Soil Science and Geology: Connects, Disconnects and New Opportunities in Geoscience Education

Edward R. Landa U.S. Geological Survey, 430 National Center, Reston VA 20192,
erlanda@usgs.gov

ABSTRACT

Despite historical linkages, the fields of geology and soil science have developed along largely divergent paths in the United States during much of the mid- to late- twentieth century. The shift in recent decades within both disciplines to greater emphasis on environmental quality issues and a systems approach has created new opportunities for collaboration and cross-training. Because of the importance of the soil as a dynamic interface between the hydrosphere, biosphere, atmosphere, and lithosphere, introductory and advanced soil science classes are now being taught in a number of earth and environmental science departments. The National Research Council's recent report, *Basic Research Opportunities in Earth Science*, highlights the soil zone as part of the land surface-to-groundwater "critical zone" requiring additional investigation. To better prepare geology undergraduates to deal with complex environmental problems, their training should include a fundamental understanding of the nature and properties of soils. Those undergraduate geology students with an interest in this area should be encouraged to view soil science as a viable earth science specialty area for graduate study. Summer internships such as those offered by the National Science Foundation-funded Integrative Graduate Education, Research, and Training (IGERT) programs offer geology undergraduates the opportunity to explore research and career opportunities in soil science.

INTRODUCTION

Geology's traditional sub-specialties have looked at the earth divided by major rock types (*e.g.*, igneous, sedimentary, and metamorphic), by links to engineering, chemistry, physics, and biology (*i.e.*, engineering geology, geochemistry, geophysics, and geobiology), by a focus on specific environment or resources (*i.e.*, oceanography, hydrogeology, and economic geology), or by a focus on the static and dynamic properties of earth materials (*i.e.*, mineralogy, geomorphology, and structural geology). Soil science looks at the outer skin of the terrestrial earth. By definition, its place as a geology sub-specialty is clear. But the reality is that soil science in the United States has developed remarkably separate and distinct from geology, typically being regarded as an agricultural science rather than an earth science. In the past two decades, however, both fields have shown major shifts towards a focus on environmental quality issues. Soils play an essential role in supporting life on Earth; are a scarce resource of great economic value; are easily disturbed and respond quickly to environmental changes; and indeed, as Haff (2002) has noted, bear the brunt of human impact on the land surface.

The need for interdisciplinary approaches to address complex issues of resource- and waste-management in the surficial environment has created greater opportunities for geologists and soil scientists to work together. With this shift has come the need for greater cross-training of students in each field. To encourage such interaction, it is of value to look at areas of connection in the past and present, and to examine ways to bridge the gaps that divide the disciplines.

HISTORICAL SETTING AND CURRENT SITUATION

Soil science emerged as an integrated discipline from work in geology on soil formation, and work in agricultural chemistry on plant nutrition. Agricultural geology was a recognized specialty for geologists in the nineteenth and early twentieth century (Tandarich, 1998). The term "soilist," for a geologist specializing in soils, was introduced by U.S. Department of Agriculture (USDA) soil survey specialist George N. Coffey, who received a Ph.D. in 1912 in geology from George Washington University for a dissertation on soil classification. However, the term never caught on (Brevik, 1999). At the beginning of the twentieth century, there were geological institutes in Hungary and elsewhere in Europe with departments of agrogeology (Szabolcs, 1997). In the United States, many early state geological survey reports contained sections on the distribution of soils and crop production (*e.g.*, Jackson, 1840).

While geology departments exist in the colleges of arts and sciences at many United States institutions of higher learning, soil science departments typically have been confined to the land grant universities in each state. The Morrill Acts of 1862 and 1890 established the land grant institutions to promote education in agriculture, and it was within this academic setting and its associated system of agricultural experiment stations that the field of soil science was taught and practiced. In some universities outside of the United States (*e.g.*, Massey University in New Zealand, the Czech University of Agriculture in the Czech Republic, Ghent University in Belgium, and Wageningen University in the Netherlands), joint soil science and geology departments presently exist. Indeed, this was the case at some American land grant colleges at the turn of the twentieth century. For example, at South Dakota Agricultural College [now South Dakota State University (SDSU)], a combined geology and agronomy or soil physics department existed from 1897 to 1905 (written communication, Elizabeth B. Scott, Archivist, Hilton M. Briggs Library, SDSU, Dec. 21, 2000). At the University of Maryland, the geology and agronomy faculties were in the same department until 1973 (Robert Ridky, oral communication, 3 July 2002).

Soil scientists and geologists in academia and federal agencies have worked together in a variety of settings in the past few decades. Examples in pedology (the specialty dealing with the genesis, morphology, taxonomy, and landscape relations of soils) and geomorphology are most evident. Leaders in this regard within the geologic community have included Peter Birkeland at the University of Colorado (author of the textbook *Soils and Geomorphology*, now in its third

Isolation and characterization of soil and aquatic humic substances (Malcolm, 1986; Leenheer and others, 2003).
Retention of trace elements by iron and manganese oxides, and development of selective extraction techniques for use in geochemical prospecting (Chao, 1972; Jenne, 1977).
Water quality assessment (Krieger and others, 1957).
Effects of industrial activities on the distribution of trace elements in soils and plants (Severson and Gough, 1979).
Carbon cycling and sequestration in watersheds (Harden, et al., 1999).
Characterization of geochemical form of radionuclides in uranium mill tailings and their mobilization by anaerobic microbial processes (Landa and others, 1991).
Relation of ground water quality to land use (Eckhardt and Stackelberg, 1995).
Modeling transport of reactive solutes in porous media (Rubin, 1983).
Investigation of the movement of water, soil gases, and contaminants in the unsaturated zone at nuclear waste burial- and other sites (Andraski and others, 2003; Healy and others, 1996).
Methods development in unsaturated flow (Nimmo and others, 1987).
Effects of temperature on hydrological processes in the unsaturated zone (Constantz and others, 2003).

Table 1. Examples of research by soil scientists at the USGS.

edition), John Hawley of the USDA's Desert Soils Project, and Robert Ruