use of tracers. These include (1) the global carbon cycle integrated across multiple timescales and the associated fundamental processes of carbon cycling in soil and (2) separating soil formation and degradation processes across spatial and temporal scales.

Some of the more powerful tracers, such as radiocarbon and cesium-137 that entered the atmosphere upon aboveground weapons testing, are decreasing in atmospheric and soil signals owing to both environmental processes and radiogenic decay. Therefore, there is an urgency for some of these studies to be conducted in the near future.

Janet Herman, University of Virginia, in discussing Trumbore's presentation, noted that scientists could benefit from interdisciplinary interactions and that soil science would benefit by moving from descriptive surveys of soil formation and degradation to more mechanistic-driven studies to elucidate rates of soil formation and degradation. Herman proposed the use of gradients to derive rates of reactions. She noted that the heterogeneity that is inherent in soils would require new methods and mathematical tools to quantify spatial and temporal dynamics. She proposed establishing common research platforms by identifying specific hydrogeologic questions in specific locations to effectively apply these tools. In discussing the strategy, she highlighted an issue that Trumbore had briefly mentioned—the use of purposeful tracers in a carefully sampled experimental site. Common research platforms would also result in a move toward intense instrumentation and sampling; increased cooperation among physical, chemical, and biological scientists; and a move from description of outcome as dictated by state factors toward elucidation of mechanisms that link state factors to the outcome.

John Norman, University of Wisconsin, Madison, commented on the proposal of a grand experiment using tracers. He first discussed why soil scientists, such as he, do not use tracers now and noted that it is often because of a lack of understanding of the ways tracers can be used in their own research. For an idea such as this to catch on in a scientific community, the gap between the specialist (the geoscientist who works with tracers) and the user (the average soil scientist) needs to be bridged. Researchers need to be convinced that they can use this tool to answer their questions, and tracers need to be placed into a context for soil science.

SESSION 2: USING MICROSCOPIC AND SPECTROSCOPIC TECHNIQUES TO ELUCIDATE CHEMICAL PROCESSES

Scott Fendorf, Stanford University, presented a talk on the molecular-level understanding of processes governing the fate and transport of ions and chemicals within soils, and discussed the challenges we face in upscaling our molecular understanding to the practical field scale. He outlined four necessary steps in moving to the field scale: (1) define the biochemical reactions at the molecular scale under field scale variability, (2) obtain the relevant kinetic parameters driving reactions, (3) capture the effect of heterogeneity on biogeochemical processes in soil, and (4) place the reaction description within an appropriate transport framework. He continued on a theme from the first session—that processes are integrated, even at a molecular level. His presentation covered the complexity of reactive transport processes in soils, illustrating how coupled physical, chemical, and biological processes control the fate and transport of ions and chemicals in soil systems (see Figure 3-1). A major emphasis was placed on molecular-level processes governing sorption and the processes governing the release of ions and chemicals as well as their rates of adsorption and desorption.

Fendorf presented examples of how physical, chemical, and biological processes are coupled in complex ways to control sorption, requiring an understanding of these processes at the molecular level. He discussed concepts on how and when molecular-level processes at the nano- and micrometer scales operate over a range of temporal scales. These nanoscale processes can be manifested as phenomenological observations at the field and landscape scales; however, there are challenges to linking observations at these various scales. Fendorf illustrated that advances during the past decade in microscopic and spectroscopic techniques, particularly those allowing for the interrogation of soil materials in situ, have greatly advanced our ability to elucidate complex coupled hydrobiogeochemical processes leading to the sorption or release of ions and chemicals. He also suggested that we are at the leading edge of efforts to develop conceptual and mathematical models based on these molecular-level data that will ultimately facilitate the ability to generalize processes from individual studies.

The presentation was discussed by Gary Pierzynski, Kansas State University, and Donald Sparks, University of Delaware. Pierzynski emphasized the difficulties in scaling from single mineral systems or simple mixtures to the complexity of soils. He identified the need to develop a mechanistic, versus an empirical, approach while acknowledging that a fully mechanistic

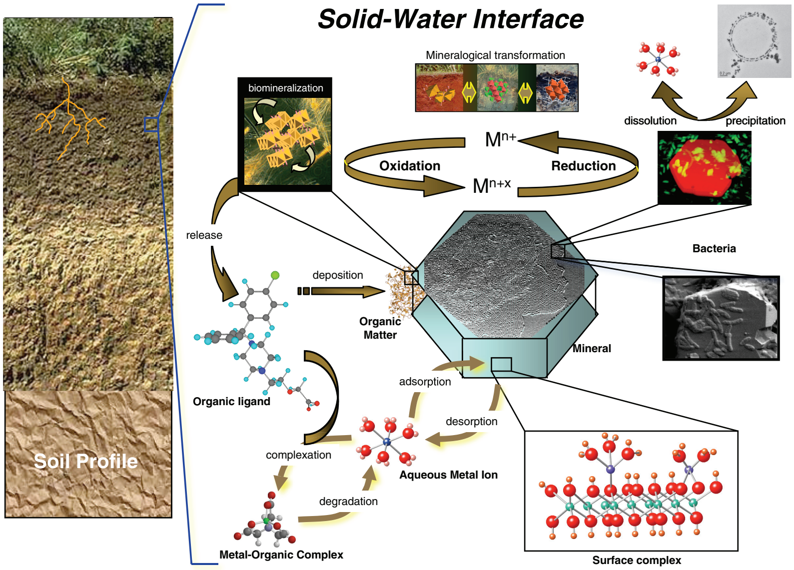

FIGURE 3-1 Fate and transport of ions and chemicals.
SOURCE: Scott Fendorf presentation.

transport and fate model would be enormously complex and have a prohibitive number of input parameters. The goal of a mechanistic approach is, in itself, worthwhile, but equally so is the knowledge that would be gained from working toward that goal. He also noted that techniques need to be found to solve the problems, not problems to solve with the techniques that are available.

Donald Sparks commented that the Critical Zone should be a focus in many geosciences leading to a better understanding of physical, chemical, and biological processes over many scales. He emphasized the importance of reactions at the interfaces, especially the microbe-mineral interface and the root-soil interface. Concerning the issue of scale, he noted that the temporal scale should be considered in all studies. There needs to be a focus on how to measure the more rapid processes, where a large part of the reaction is over before measurements can be made. He suggested that environmental science combine with genomic technologies to understand important processes at the plant-soil interface. He also stressed the need to interact with people from other disciplines, using various tools, to look at these processes, noting that the recently established Critical Zone Exploration Network (www.czen.org), sponsored by the National Science Foundation, is attempting to do just that. He concluded by identifying five frontiers of soil science at the molecular scale:

1. Effect of coupling on transport
2. Nanoparticle kinetics
3. Interfacial analysis
4. Effect of biofilms on transport and reaction processes
5. The plant-soil interface

SESSION 3: NATURE'S GREATEST BIOLOGICAL FRONTIER—THE SOIL COMMUNITY

James Tiedje, Michigan State University, discussed controls on biodiversity belowground. He emphasized the scope of the soil biological frontier with the following statements: (1) The biggest challenge in biology is to understand the soil community. (2) The human genome project was a pilot project compared to the soil microbial genome.

Future understanding of microbial biology in the natural environment belowground will require knowledge of three types—depth, breadth, and environment—that together can define the microbial world. Depth focuses on the details of how a cell functions. However, studies of this type generally use model organisms, so we need to learn how to relate information obtained from these studies back to the functioning of the entire soil community in its natural environment. Breadth is concerned with learning about the diversity of the soil microbial community residing in the soil environment. Environment relates to understanding how organisms interact with their environment—including physical space, chemical conditions, and interactions with other biological entities and their effects.

Tiedje discussed a series of four questions regarding our understanding of the soil biological frontier, with examples given or research needs identified, or both, for each question. First, he discussed the five factors controlling soil biodiversity: (1) the amount and heterogeneity of food resources; (2) the spatial isolation of microbes within the soil environment, which reduces direct competitive interactions; (3) time—for example, prokaryotes have developed and adapted over 3.8 billion years; (4) that microbes have faced and adapted to a wide range of selective conditions, with the resulting capabilities stored in their genome; and (5) the biological mechanisms used by microbes in their ongoing responses to their environment. He noted that the first two factors are key determinants of bacterial diversity. The availability of resources and the relative isolation of microbes, and therefore the level of competitive interactions, can determine whether a poor competitor will survive alongside a stronger competitor. In sum, to manage the soil biological community, the forces controlling its structure must be understood.

Second, Tiedje explored the extent of microbial diversity in soil. He noted that everyone knows that the diversity is high, but the question is how the level of biodiversity affects the soil's ecosystem services. There are two types of diversity: (1) genetic diversity, the variations in type and composition; and (2) spatial diversity, variations in space or biogeography. Tiedje used various studies to illustrate the high genetic diversity in soil as well as the diversity in microbes across continents and even within a corn row.

Third, Tiedje addressed how knowledge gained through *omics*—the comprehensive analysis of biological systems—can be used to advance soil science. This is generally still a potential, but it can be done, particularly for targeted, applied goals. If a function of interest is targeted, "molecular biological tools" can potentially be defined at any degree of desired resolution. Two types of resolution are needed: (1) at the "species" level, identifying genetic sequences, and (2) at the specific function level, relating a gene to function. Multilocus sequence typing is likely to be the next species-tracking tool. A functional gene repository has also been developed for genes that have a function of environmental importance. Tiedje used biofilms as an example of applying omics to investigating the soil environment.

Fourth, Tiedje discussed the interaction between biodiversity and coupled chemical, physical, and biological processes and how biodiversity influences the processes. These processes define the microbial niche—including niche chemistry and niche scale (small)—and make the niche dynamic (or not). Methods and tools for characterizing the niche are becoming available, but developing nondestructive techniques that can be used at very small scales will be a challenge.

Tiedje also noted that the soil community is more than bacteria; it also includes a diversity of animals, fungi, protozoa, archaea, and viruses. These organisms interact in soil food webs to regulate soil microbial activity and diversity.

Finally, Tiedje made a plea to take advantage of opportunities at interfaces by building bridges across disciplines—in particular, soil scientists must work together with the scientists developing the rapidly expanding worldwide sequencing and metagenomics capabilities to better identify the questions and strategies that will help minimize complexity issues in the soil and to enhance interpretive capabilities.

Cindy Nakatsu, Purdue University, commented on Tiedje's presentation by addressing spatial and functional heterogeneity. Heterogeneity in situ is caused by variability in carbon source, physical location, environmental conditions, and different founder communities. Yet even when these sources of heterogeneity are controlled, there can still be a large functional redundancy of organisms. Therefore, spatial and functional diversity are valuable because such diversity provides functional redundancy.

Ken Nealson, University of Southern California, challenged some of the assumptions that need to be addressed when working with genomics. First, he stated that the assumption of homology is wrong: The same 16S ribosomal RNA sequence does not necessarily mean that the organisms are the same. The second assumption he challenged is that once the genetic code of an organism is identified we know what that organism can do. For example, 4,000 genes have been identified in *Shewanella*, an aquatic microorganism, but the function is only known for 2,000. Genomics is a fantastic, powerful tool, but it must be recognized that not everything is known. He also noted that to understand function, we need to relate genetic data to physiological and biological data; this requires two different types of datasets and expertise. Also, the time it takes to acquire the combined information occurs at different rates (1,000 genes can be sequenced in the time it takes to identify the function of a single gene).

Nealson discussed other aspects of microbial studies. As an example, biofilms have high heterogeneity represented by high activity in localized environments. In nature, biofilms grow on active substrates that serve either as electron acceptors or donors, and this needs to be incorporated into research on function in the soil environment. Microbes never live alone; members of the microbial community interact with each other and evolve together within each environment. Thus, only with unusual substrates such as methane will taxonomic and functional convergence be possible. Microbes in the environment have different strategies and abilities than those that evolved with eukaryotic hosts, which must deal with host immune systems. Better indicators of total biomass are needed to couple with molecular method to understand how much microbial biomass is present in a given soil environment and what it is doing. He suggested that nitrogen or carbon-nitrogen bonds would be a better proxy for biomass than carbon alone.

SESSION 4: EFFECT OF IN SITU SOIL ARCHITECTURE ON SOIL PHYSICAL, CHEMICAL, AND BIOLOGICAL PROCESSES

This session focused on the integration of the soil matrix and its architecture as affecting soil system processes. Iain Young, Scottish Informatics, Mathematics, Biology, and Statistics (SIMBIOS) Centre, University of Abertay, Scotland, noted in his presentation that their center was designed specifically to encourage interdisciplinary research to examine how a heterogeneous architecture affects biological function and whether that biological function influences architecture.

In situ soil architecture has a determining effect on soil physical, chemical, and biological processes. New visualization techniques are available to dynamically and reproducibly characterize soil structure using X-ray computer-aided tomography systems and geostatistical and fractal analysis of data obtained to derive three-dimensional pore continuity patterns. Gaming techniques can be used to visualize three-dimensional pore patterns and allow "travel" through the soil pore system, which is effective for communicating soil information to nonsoil scientists and the public. He pointed out that a case could be made that the water characteristic curve $\psi(\theta)$ controls all life on Earth, because the complexity of pore-scale soil architecture allows water and air to coexist in soil, a vital fact for sustaining life. Moreover, relative water contents determine the rate of key processes. On average, less than 0.01 percent of the surface area of soil is occupied by microbes. Their effect on the soil environment will therefore be determined by niche-effects and by the manner in which such niches are connected with soil-pore patterns and the associated flow patterns of water and air. Microorganisms may change water properties such as the viscosity, which affects water availability, and soil properties such as hydrophobicity, which changes flow patterns of water into and through soil. This is hypothesized to be part of a self-organizational mechanism in which microorganisms create microenvironments that are particularly favorable to their survival and illustrate a close relation between physical and biological soil processes at the microscale.

Young also discussed the value of ecosystem services and cited a study (Boumans et al., 2002) where the value of soil was estimated at $20 trillion.[1] A strong plea was made for more analyses on the financial value of ecosys-

[1]The committee recognizes that there are several different typologies for valuing ecosystem services, which result in different values. Estimates from the World Resources Institute (1998, based on Costanza et al., 1997) place soil formation at 17.1 trillion U.S. dollars, the

tem services and sustainable management of soils. Sustainable management of soils—the most complex biosystems on Earth—is the key to the survival of humankind.

The discussion by Brenda Buck, University of Nevada, Las Vegas, noted that at the macrolevel, that is, both field- and landscape-scale, soil architecture can be strongly affected by regional climate, as for example by salts in dry or semiarid climates causing heaving of the soil and patterned grounds. Frost effects in cold soils may result in comparable features. Geomorphology always strongly affects these processes by mass movement or preferential, topography-related flow processes. Vesicular horizons have large pores that are not interconnected and therefore hinder flow through the soil matrix.

Larry Wilding, Texas A&M University, began his discussion by pointing out that shrink-swell soils are as costly as hurricanes in the United States in terms of damage to property. He stressed the need for more in situ observation of soil processes, an increase in multidisciplinary research, and more progress in working across spatial scales. He demonstrated how soil classification and soil profile descriptions provide comprehensive information on soil architecture for a wide range of soils and their horizons from the global to the local level. Qualitative descriptions of soil pores that have been quantified by thin sectioning and staining allow estimates of water fluxes in soil. In addition, soil features, such as clay coatings and iron mottling, provide permanent signatures in the soil that can be "read" by trained pedologists, again indicating water flow patterns and estimates of the associated biochemical processes, such as oxidation and reduction.

During the discussion, it was brought out that boundary conditions of the soil system, particularly conditions at the soil surface, have a major effect on soil processes. Microfabrics in the soil should not be studied in isolation. Hydrophobicity at the surface can drastically change infiltration patterns and may lead to serious runoff and erosion as a function of landscape morphology.

SUMMARY OF THE FIRST DAY'S DISCUSSIONS

At the start of the second day, the rapporteurs reported on the breakout sessions, and the first day was summarized briefly. Four gaps in understanding were identified:

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highest of all ecosystem services. The point is that, although estimates may vary, the value of soil as an ecosystem service is extremely high.

1. There is a need for simple indicators of soil health.
2. Soil scientists must link ecosystem services to soil health.
3. In situ measurements of biota interacting with the environment are needed.
4. There are problems in scaling chemical and biological processes.

In addition, two limitations on soil science research were recognized:

1. Soil scientists often limit themselves by staying within their disciplines and scientific societies.
2. Soil scientists often make it difficult to collaborate with scientists of other disciplines.

In the field of education, two needs were noted:

1. The focus of soil science education should be broadened.
2. Soils are critical to the world's population and the linkage to global problems should be emphasized in teaching programs as well as ways in which innovative soil management can help to alleviate these problems.

SESSION 5: UPSCALING TO A REGIONAL LEVEL

César Izaurralde, Joint Global Change Research Institute of the Pacific Northwest National Laboratory and the University of Maryland, explored how landscape architecture affects upscaling of soil processes to a regional level. Landscape modifications affect many soil processes. His presentation focused on water cycling (hydrological processes), carbon cycling, and trace gas fluxes as examples of the inherent complexity of upscaling soil processes to regional scales. He also discussed the need to integrate disciplines, scales, and data.

Water is a critical resource used for more than just consumption and food production; it is also used for energy production, transportation, tourism, and functioning of natural ecosystems. In soils, water is the medium, support, and regulator of all chemical, biological, and physical reactions. Landscape architecture affects size and spatiotemporal dynamics of water fluxes, and has a dominant effect on water storage. There is a relatively good quantitative understanding of how to describe water fluxes at the pedon scale, and equations exist to upscale predictions made at the pedon scale to fields and watersheds based on a uniform spatial distribution of hydrologic properties. However, hydrologic properties may exhibit large spatial variations. In addition, models are developed based on static soils. Since landscape architecture evolves with time and changes in spatial scales, the study of water fluxes can provide the necessary information to understand many features of landscape architecture and how it influences the upscaling of hydrologic and other soil processes.

The adoption of soil carbon sequestration as a technology to mitigate climate change requires estimates of carbon changes at different scales under different land use and management practices to make regional, national, and global projections. Currently, there are direct methods (field and laboratory measurements, minimum detectable differences, eddy covariance) and indirect methods (stratified accounting, remote sensing, models) to detect soil carbon changes. However, it has been difficult to estimate changes over short periods of time. Izaurralde noted three emerging technologies for rapid and accurate monitoring of soil carbon at different scales and over time: (1) laser-induced breakdown spectroscopy, (2) mid- and near-infrared spectroscopy, and (3) inelastic neutron scattering. He noted that geostatistical methods can be used to predict the spatial distribution of soil attributes. Breakthroughs and innovations in research will come from the need to connect the carbon cycle across scales. Great insight is being obtained about soil carbon processes as regulated by physical, chemical, and biological mechanisms. Because these processes are affected by landscape conditions (e.g., vegetation cover, topography, and manipulations), there is a need to study how to connect or preserve this information during upscaling procedures.

Soil is an immense global reactor for the production and consumption of trace gases. Trace gases can be measured at field scale combining diode laser absorption spectroscopy and micrometeorological techniques. Instrumentation offers rapid sampling rates to be used with eddy correlation and flux gradient techniques. In the estimation of trace gas fluxes, there is an exciting opportunity for collaboration among soil scientists, meteorologists, and atmospheric chemists to improve the understanding of the upscaling of nitrous oxide production from the microbial to the regional scale.

Izaurralde noted that temporal scaling, not just spatial scaling, needs to be considered when aggregating data across scales. We can consider timescales by looking at the biogeochemical cycles that exist in nature. There is also a disconnect when going to regional scales. Do the bottom-up estimates converge with the top-down estimates done with inverse modeling?

In his discussion of the presentation, Henry Lin, Pennsylvania State

University, illustrated how to understand landscape architecture, soil processes, and upscaling. He noted that processes have to be considered in situ and in context, and reiterated the challenges that spatial variability poses to delineating processes. He highlighted the geophysical tools that can be used for upscaling, and suggested that pattern recognition may assist in characterizing spatial variability and its effects. Lin emphasized the interrelationship of soil and water and the need to integrate soil science and hydrology.

Susan Moran, U.S. Department of Agriculture–Agricultural Research Service Southwest Watershed Research Center, discussed the role of remote sensing in the upscaling of soil processes. She highlighted a quote from Izaurralde's paper: "Data acquisition and availability has been a key impediment for applying models across spatial scales." She noted that the use of satellite imaging for soil processes is a known tool, but using it for upscaling is a new technique. Using remote sensing for data at a larger scale may be less accurate, but it is better than no data at all. In quoting Izaurralde's comment on the inherent complexity of upscaling soil processes to regional scales, she questioned whether there is an optimal scale for remote sensing. The data are available; they just need to be used, which can lead to breakthroughs in soil modeling. She stated that the biggest breakthrough in upscaling of soil models to a regional level will be made when satellite-derived model parameters become available to everyone at no cost.

SESSION 6: NEW TOOLS FOR IN SITU AND LABORATORY MEASUREMENTS

Kenneth Kemner, a physicist from Argonne National Laboratory, discussed how X-ray imaging and spectroscopy are being used to make in situ measurements of soil biological and physicochemical properties and processes. He began with an introduction to synchrotrons and X-ray physics, X-ray absorption spectroscopy, and X-ray microscopy, giving examples of the use of X-ray micro(spectro)scopy to investigate soil bio(geo)chemical processes. He provided an overview of some techniques that soil scientists could incorporate into their research. He noted how his research has been an integrated multidisciplinary process, working with several scientists from other fields. The goal of his presentation was to spur some interest in how this type of research could be applied to soils.

He provided several points to explain why hard X-rays could be used to investigate soil biogeochemical processes: Hard X-rays (i.e., greater than

~2 keV) interact "weakly" with matter (relative to charge particle probes) and enable the investigation of hydrated and buried samples; hard X-rays enable highly sensitive elemental analysis on extremely small objects; high sensitivity of X-rays enables X-ray absorption spectroscopy (i.e., interrogation of chemistry); high intensity and brilliance at synchrotrons enables X-ray microscopy investigations.

Kemner proposed that the integration of new techniques and tools such as third-generation light sources with multiple scientific disciplines provides new and exciting opportunities for addressing a variety of highly relevant soil science issues. The integration of the strengths of both X-ray and electron microscopies to investigate geomicrobiological systems is especially promising. Hard X-ray micro(spectro)scopy offers many exciting possibilities for future environmental and biogeochemical soil science investigations.

Kenneth Klabunde, Kansas State University, gave an overview of nanotechnology, the use of nanoparticles in environmental remediation, and examples of tools used. He pointed out that we have difficulty describing things at the 1-to-10 nanometer scale, where nanoparticles reside. He mentioned some of the ways in which nanotechnology may be relevant to soil science research: environmental remediation; the building of sensors from nanomaterials (at low cost); and the use of tools such as X-ray diffraction, electron diffraction, atomic force microscopy, electron microscopy, and standardized chemical reactivity tests.

SESSION 7: KEY INDICATORS FOR DETECTING THE RESILIENCE AND STABILITY OF THE SOIL SYSTEM

The multitude of ecosystem services that soils provide is increasingly recognized in the context of sustainable agriculture, climate change, desertification, and other global phenomena. The resilience of terrestrial, and some aquatic, ecosystems in the face of intensifying human disturbance relies, in part, on structural and functional attributes of soil. This growing recognition is important because soils are not renewable within the timescales in which human societies make decisions and plan ahead. However, soils do recover from disturbance and destruction faster than once thought, but it is not known how fast or under what circumstances.

Kate Scow, University of California, Davis, introduced the topic by discussing the essential services that soils provide and describing the major threats that soils are facing worldwide. She categorized the important functions of soil to be sustaining biology; regulating water and solute flow; filtering, buffering, and reclamation functions; storing and cycling of water and nutrients; and physical support and protection. She noted that some functions are "ecosystem services," defined as conditions and processes through which natural ecosystems, and the species that are part of them, help sustain and fulfill human life. She emphasized the need to include humans as part of the landscape. Then, borrowing from the Millennium Ecosystem Assessment (2005), she noted how soils fit into all four aspects of ecosystem services:

1. Provisioning (food, water, timber, fiber, genetic resources)
2. Regulating (climate, floods, disease, water quality)
3. Cultural (recreation, aesthetic, spiritual)
4. Supporting (nutrient cycling, soil formation)

Over the next 50 years, soils will be severely affected by population growth and changing land use. Soil, already in a state of degradation, will suffer further from various threats: erosion, a decline in organic matter, contamination, compaction, a loss of biodiversity and pedodiversity, salinization, and floods and landslides. The resulting changes will in turn affect other systems—hydrosphere, atmosphere, biosphere, as well as human beings.

Scow's presentation focused on the challenges of defining soil indicators that diagnose problems before they manifest into real damage that seriously impairs soil function. She described the attributes of resistance and resilience and categorized soils by how they respond to threats. Resilience, resistance, and inertia are all aspects of soil stability. Resistance is difficult to study because it is an absence of change and therefore not observable. Many systems also have an appreciable lag time before deteriorating under stress. Others may respond slowly over long timescales. She used Figure 3-2 to illustrate the possibilities where soil A (solid line) has high resistance and high resilience, soil B (dashed line) has low resistance and low resilience, and soil C (dotted line) has low resistance and high resilience.

She noted that there should probably also be a fourth curve that slowly descends after disturbance and a fifth that descends only after a long lag time. Several stresses are difficult to reverse: desertification, sediment loading of waterway, wind erosion with dust migration, salinization, soil and groundwater contamination, wetlands destruction, coastal erosion, and unsustainable crop production.

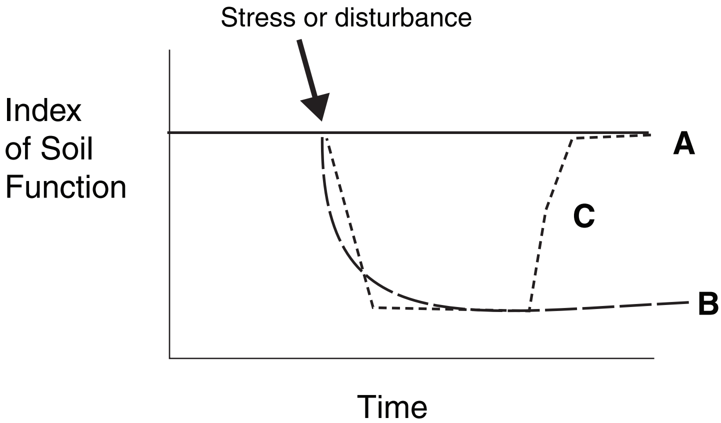

FIGURE 3-2 Function, disturbances, resistance, and resilience.
SOURCE: Kate Scow (committee interpretation of figure from presentation) redrawn from Herrick and Wander (1998) and Seybold et al. (1999).

She described the requirements that indicators must fill to be useful, and stated that it will be difficult to come up with a single meaningful indicator. Indicators must be relevant to all aspects of function, respond to management within a practical time frame, be easy to estimate, have a robust methodology for estimation, and be cost-effective. In addition, when deciding which indicators to use, it is necessary to know the issue or ecosystem that is being studied and the purpose for which the indicators will be used.

Scow categorized indicators into four types:

1. Physical: water retention and transmission, soil structure
2. Chemical: cation exchange capacity, pH, exchangeable cations, nutrient levels
3. Biological: diversity, fauna, microbial population, rooting depth, organic matter content
4. Computational/archival: regional modeling may have a role to play; databases, such as the soil survey, are useful but are not used much

In conclusion, Scow noted that there needs to be a shift from *assessing* to *managing* soil resilience and resistance.

Throughout her talk, Scow made note of the following research needs:

- Developing a better definition of soil as an ecosystem services provider
- Finding ways of assessing the value of soil services other than agriculture
- Scaling up from an indicator to big-picture influences
- Adapting conceptual models to serve as indicators
- Anticipating when degradation will occur in the future before it happens
- Evaluating trade-offs
- Bringing in stakeholders
- Developing a reward system for soil managers utilizing soils as an ecosystem services provider

Following Scow's presentation, Jayne Belnap, U.S. Geological Survey, discussed why defining indicators is difficult. Different users have different definitions of soil quality. There is a desire to have a "Grand Unifying Theory of Soil," which she felt could not be done at this time. The importance of indicating factors changes among systems, as well as temporally and spatially. The changes in one aspect may or may not change other factors, depending on conditions. Some known factors (e.g., climate) are underemployed as indicators. There is a poor understanding of the relationship between environment, food web structure, and function in soils.

She then divided indicators into three classes: (1) climate, which is not really an indicator, but a dominant influence; and the problem is that most of our past information will not help us as climate changes in the future; (2) soil stability, the resistance to erosion; and (3) soil function, including soil structure, processes, and biotic activity—the first two being relatively well known, but biotic activity is difficult to assess.

Birl Lowery, University of Wisconsin, Madison, discussed how maps can be useful indicators of, for example, soil quality and contamination. He noted that we can also determine some soil properties simply by looking over a landscape when we know what to look for. He echoed others earlier in the workshop with his comment that soils need to be viewed three-dimensionally, not just in two dimensions.

The workshop concluded with a plenary session during which participants discussed the various presentations and expressed their opinions on the gaps and needs in soil science research. Highlights of these discussions are noted in Chapter 4.

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4

The Frontiers in Soil Science Research

All of the speakers and participants in the workshop were asked to consider the following:

- Challenges and priorities within basic soil science research
- Opportunities for inter- and cross-disciplinary research
- Technological and computational opportunities to advance soil science research
- Student and early career training issues

The main ideas that came out of the presentations, the discussions, and the breakout groups are summarized below in five sections: (1) Overarching Challenges, (2) Research Needs and Opportunities (divided into six subcategories), (3) Tools, Techniques, and Current Opportunities, (4) Interdisciplinary Collaborations and Emerging Research Opportunities, and (5) Student and Training Issues.

OVERARCHING CHALLENGES

Throughout the workshop, two main challenges were frequently mentioned. One was the need to place a value on the soil resource and give the soil science discipline societal relevance by relating it to global issues such as food and energy security, human health, and environmental sustainability. This topic was addressed in Chapter 2 of this report.

The second main challenge, which is also a research frontier, was that of scale. Several of the speakers addressed the topic, introducing the need to consider both spatial scale (from the molecular level to landscape and beyond) and temporal scale (across time and also across processes that operate at different speeds). For example, Session 2 included discussion on using microscopic and spectroscopic techniques to elucidate physical, chemical, and biological processes at the microscopic level to understand impacts at the "field scale." Session 5, "Upscaling to a Regional Level," considered the roles of landscape structure and remote sensing in translating soil processes from the laboratory to the field and regional scales. Both sessions addressed the issue of temporal scale. At one end of the scale, Don Sparks noted in Session 2 that there are processes that happen within nanoseconds and cannot be measured. At the other end of the spectrum, César Izaurralde and others noted that some landscape processes occur over geologic scales beyond human perception.

Scaling up of processes, rather than simply scaling up of properties, by soil scientists is particularly understudied, and soil scientists are often uncomfortable in doing so, as noted by one of the breakout groups. Soil scientists must focus on research at multiple scales ranging from nanometers to watersheds. While small-scale research is often interesting and more likely fundable, large-scale research is needed to translate small-scale research to appropriate societal and global issues. The ability to "scale down" is also needed and tractable by soil scientists. For example, the effects of global climate change on specific regions or landscapes can be translated at a scale that society and managers can understand and act on. The notion of a coordinated "grand experiment" was discussed to facilitate soil scientists in addressing the issue of scaling.

Overarching challenges:

- Placing a value on the soil resource
- Integrating research from different spatial and temporal scales

RESEARCH NEEDS AND OPPORTUNITIES

Ecosystem Functioning

As was described extensively in Chapter 2, there is a need to develop methodologies for valuing, both financially and culturally, ecosystem services provided by soil. However, to do this, identification and quantification of the key ecosystem services performed by soil is needed, as was noted by Kate Scow in the last presentation. Several speakers—including Fendorf, Pierzynski, Sparks, and Tiedje—discussed the need to develop measurements that extrapolate to the ecosystem scale both spatially and temporally. A future growth need stressed by workshop participants was the development of appropriate indicators of soil function to allow for the anticipation of degradation. Opportunities were mentioned for the application of soil science research to urban ecosystems. Long-term monitoring is needed to quantify global dynamics rather than static soil properties so that the resulting measurements can be more meaningful.

Ecosystem functioning research needs:

- Identify and quantify key ecosystem services provided by soil
- Measure the value of ecosystem services performed by soil
- Develop measurements to extrapolate to the ecosystem scale
- Develop appropriate indicators of soil function
- Long-term monitoring to quantify global dynamics
- Incorporate soils into studies of urban ecosystems

Role of Soils in Human Health

There is a general need to characterize the relationship between soil quality and human health, including processes at the landscape scale. For example, the relationship between the transport of biologicals and their fate in soil and human health issues needs to be explored. There is a need to understand the effect of land management on the fate and transport of compounds and organisms that affect human health. The topic of desertification and resulting effects of soil particulates on human health was identified as a research need. There are also less direct links that need further exploration, such as the role of soil on water quality, and indirect links, such as soil and environmental quality.

Human health research needs:

- Characterize the relationship between soil quality and human health
- Relate virus transport and fate in soil to human health
- Characterize the effect of soil particulates from desertification on human health
- Characterize the role of soil quality in water quality and its effect on human health

Transport Processes

To better interface within the soil science community and with other sciences, it is important to understand transport processes in soil and to scale up to global processes. For example: (1) the characterization of gas fluxes to the atmosphere in relation to climate change; (2) the effect of water flow through the soil column on the hydrosphere; (3) how this flow is scaled up to a complex landscape; and (4) the impact of the transport of viruses and other microorganisms in soils on human health. There is a need for studying the interaction of physical transport through soil with microbial or chemical processes. There needs to be better characterization of transport and reactions by exploring, for example, the use of in situ tomographic and spectroscopic techniques.

Research at interfaces between soil and the atmosphere, hydrosphere, lithosphere, and biosphere is a need noted by many speakers (Trumbore, Izaurralde, Fendorf, Young, and Tiedje). Greater use of tracer techniques provides an opportunity to characterize the interactions between the "spheres" as discussed by Trumbore. The role of colloids as facilitators of transport of natural material and contaminants and as accelerators in soil formation was identified as a research opportunity during the breakout session. In addition, small-scale experiments should be better related to the natural environment (landscape scales). It was noted that there are opportunities to combine geomorphological landscape analysis and remote sensing techniques to facilitate scaling.

Transport processes research needs:

- Research transport processes at interfaces between soil and atmosphere
- Characterize gas fluxes to the atmosphere in relation to climate change
- Characterize the impact of water flow through the soil column on the hydrosphere
- Identify the impact of the transport of viruses and other microorganisms in soils on human health
- Employ in situ tomographic and spectroscopic techniques to characterize transport and reactions
- Characterize reactions at the interface of the various "spheres"
- Research the role of colloids as facilitators of transport

Plant-Soil-Microbial Interface

Basic research at the plant-soil-microbial interface is needed, including a particular emphasis on applying modern genomics techniques as noted by several speakers. The role of plant-soil-microbial interfaces on nutrient cycling needs to be characterized. The need to better understand the effect of biofilms was noted in Sessions 2 and 3 as well as in several breakout groups. The biofilm-microbe surface interaction and biotic interaction at surfaces relates to geochemical cycling processes, not just to nutrient cycling. It was noted that the plant-soil interface relates to soil formation, that is, the role of interfaces in controlling rates of weathering. Similarly, Young emphasized how soil architecture and the properties of soil surfaces, such as hydrophobicity, are greatly influenced by microbial activities occurring at plant-soil-microbial interfaces. Fendorf expressed the need to understand the role of plant-soil-microbial interfaces in contaminant fate.

Interfacial research needs:

- Conduct basic research at the plant-soil-microbial interface
- Apply genomics techniques
- Characterize the role of interfaces on nutrient cycling, in contaminant fate, and in weathering processes
- Research the role of biofilms in geochemical cycling processes

Characterization of Coupled Reaction Processes in Soil

A general need raised throughout the workshop was that of a better understanding of feedback mechanisms between physical, chemical, and biological processes. Young noted that in situ techniques could help provide that understanding. Other speakers, notably Fendorf, Sparks, and Tiedje, discussed how the integration of in situ physical, chemical, biological (omics), and imaging techniques could be used to elucidate the coupling of soil processes. The tools exist, but integration is needed.

As was noted in one of the breakout groups, it is important to emphasize and understand that reactive phases are dynamic. Research opportunities that were brought forth were feedback mechanisms among linked soil processes and improved characterization of the dynamics and coupling between physical, chemical, and biological soil processes. Young noted the need to understand the feedback mechanisms between biotic activity and soil architecture. There is also a need to characterize the reaction of soil to external perturbations from climate, as well as the long-term stability and resilience of soil experiencing degradation from human activity.

Coupled reaction processes research needs:

- Employ in situ imaging techniques
- Understand dynamic reactive phases
- Improve characterization of the dynamics and coupling between physical, chemical, and biological processes
- Improve the understanding of feedback mechanisms between physical, chemical, and biological processes

- Characterize the reaction of soil to external perturbations from climate or change
- Characterize long-term resilience of soil experiencing degradation from human activity

Data Acquisition and Synthesis

Throughout the workshop, discussion included how data are acquired, assimilated, and integrated. For example, it was suggested that existing pools of data be organized and standardized to permit improved interchange among scientists across disciplines. Data from long-term studies could be synthesized and analyzed to improve and update future monitoring practices.

As mentioned above, the integration of in situ physical, chemical, biological (omics), and imaging techniques is needed to elucidate soil processes. James Tiedje suggested expanding omics studies on important soil bacteria to discern and investigate genes relevant to soil ecology. He also noted that metagenomics (the community genome) could be used to reduce the complexity of information for a given microbial community for use by other soil science disciplines. There is a need to interface the interpretive expertise of soil scientists with the expanding efforts and new initiatives in metagenomics to better identify the questions and strategies that will help minimize complexity issues in the soil and to enhance interpretive capabilities.

Upscaling of soil processes requires improved data acquisition and modeling. In his paper, César Izaurralde stated, "Data acquisition and availability has been a key impediment for applying models across spatial scales." Remote sensing and geographic information systems (GIS) at various scales combined with interactive computer models were noted as needs. Susan Moran noted that "the biggest breakthrough in upscaling of soil models to a regional level will be made when satellite-derived model parameters are available for *free* to everyone." Henry Lin noted in his discussion paper that pattern recognition or "spatial-temporal organization" may improve the understanding of soil variability. New measurement technologies will aid in upscaling processes. For example, the potential for using laser-induced breakdown spectroscopy, mid- and near-infrared spectroscopy, and inelastic neutron scattering to monitor soil carbon levels is currently being explored.

Data research needs:

- Standardize and synthesize existing databases and improve access
- Integrate in situ physical, chemical, biological, and imaging techniques
- Improve modeling across spatial and temporal scales
- Develop new measurement techniques

TOOLS, TECHNIQUES, AND CURRENT OPPORTUNITIES

One of the goals of this workshop was to identify tools and techniques—some already in use by other disciplines, some new—that could be applied to soil science research. Although many soil scientists already use some of these tools (for example, many soil scientists are already using synchrotrons), more soil scientists need to be made aware of them and how to use them. Several attendees at the workshop expressed their desire to learn more about the tools and techniques they were hearing about, some for the first time.

The integration of new techniques and tools such as third-generation light sources with multiple scientific disciplines provides new and exciting opportunities for addressing a variety of highly relevant soil science issues, as presented by Kenneth Kemner. The integration of the strengths of both X-ray and electron microscopies to investigate geomicrobiological systems is especially promising. Hard X-ray micro(spectro)scopy offers many exciting possibilities for future environmental and biogeochemical soil science investigations.

The use of geospatial technology to better understand soil was demonstrated in Session 4. In his presentation, Iain Young used a three-dimensional display that got all workshop participants interested in—and excited about—how to use such a tool in their own research. The development and use of nondestructive imaging methods to characterize three-dimensional soil structures of nondisturbed soil horizons, and the development of dynamic flow theory that transforms three-dimensional soil architecture into function is a frontier research area. Such spatial informatics can be applied at multiple scales.

In her presentation, Susan Trumbore discussed the use of isotopic tracers as a soil science research tool and emphasized that some powerful opportunities exist today but will not be available in the future, for example, isotopes of carbon and cesium as a result of aboveground weapons testing. In addition, several needs or research gaps were identified during the presentation and the following discussion. How can tracers be effectively used to address a series of questions that quantify state factors in soil? How can interactions among the physical, biological, and chemical processes within soil be quantified across a range of ecosystems? What new insights into soil processes can be gained through application of isotopic tracers to soils?

Microscopic and spectroscopic techniques need to be applied for improved understanding of coupled processes in soil, as noted by Scott Fendorf in his presentation. He also noted that we are on the leading edge of efforts to develop conceptual and mathematical models based on molecular-level data that will facilitate the generalization of processes from individual studies.

Throughout the workshop, the need for the development of more tools for use in soil science research was identified. Further advances in soil science could be accomplished with tools that allow for in situ studies of the chemistry, structure, and biology of soil. There is a need for improved modeling techniques that allow for extrapolating experiments across scales and techniques to capture the variability and heterogeneity related to the function and processes of soil. Related to this is the need for a greater use of mathematical and computational capabilities. And, as noted above, a greater use of geospatial technology, along with GIS and remote sensing, can lead to breakthroughs in soil science research.

The development of computational methodologies could help address complexity problems such as heterogeneity, variability, and scaling, as noted in Session 3. Furthermore, new techniques characterizing mineral surfaces could contribute to understanding microbial interactions with charged surfaces and help create bridges between soil chemistry and soil biology.

In addition to using already existing tools, new tools do need to be developed. The challenge is to make more soil scientists aware of these existing and emerging tools and techniques and how to use them for their research. One way to do this is to encourage collaboration of soil scientists with the scientists in other disciplines who are either developing these tools or are using them for their own research.

Research opportunities using new tools and techniques:

- Encourage greater employment of micro(spectro)scopy by soil scientists
- Employ isotopic tracers in soil science research
- Develop new tools for in situ studies of the chemistry, structure, and biology of soil
- Improve modeling techniques for extrapolating across scales
- Employ more mathematical and computational capabilities in modeling
- Employ modeling to transform architecture into function

INTERDISCIPLINARY COLLABORATIONS AND EMERGING RESEARCH OPPORTUNITIES

Soil science is intrinsically an interdisciplinary science that integrates physics, chemistry, biology, geology, and computational sciences. Soil scientists have long been at the forefront of applying state-of-the-science technologies and methodologies to complex environmental systems. Perhaps "soil system science" would be a more effective term to describe the transformations that this discipline has already undergone and will continue to undergo.

As was seen in several of the workshop presentations (Fendorf, Young, and Kemner, in particular), the advances in separation, spectroscopic, and imaging technologies in recent years have resulted in major breakthroughs in understanding complex physical and chemical properties of soil that control the fate and transport of fluids, nutrients, carbon, and contaminants. Furthermore, the revolution in molecular biology and the fusion and integration of rapidly advancing analytical and molecular biological methods are enabling key biogeochemical processes to be probed at very high resolution at submicron to millimeter scales. The integration of this physical, chemical, and biological information collected in situ with these advanced techniques will provide an unprecedented opportunity to understand how physicochemical and biological processes are coupled and to elucidate various feedbacks that are operating in complex environmental systems.

There has never been a period where revolutionary breakthroughs in understanding soil and the hydrobiogeochemical processes occurring within soil are so likely. As was noted by several participants in the workshop, these breakthroughs will only be possible if soil scientists greatly expand their collaborative efforts with colleagues in other scientific disciplines to bring the most advanced techniques and approaches to bear on unraveling the mechanisms underlying key physical, chemical, and biological processes; understanding how these processes are coupled; as well as the feedback systems operating across temporal and spatial scales. Brent Clothier noted in his presentation that the complete scientific study of soil requires researchers from a wide range of disciplines. Breakthroughs in soil science will require mathematicians, physicists, chemists, and biologists to work together, and for them to link with economists and sociologists. Breakthroughs and innovations will come from the synergy of collaboration and from research at the interfaces between disciplines.

In addition to areas of research, it is helpful also to consider the ways in which the conduct of research may be most effective in the future. Iain Young assembled a diverse group of 23 young scientists at the Scottish Informatics, Mathematics, Biology, and Statistics (SIMBIOS) Centre (based at the University of Abertay, Scotland). The group has expertise in a wide variety of fields: experimental soil mechanics, mycology, cell biology, computational fluid mechanics, statistical mechanics, theoretical biology, plant physiology, computer gaming, and information technology. This forms a flexible, interdisciplinary research team that can tackle soil problems in an innovative manner, not being bound by traditional approaches. They work together in an open environment without doors, creating synergy and opportunities for serendipity. This work-model is not new in general, but it is for the soil science community and presents an intriguing approach to solving problems in the future.

New areas of collaboration need to be more aggressively pursued. For example, the role of soils in human health had been traditionally thought to be tied to food supply, nutrition, and water quantity and quality. However, many additional aspects are involved, including the role of soil in exposure pathways to contaminants and pathogens and the involvement of soil in emerging diseases. Informatics is another area where stronger collaborations between soil scientists and colleagues from other disciplines will be required. Integrating advances in bioinformatics, spatial informatics, and ecoinformatics, as well as molecular modeling will be critical to advancing soil science research and will demand new collaborations. Another emerging area identified by workshop participants was the area of urban soils. While soil science research has traditionally focused on wildland and managed forest ecosystems and agricultural soils, many problems and issues surrounding the urban soil resource require attention and provide opportunities for soil scientists to work with engineers and others to address these issues. It was clear from the workshop that, while many soil scientists are at the leading edge of utilizing the most advanced techniques and approaches through collaborative efforts, there needs to be much greater effort in making the tools and approaches more widely available and collaborations with colleagues in other disciplines more mainstream. Workshop attendees, many of whom were unfamiliar with the advanced tools, techniques, and approaches available, expressed enthusiasm to collaborate with other colleagues.

Other emerging interdisciplinary research opportunities for soil scientists involve Earth-observing systems. Workshop participants mentioned several major new research initiatives funded by the National Science Foundation, such as the National Ecological Observatory Network (NEON), the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER), and the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI), that involve measurement of soil properties and processes over large spatial and temporal scales. The NEON will be the first national ecological measurement and observation system designed both to answer regional- to continental-scale scientific questions and to have the interdisciplinary participation necessary to achieve credible ecological forecasting and prediction. The CLEANER and CUAHSI programs are planning a dual-purpose network called the Water and Environmental Research Systems (WATERS) Network. The WATERS Network is proposed as a networked infrastructure of environmental field facilities working to promote interdisciplinary research and education on complex, large-scale environmental systems. While many in the soil science community have been involved in the planning and execution of these major interdisciplinary research initiatives, more soil scientists have to become involved to ensure that the role of soil is properly appreciated up front and that appropriate measurements of soil properties and processes are integrated into the observatory and experimental platforms.

Several presenters and participants noted that there are major challenges in scaling up from understanding mechanisms involved in coupled hydrobiogeochemical processes in soil that control the fate and transport of water, nutrients, carbon, contaminants, and pathogens to addressing issues manifested at larger scales. The link between key soil processes and critical ecosystem services needs to be more firmly established, as does the value of these services, as was discussed in Chapter 2. Additionally, the importance of the soil resource as the foundation of terrestrial ecosystem health, water resources, global carbon budgets, and global biogeochemical cycles needs to be better articulated to policy makers and members of the general public. To address these larger-scale issues and to properly integrate advances and breakthroughs in soil science research into policy will require collaborations with colleagues in the social sciences, humanities, and economics.

Jayne Belnap, in discussing the final presentation, stressed how soil scientists must collaborate with others to make them aware of the importance of soils. Soil scientists need to be active collaborators and not expect those from other disciplines to come to them if they are not reaching out to other scientists. Attending meetings of other related disciplines is important to raise awareness of the relevance of soil science to those other disciplines. Equally important is understanding how to make soil science relevant to the audience being addressed, whether it is that of another scientific discipline or stakeholders, end users, or policy makers.

Opportunities for soil science in interdisciplinary collaborations:

- Research at the interface of disciplines could lead to breakthroughs
- Consider new models for interdisciplinary collaboration
- Participate in Earth-observation systems and other new multidisciplinary research initiatives
- Collaborate with colleagues in social sciences, humanities, and economics to integrate advances and breakthroughs in soil science research into policy making

STUDENT AND TRAINING ISSUES

Throughout the workshop, participants were asked to consider whether there were any issues related to education and training that needed to be addressed for soil science to reach new frontiers in research. Several generalities were made in the discussion periods and breakout groups; many of these echo the challenges raised under other subheadings: teach students to work across the discipline and with other disciplines; provide internships to work with new tools and techniques; train students to understand the societal relevance of their research; teach the capacity to communicate with nonscientists.

During one breakout session, it was noted that there has been a paradigm shift in the approach to soil science research that affects how soils should be taught, but the soil science curriculum has not undergone the same change. Many soil science departments have become part of larger programs with labels such as environmental science. This may attract more students, but some scientists question whether it dilutes the fundamentals of the discipline. Collaboration with other departments is necessary, however, to allow students to be involved in interdisciplinary opportunities and have access to high-tech instruments not found in most soil science departments. Ways to introduce undergraduates in other disciplines to soil science were discussed in several breakout groups, such as research experiences and summer field courses.

The issue of certification and licensing was also discussed during the breakout sessions. Engineers and geologists, who are licensed and certified, work in environmental consulting. Soil scientists are not being extensively involved in much of this work, and the work may be suffering by not having greater involvement by soil scientists. There is voluntary certification for soil scientists, and some states have licensing of soil scientists, but this is not widespread.

Issues in student training:

- Teach students to
  - collaborate across disciplines
  - think at larger scales
  - relate to the general public
- Provide interdisciplinary opportunities
- Collaborate with other departments to give students access to high-tech instruments

Epilogue

This workshop was not intended to be a one-time event, but rather a step in a process of identifying how soil science research can expand and grow to meet the needs of science and society. We must understand soil in terms of its *dynamics*, its *stability*, and the resulting *rates* and *efficiencies* of soil processes. Many of the research topics and issues raised at the workshop will be important in the future. Among them are the following:

- Valuing soil as an ecosystem service
- Translating research across both temporal and spatial scales
- Sharing and using data already available for other purposes in soil science research
- Incorporating existing and new technologies from other disciplines to study soil systems
- Collaborating across disciplines
- Translating soil science research into information for stakeholders and end users (e.g., policy makers, regulators, farmers, land developers, and engineers)

Many of these topics are interrelated. Using available data may require up-scaling or downscaling of results owing to the disparate scales at which soils and, for example, vegetation, water, sediment, and atmospheric measurements are made. Likewise, interdisciplinary collaboration may result as soil scientists apply new and existing technologies to soil science research.

There is an identified need for more funding for both agricultural-related *and* environmental soil science. As was noted several times during the workshop, soil science lacks a primary sponsor or steward, which partly emanates from its interdisciplinary nature.

In recent years when science budgets have diminished, it is increasingly important for soil scientists to continue to collaborate across and outside the discipline, finding ways to relate their science to the societal needs, as well as linking it to such issues as environmental policy. This is a struggle not just in the United States, but in other countries as well, as witnessed by Brent Clothier's presentation to the workshop on efforts to link soil science to policy in New Zealand, and recent meetings in Europe on the future of soil science research.

Several networks mentioned during the workshop—including, for example, the National Ecological Observatory Network and the Critical Zone Exploration Network—are working across disciplines on research issues of interest to soil scientists. Soil scientists need to continue to find ways to link their basic research to broader research efforts, in an effort both to bring soil science research to the forefront and to raise awareness in the broader scientific community as to what soil science research can offer to the larger scientific endeavor.

It is up to soil scientists to continue to search for the frontiers in research, linking research to important societal and global issues, such as food security, sustainability, climate change, and water resources. However, to do so, we must continue to collaborate, keeping ourselves open to learning from other disciplines, and reaching out to our scientific colleagues, scientific societies, and research endeavors.

Appendixes

Appendix A

Workshop Agenda

Frontiers in Soil Science Research
December 12-14, 2005
National Academy of Sciences, Lecture Room
Washington, DC

Monday, December 12

6:00	Workshop introduction by Charles Rice, Kansas State University Welcome comments from National Academy of Sciences President Ralph J. Cicerone **Keynote address**: Brent Clothier, Horticultural and Food Research Institute of New Zealand *Sustaining Soil Science: Participation, Policy, Purchase and Progress*
7:00	Discussion
7:30-9:00	Reception buffet in the Great Hall

Tuesday, December 13

8:00	**Session 1**: How well do we understand the interaction of physical, chemical, and biological processes in soils that impact the atmosphere, vegetation, and the hydrogeosphere? Where are the innovations? What gaps need to be addressed?

For example, with respect to greenhouse gas fluxes or liquid, gas, and biologic transport.

Speaker: Susan Trumbore, University of California, Irvine
Transient Tracers on Land: Coordinated Use of Tracers to Quantify Soil Processes within the State Factor Framework

Discussants: Janet S. Herman, University of Virginia
John M. Norman, University of Wisconsin, Madison

Moderator: Jerry Hatfield, USDA-ARS, National Soil Tilth Laboratory

9:30 Break

10:00 **Session 2**: What are the chemical interactions at the molecular level that define the fate of ions, chemicals, and/or microbes as they are transported through soil systems? How can knowledge gained through molecular investigations be used to constrain studies focused on the chemical interactions and how are these linked to physical and biological processes?

Speaker: Scott Fendorf, Stanford University
Toward Gaining a Molecular-level Understanding of Processes Governing the Fate and Transport of Ions/Chemicals within Soils

Discussants: Gary Pierzynski, Kansas State University
Donald Sparks, University of Delaware

Moderator: Paul M. Bertsch, University of Georgia

11:30 Lunch

1:00 **Session 3**: What controls biodiversity belowground? How can knowledge gained through molecular biological investigations (i.e., genomics, proteomics, metabolomics) be used to advance soil science? How do coupled chemical, physical, and biological processes influence biodiversity? How does this biodiversity affect the function of the soil system?

Speaker: James M. Tiedje, Michigan State University
Attacking Nature's Greatest Biological Frontier, the Soil Community

Discussants: Cindy H. Nakatsu, Purdue University
Kenneth H. Nealson, University of Southern California

Moderator: Julie D. Jastrow, Argonne National Laboratory

2:30 Break

3:00 **Session 4**: What is the effect of in situ soil architecture on soil physical, chemical, and biological processes? How does it vary from one soil system to another? What are the controlling factors?

Speaker: Iain M. Young, Scottish Informatics, Mathematics, Biology, and Statistics (SIMBIOS) Centre, University of Abertay
Architecture and Biology of Soil Systems

Discussants: Brenda J. Buck, University of Nevada
Larry P. Wilding, Texas A&M University

Moderator: Johan Bouma, Wageningen University, Netherlands

4:30 Breakout Groups. See listing for assignments and locations.

6:00-7:00 Poster display and beer and wine reception

Wednesday, December 14

8:00 Report on Tuesday's breakout groups

9:00 **Session 5**: How does landscape architecture (topography, vegetation, land use) affect the upscaling of soil processes to a regional level?

Speaker: César Izaurralde, Joint Global Change Research Institute, University of Maryland
How Does Landscape Architecture Affect the Upscaling of Soil Processes to a Regional Level?

Discussants: Henry Lin, Pennsylvania State University
Susan Moran, USDA-ARS Southwest Watershed Research Center

Moderator: Jennifer Harden, U.S. Geological Survey

10:30 Break

11:00 **Session 6**: What are the new tools for making in situ and laboratory measurements of soil biological and physicochemical properties and processes? How can soil science use technologies and tools already used in other disciplines to advance soil science research?

Speakers: Kenneth Kemner, Argonne National Laboratory
X-Ray Imaging and Spectroscopy for Making In Situ Measurements of Soil Biological and Physicochemical Properties and Processes

Kenneth J. Klabunde, Kansas State University
Nanotechnology and Its Possible Applications to Soil Science

Moderator: Joaquin Ruiz, University of Arizona

12:30 Lunch (on your own, available in cafeteria downstairs)

2:00 **Session 7**: From a systems analysis standpoint, what are the key indicators for detecting the resilience and stability of the soil system? What are critical factors that control the resilience and stability? Our understanding of soils in the United States is based largely on observations, measurements, and maps generated during the past 60 years. How might our current understanding of soils and soil processes be impacted by changes in climate, land use, and water-nutrient-biotic interactions? What types of monitoring might be needed to detect such changes?

Speaker: Kate Scow, University of California, Davis
Soil and Ecosystems: Stability, Resilience, and Resistance in the Face of Disturbance

Discussants: Jayne Belnap, U.S. Geological Survey Canyonlands Research Station, Utah
Birl Lowery, University of Wisconsin, Madison

Moderator: William A. Jury, University of California, Riverside

3:30 Plenary discussion

6:00 Adjourn

Appendix B

Speakers and Discussants*

Ralph J. Cicerone, President, National Academy of Sciences
An atmospheric scientist, Ralph J. Cicerone became president of the National Academy of Sciences in 2005. His research in atmospheric chemistry and climate change has involved him in shaping science and environmental policy at the highest levels, nationally and internationally. His research was recognized on the citation for the 1995 Nobel Prize in chemistry award to his University of California, Irvine, colleague F. Sherwood Rowland. In 1997 he received a United Nations Environment Program Ozone Award for research in protecting the earth's ozone layer. The Franklin Institute recognized his outstanding contributions to the understanding of greenhouse gases and ozone depletion and his fundamental research in biogeochemistry by selecting Cicerone as the 1999 laureate for the Bower Award and Prize for Achievement in Science. In 2001 he led a National Academy of Sciences study of the current state of climate change and its impact on the environment and human health. The American Geophysical Union awarded him its 2002 Roger Revelle Medal for outstanding research contributions to the understanding of Earth's atmospheric processes, biogeochemical cycles, or other key elements of the climate system. In 2004 the World Cultural Council hon-

*Listed in same order as agenda. (These biosketches were current at the time of the workshop.)

ored him with the Albert Einstein World Award in Science. He received his bachelor's degree in electrical engineering from the Massachusetts Institute of Technology, where he was also a varsity baseball player, and both his master's and doctoral degrees from the University of Illinois in electrical engineering, with a minor in physics.

Brent Clothier, Horticultural and Food Research Institute of New Zealand (HortResearch)
Brent Clothier is a soil physicist and environmental scientist who is science leader of the Sustainable Land Use team within HortResearch. In his 30-year research career, he has published more than 165 scientific papers on the movement and fate of water and chemicals in production systems and the environment. He has led projects on risk assessments of land-use practices and the protection of soils, surface water, and groundwater from contamination, both in New Zealand and in the Pacific islands. Clothier is the program leader of New Zealand's major soil-science research program SLURI (Sustainable Land Use Research Initiative). He has a B.Sc. (Honors) from Canterbury University, and a Ph.D. and D.Sc. in soil science from Massey University. He is a fellow of the Royal Society of New Zealand, the Soil Science Society of America, the American Society of Agronomy, the New Zealand Soil Science Society, and the American Geophysical Union. He received the Don and Betty Kirkham Soil Physics Award from the Soil Science Society of America in 2000.

Susan Trumbore, University of California, Irvine (UCI)
Susan Trumbore is professor of earth system science and director of the UCI branch of the UC Institute for Geophysics and Planetary Physics. She received a B.S. in geology from the University of Delaware and a Ph.D. in geology and geochemistry from Columbia University's Lamont-Doherty Geological Observatory (1989). After postdoctoral work at the Swiss Federal Institute of Technology and Lawrence Livermore National Laboratory, she joined the Earth system science faculty at UCI as a founding member in 1991. Dr. Trumbore studies how the Earth's natural exchanges of carbon among ocean, land, and atmosphere are altered by human activity. She uses the distribution of radiocarbon added to the atmosphere in the 1960s during nuclear weapons testing to determine the timescale of carbon exchange between ecosystems (plants and soils) and the atmosphere. With Ellen Druffel and John Southon,

she established the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Facility at UCI in 2002 to expand the use of radiocarbon in studies of the carbon cycle. Professor Trumbore was the recipient of a National Science Foundation National Young Investigator Award in 1993. She was the first president of the Biogeosciences Section of the American Geophysical Union (AGU), and is a fellow of the American Association for the Advancement of Science and the AGU.

Janet S. Herman, University of Virginia
Janet S. Herman is full professor in the Department of Environmental Sciences at the University of Virginia and is director of the interdepartmental Program of Interdisciplinary Research in Contaminant Hydrogeology. She obtained her B.S. in geological sciences and her Ph.D. in geochemistry (1982), both from the Pennsylvania State University. Her numerous publications contribute to understanding the chemical evolution of natural waters through water-rock interactions. Her research is focused on the complex interactions among hydrological transport, microbiological processes, and geochemical reactions in the groundwater environment. Dr. Herman has attracted approximately $4 million in research funding to the University of Virginia from federal agencies, including the National Science Foundation, the Environmental Protection Agency, the Department of Energy, and the U.S. Geological Survey. Recently, Dr. Herman served as chair of the Hydrogeology Division of the Geological Society of America and as chair of the F. W. Clarke Award Committee of the Geochemical Society. Notable honors include election to fellow of the Geological Society of America in 1994 and receipt of the Presidential Award for Excellence for Mentoring in Science, Engineering, and Mathematics in 1996.

John M. Norman, University of Wisconsin, Madison
John M. Norman has been professor of soil science and also professor of atmospheric and oceanic science at the University of Wisconsin, Madison, since 1988. Following his Ph.D. in 1971 from the University of Wisconsin, Madison, he was an associate professor of meteorology at the Pennsylvania State University until 1978 and professor of agronomy at the University of Nebraska, Lincoln, until 1988. He conducts biophysical research involving studies of the interaction between plants and their environment, including measurements of soil, plant, and atmospheric characteristics and integrative modeling of the soil-plant-atmosphere system. Applications to ecology, agriculture, forestry, and meteorology have included plant productivity

and water-use efficiency, integrated pest management, irrigation water use, precision agriculture, agrochemical leaching losses, remote sensing, and measurement and modeling of soil surface carbon dioxide fluxes. Recent research focuses on the sustainability of agricultural production and the importance of soil in the spatial and temporal distribution of crop production and environmental consequences. He is a fellow of the American Society of Agronomy and the Crop Science Society of America and received the American Meteorology Society Award for Outstanding Biometeorologist in 2004.

Scott Fendorf, Stanford University
Scott Fendorf is an associate professor of soil and environmental biogeochemistry in the School of Earth Sciences at Stanford University. He conducted his graduate work in soil chemistry at the University of California, Davis (M.S., 1990), and the University of Delaware (Ph.D., 1992) and then joined the soil science faculty at the University of Idaho in 1993. After spending six years (1993-1998) in Idaho, Professor Fendorf joined the School of Earth Sciences at Stanford University in 1999 to initiate a program in soil biogeochemistry. Broadly, he is interested in defining chemical environments that develop as a result of biotic and abiotic processes within physically complex and dynamic media. His research focuses on the chemical and biological processes that drive the fate and transport of trace elements such as arsenic and chromium within soils, sediments, and surface waters. A thrust of his research, for example, is presently on deciphering the processes responsible for arsenic release into aquifers throughout Southeast Asia.

Gary M. Pierzynski, Kansas State University
Gary M. Pierzynski is a professor of soil and environmental chemistry in the Department of Agronomy at Kansas State University. Dr. Pierzynski's research interests include trace element chemistry, remediation of trace element-contaminated soils, phosphorus bioavailability, water quality, risk assessment, and land application of by-products. Professional activities include serving as soil and environmental division chair for the Soil Science Society of America; U.S. Department of Agriculture (USDA) National Research Initiative panel manager for the Soils and Soil Biology Program; vice chairperson for the Soil Remediation Subcommission of the International Union of Soil Sciences; cochair of the USDA Chemistry and Bioavailability of Waste Constituents in Soils regional research committee; peer reviewer

for the Environmental Protection Agency's risk assessment efforts; member and chair of the technical and organizing committees for the International Conference on the Biogeochemistry of Trace Elements Series; and technical advisor for citizen groups in the Tri-State Mining Region. Dr. Pierzynski teaches courses on environmental quality, plant nutrient sources, soil and environmental chemistry, and advanced soil chemistry. He is a fellow of the American Society of Agronomy and the Soil Science Society of America. Dr. Pierzynski received his B.S. in crop and soil science (1982) and his M.S. in soil environmental chemistry (1985) from Michigan State University in East Lansing, Michigan. He earned his Ph.D. in soil chemistry (1989) from the Ohio State University, Columbus.

Donald L. Sparks, University of Delaware
Donald L. Sparks is the S. Hallock du Pont Endowed Chair in Soil and Environmental Chemistry at the University of Delaware and chairman of the Department of Plant and Soil Sciences. He is former president of the International Union of Soil Sciences and former president of the Soil Science Society of America (SSSA). Dr. Sparks is internationally recognized for his research in the areas of kinetics and surface chemistry of soil chemical processes. He has pioneered the application of chemical kinetics to soils and soil minerals, including development of widely used methods, elucidation of rate-limiting steps and mechanisms, and coupling of kinetic studies with molecular scale investigations. He and his research group's discoveries on the formation and role of surface precipitates in the retention, fate, and transport of metals in natural systems have received worldwide attention and had major influence in the areas of sorption models, metal speciation, and soil remediation and contamination. He is a fellow of the SSSA, American Society of Agronomy, and American Association for the Advancement of Science. He has received numerous awards, including the M. L. and Chrystie M. Jackson and Soil Science Research Awards, the Environmental Quality Research Award, McMaster Fellowship from Australia's Commonwealth Scientific and Industrial Research Organisation, the Sterling Hendricks Lectureship from the U.S. Department of Agriculture–Agricultural Research Service, and the University of Delaware Francis Alison Faculty and Outstanding Doctoral Advising and Mentoring Awards.

James Tiedje, Michigan State University
James Tiedje is a university distinguished professor of microbiology and soil science, and is director of the Center for Microbial Ecology at Michi-

gan State University. He has 30 years of experience leading research in microbial ecology and physiology, especially regarding the nitrogen cycle and biodegradation of environmental pollutants. His group has discovered several new microbes that live by halorespiration on chlorinated solvents. Some of the dechlorination processes carried out by these microbes have reduced the environmental burden of PCB, DDT, and chlorinated solvents. He has been editor-in-chief of *Applied and Environmental Microbiology* and editor of *Microbiology and Molecular Biology Reviews*. He has received the Environmental Award from the American Society for Microbiology and shared the 1992 Finley Prize given by UNESCO for research contributions in microbiology of international significance. He is a fellow of the American Association for the Advancement of Science, the American Academy of Microbiology, and the Soil Science Society of America, and is past president of the International Society for Microbial Ecology. He is a member of the National Academy of Sciences and a former president of the American Society for Microbiology. He received his B.S. degree from Iowa State University and his M.S. and Ph.D. degrees from Cornell University.

Cindy H. Nakatsu, Purdue University
Cindy H. Nakatsu is currently a professor and University Faculty Research Scholar at Purdue University. She has been on faculty in the Department of Agronomy at Purdue University since 1995. She was a postdoctoral fellow at Michigan State University's Center for Microbial Ecology after receiving her Ph.D. in 1993 from Carleton University in Ottawa, Canada, and her M.S. (1983) and B.S. (1978) degrees from the University of Toronto in Toronto, Canada. Her research is focused toward gaining a greater understanding of the diversity of microorganisms in nature and the genetic mechanisms used by bacteria to adapt to their environment. Molecular genetic, traditional microbiology, and ecology experiments are used in her research program. Major projects currently being investigated are (1) to determine the diversity and role of microbial populations in communities of various ecosystems, (2) to determine methods to detect potential sources of pathogenic microorganisms in the environment, and (3) to determine the genetic elements and mechanisms involved in horizontal gene transfer in the environment.

Kenneth H. Nealson, University of Southern California
After receiving his B.S. degree in biochemistry (1965) and Ph.D. in microbiology (1969), both from the University of Chicago, Dr. Nealson did

postdoctoral work with Dr. J. W. Hastings at Harvard University. He then moved to the Scripps Institution of Oceanography (University of California, San Diego), where he remained for 12 years, studying various aspects of marine bioluminescence, particularly the physiology and ecology of luminous bacteria and the organisms with which they are symbiotically associated. During this time, the process of autoinduction (later called quorum sensing) was defined, the active molecules were isolated, and the genes were cloned. In 1982, utilizing a Guggenheim Fellowship for sabbatical leave, Dr. Nealson shifted his area of work to environmental microbiology and biogeochemistry, with a focus on the interactions between microbes and metals. In 1985 he took a position as the Shaw Distinguished Professor of Biology at the University of Wisconsin's Center for Great Lakes Studies, where he continued his studies of metals and microbes. Dr. Nealson is a fellow of the American Academy of Microbiology and has received several awards and commendations, including several from the Society for Industrial Microbiology and the American Society for Microbiology. In 1997 Dr. Nealson moved to the Jet Propulsion Laboratory at the California Institute of Technology, where he established the Center for Life Detection, and served as director of the astrobiology group, developing new methods for life detection. In 2001 he moved to a new position as the Wrigley Professor of Geobiology at the University of Southern California, setting up the program in geobiology, and continuing studies of organisms and communities in extreme environments on Earth and, perhaps, elsewhere.

Iain M. Young, Scottish Informatics, Mathematics, Biology, and Statistics (SIMBIOS) Centre, University of Abertay

Iain M. Young has a background in experimental soil mechanics and moved into soil biophysics 12 years ago. He was head of the Soil-Plant Dynamics Theme (a multidisciplinary team of 35 scientists comprising microbiologists, physicists, and plant scientists) at the Scottish Crop Research Institute. Since January 2000 he has held the chair of environmental biophysics at the University of Abertay, in Dundee, Scotland. In partnership with Professor John Crawford, he established SIMBIOS at Abertay, which now comprises a multidisciplinary staff of 23. After only two years, SIMBIOS was rated as the top environmental research center in Scotland and in the top five in the United Kingdom. The main drive for his work relates to the integration of physics with microbiology of soil systems, in the context of how geometrically complex architectures impact, and are impacted by, microbial activity, and how this feeds through to function: water quality, pollutant flow, and so on. Professor Young has acted in an advisory capacity to the U.K. government on soil quality issues, and the Irish Environmental Agency on future soils research.

Brenda J. Buck, University of Nevada
Brenda J. Buck is associate professor in the Department of Geoscience at the University of Nevada, Las Vegas. Her prior positions include visiting scientist at the Desert Research Institute, Las Vegas, Nevada; assistant professor in the Department of Geoscience at the University of Nevada, Las Vegas; and assistant professor at the Southeast Missouri State University, Cape Girardeau. Her research focuses on determining and quantifying the processes involved with the genesis of arid soils and paleosols. This research is applied to solve problems involving environmental contamination (heavy metals and radionuclides), paleoclimate, geoarchaeology, landscape evolution, soil geomorphology, and salt tectonics. Dr. Buck has experience in 18 countries on 6 continents. She is a member of the Soil Science Society of America, the Geological Society of America, and Sigma Xi. Dr. Buck received a Ph.D. in agronomy (1996) and a M.S. in geoscience from New Mexico State University; and a B.S. in geology from the University of Notre Dame.

Larry P. Wilding, Texas A&M University
Larry P. Wilding is professor emeritus, Soil and Crop Sciences Department, Texas A&M University. He is a pedologist with more than 40 years teaching and research experience in near-surface geoscience processes, soil diversity, and functions of soils in ecosystem management and biosphere sustainability. He has published extensively on soil spatial diversity, pedogenic quantification through micromorphology and reconstruction analyses; silica minerals as markers of parent material uniformity and paleontology; saturation, reduction, and redoximorphic features in hydric soils; pedogenic carbonate genesis and distribution; shrink-swell phenomena in Vertisols; soil mineralogy and weathering relationships; surface mine reclamation; macropore flow and environmental risks in clayey soils; and land degradation, rejuvenation, and evaluation in Africa, China, and Latin America. He has served as president of the Soil Science Society of America, a charter member of the U.S. National Committee for Soil Science, and on several National Research Council committees. He was cochair of the 18th World Congress of Soil Science Organizing Committee. He is a registered professional soil scientist and professional agronomist with the American Registry of Certified Professionals in Agronomy Crops and Soils (ARCPACS), Soil

Science Society of America, and a professional geoscientist (soil scientist), license number 42, state of Texas.

César Izaurralde, Joint Global Change Research Institute, University of Maryland
César Izaurralde is interim director and laboratory fellow of the Joint Global Change Research Institute at College Park, Maryland. The institute is a collaboration of the Pacific Northwest National Laboratory and the University of Maryland. He also has adjunct appointments in the departments of Geography and Natural Resource Sciences and Landscape Architecture at the University of Maryland. Dr. Izaurralde earned his agronomist engineer degree from the University of Córdoba (Argentina) and his M.Sc. and Ph.D. degrees from Kansas State University. Dr. Izaurralde's research focuses on three areas: (1) sustainable agriculture, (2) climate change impacts on agriculture and water resources, and (3) climate change mitigation through soil carbon sequestration and reductions in soil emissions of nitrous oxide. Dr. Izaurralde is an active member of the American Society of Agronomy, the Soil Science Society of America, the American Association for the Advancement of Science, the American Geophysical Union, and the American Society for Photogrammetry and Remote Sensing.

Henry Lin, Pennsylvania State University
Henry Lin is an assistant professor of hydropedology/soil hydrology at the Pennsylvania State University. He holds a B.S. in soil science and agricultural chemistry from Fujian Agricultural University, China; a M.S. in soil geography from Nanjing Institute of Soil Science of the Chinese Academy of Sciences; and a Ph.D. in soil science (soil physics and pedology) from Texas A&M University. His research and teaching program focuses on the development of hydropedology as an intertwined branch of soil science and hydrology that embraces interdisciplinary studies of landscape-soil-water relationships across scales. He is the chair of the Hydropedology Working Group of the Soil Science Society of America and of the International Union of Soil Sciences, an associate editor of the *Soil Science Society of America Journal*, and a cochair of the Committee on Soil Survey and Water Movement of the National Cooperative Soil Survey Conference. He has led a team of interdisciplinary and international scientists in completing a vision paper for the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), a National Science Foundation-sponsored and community-based professional organization.

Susan Moran, U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center
Susan Moran is a hydrologist and research leader for the USDA-ARS Southwest Watershed Research Center in Tucson, Arizona. She received her Ph.D. and is an adjunct professor at the University of Arizona Department of Soil, Water, and Environmental Science. Her research addresses estimation of soil water and carbon flux at local and regional scales utilizing a combination of physical models and remote sensing techniques. Dr. Moran has also served on the National Aeronautic and Space Administration's Landsat Science Team and EO-1 Validation Team to evaluate selected technologies for meeting soil science needs in the twenty-first century.

Kenneth Kemner, Argonne National Laboratory
Kenneth Kemner obtained his Ph.D. in condensed matter physics at the University of Notre Dame in 1993. From 1993 to 1996 he was a National Research Council postdoctoral fellow at the Naval Research Laboratory in Washington, D.C., where he focused on the investigation of magnetic materials and environmental research. In 1996 he joined the Environmental Research Division at Argonne National Laboratory near Chicago, Illinois, where he began development of the Molecular Environmental Science Research Group, an integrated multidisciplinary research group interested in making use of third-generation synchrotron radiation for environmental research. Since 1997 he has been investigating mineral-microbe-metal interactions and their role in effecting the mobility of contaminant metals and radionuclides, with an emphasis on understanding the role of microbial exudates and microbial surface adhesion on these interactions. In 1999 he received the Presidential Early Career Scientist Award and the Department of Energy Office of Science Early Career Scientist Award. In 2000 he received the International Union of Crystallography Young Scientist Award.

Kenneth J. Klabunde, Kansas State University
Kenneth J. Klabunde is a university distinguished professor of chemistry at Kansas State University, and founding director of NanoScale Materials, Inc., in Manhattan, Kansas. Dr. Klabunde received his education at Augustana College in Rock Island, Illinois, and earned his Ph.D. at the University of Iowa. He served a year as a postdoc at Pennsylvania State University, and began as assistant professor at the University of North Dakota. In 1979 he moved to Kansas State University, where he served as department head until 1988. In 1995 he founded NanoScale Materials, a

high-technology company that specializes in the manufacture and sale of NanoActive Materials™ as sorbents, catalysts, and other uses. Dr. Klabunde has won numerous awards (including the Breakthrough Invention Award from *Popular Mechanics Magazine* in November 2005), and he was one of the earliest workers in nanotechnology, publishing in 1976 on the unusual chemical properties of different-shaped nanoparticles. He and his students have devised synthetic methods to create numerous metal oxide and metal nanoparticles, and they have shown that metal oxide nanomaterials make up a new family of reactive, porous, inorganic materials. Extensive work on such materials has demonstrated their usefulness for sorption and destruction of toxic chemicals, chemical warfare agents, and biological agents.

Kate Scow, University of California (UC), Davis
Kate Scow is professor of soil science and microbial ecology in the Department of Land, Air, and Water Resources at UC, Davis. She is currently director of the Kearney Foundation of Soil Science, a UC-wide endowed program supporting research on 5-year defined missions, currently "Soil Carbon and California Terrestrial Ecosystems." She obtained her B.S. in biology at Antioch College (1973) and her M.S. (1986) and Ph.D. (1989) degrees in soil science at Cornell University. Her research concerns the microbial ecology of agricultural landscapes and contaminated soil and groundwater. In particular, Dr. Scow's research group is interested in how microbial communities in general, as well as specific functional groups, respond to physical disturbance and organic matter additions in organic and conventional agricultural soils. Also, Dr. Scow's lab has conducted extensive research on the microbial ecology and bioremediation of the fuel additive methyl tertiary butyl ether (MTBE), a ubiquitous contaminant of groundwater. Her research program works across different scales, from genome analysis to field-scale implementation of bioremediation systems.

Jayne Belnap, U.S. Geological Survey Canyonlands Research Station, Utah
Jayne Belnap has been a scientist with the Department of Interior since 1987, and is currently with the U.S. Geological Survey, Biological Resources Division, in Moab, Utah. Her scientific work is focused on how climate change and land use affects the fertility and stability of dryland soils around the world. She has served as an editor for *Ecological Applications*, the chair for the Soil Ecology section of the Ecological Society of America, and the president of the Soil Ecology Society.

Birl Lowery, University of Wisconsin, Madison
Birl Lowery is a professor in the Department of Soil Science at the University of Wisconsin, Madison. Dr. Lowery received a Ph.D. in soil physics from Oregon State University; an M.A. in agricultural engineering technology from Mississippi State University; and a B.S. in agricultural education from Alcorn State University. Dr. Lowery is the recipient of the following awards and honors: the American Society of Agricultural Engineers Blue Ribbon Award for an outstanding entry in the 1987 Educational Aids Competition; fellow of the Soil Science Society of America, 1997; and Vilas Research Associate 1998 to 2000. His research consists of applications of basic soil physical principles to solve soil and water management and conservation problems. This involves both field and laboratory work, focusing on the dynamics of soil water and temperature regimes, solute flux, soil compaction, and other physical properties. He is particularly interested in developing methods for better understanding spatial movement of water and pollutants in soils; soil compaction, including the effect of tree harvesting on compaction; effects of soil erosion on soil quality; and developing new management methods for crop production to reduce surface and groundwater contamination.

Appendix C

Steering Committee Members

Charles W. (Chuck) Rice (*Chair*) is professor of soil microbiology and director of the Consortium for Agricultural Soils Mitigation of Greenhouse Gases at Kansas State University, where he has served on the faculty since 1988. His current research interests include soil microbial ecology, carbon and nitrogen cycling in terrestrial ecosystems, denitrification, and nitrogen mineralization. Dr. Rice is active in many professional societies, including the Soil Science Society of America, American Society of Agronomy, and the American Association for the Advancement of Science. He earned his Ph.D. in 1983 from the University of Kentucky in soil microbiology. He is a member of the U.S. National Committee for Soil Science.

Paul M. Bertsch is professor of environmental chemistry and toxicology at the University of Kentucky. He previously served as director of the Savannah River Ecology Laboratory and professor of soil physical chemistry and mineralogy at the University of Georgia at Athens. His current research interests include molecular environmental science, biogeochemistry, surface geochemistry, and the influence of mineralogical and surface charge properties of sediments and soils on geochemical processes. Dr. Bertsch earned his Ph.D. in soil physical chemistry and mineralogy from the University of Kentucky in 1983. He is currently chair of the U.S. National Committee for Soil Science and previously served on the Committee on Earth Resources of the National Research Council.

Johan Bouma is a member of the Royal Dutch Academy of Sciences (RDAS) (1989), a fellow of the Soil Science Society of America (1983), and an honorary member of the International Union of Soil Sciences (2006). His research interests are in the field of hydropedology and land-use policy. He was a member of the Scientific Council for Government Policy in the Netherlands from 1998 to 2004. He was vice chair of the physics section board of the RDAS in Amsterdam (2004-2006) and is chair of the scientific advisory committee of a national research program on sustainable agriculture. Dr. Bouma obtained his Ph.D. in 1969 at Wageningen University, the Netherlands, in soil science and soil tillage. He was a tenured associate professor of soil science at the University of Wisconsin, Madison from 1972 to 1975. He recently retired from Wageningen University.

Jennifer Harden is a soil scientist on the research staff at the U.S. Geological Survey, where she has served as project scientist and/or project chief since 1982. She has contributed to research on geologic mapping, geochronology, geologic faulting, paleoclimate, landform evolution, carbon cycling, and biogeochemical interactions in soil systems. Her research is currently focused on the role of soils in carbon and nutrient cycling, with an emphasis on landscape disturbances such as glaciation, agricultural erosion and sedimentation, and wildfire. She received her Ph.D. in soil science at the University of California, Berkeley, in 1982.

Jerry L. Hatfield is director at the U.S. Department of Agriculture–Agricultural Research Service National Soil Tilth Laboratory at Ames, Iowa. He has developed a quantitative understanding of the interactions of water-radiation-nitrogen across different soils, leading to improved production efficiency, grain quality, and environmental quality in crop production systems. He is also involved in the integration of remote-sensed data into soil and crop management models that will lead to improved crop management decisions. Dr. Hatfield's research has also improved understanding of the energy and gas exchanges in the soil-plant-atmosphere complex that accounts for spatial and temporal variations. He earned his Ph.D. in agronomy (agricultural climatology) at Iowa State University in 1975.

Julie D. Jastrow is a terrestrial ecologist in the Biosciences Division at Argonne National Laboratory in Illinois, where she has been on the scientific staff since 1975. She is a past president of the Soil Ecology Society. Dr. Jastrow has contributed to research on restoration ecology, mycorrhizae, and soil aggregation. She is currently involved in research to understand and quantify the processes involved in soil carbon storage and turnover, which is essential for determining the carbon sequestration potential of terrestrial ecosystems. She earned her Ph.D. in biological sciences from the University of Illinois at Chicago in 1994.

William A. Jury is emeritus distinguished professor of soil physics at the University of California, Riverside, and a former member of the U.S. National Committee for Soil Science. His long-term research interests are in the areas of measurement and modeling of organic and inorganic chemical movement and reactions in field soils, and more recently in global water issues. Dr. Jury earned his Ph.D. in physics at the University of Wisconsin in 1973. He is a member of the National Academy of Sciences.

Joaquin Ruiz is the dean of the College of Science and a professor of geosciences at the University of Arizona. From 1995 to 2000, Dr. Ruiz served as the head of the University of Arizona's Department of Geosciences. Dr. Ruiz is an expert in radiogenic isotopes applied to the study of regional tectonics, origin of magmas, and hydrothermal ore deposits. He is a fellow of the Geological Society of America and Society of Economic Geologists. He is a member of the National Research Council's Board on Earth Sciences and Resources, and a former member of the Committee on Earth Resources. He received a B.Sc. in geology and a B.S. in chemistry from the University of Miami, and an M.S. and Ph.D. (1983) in geology from the University of Michigan, Ann Arbor.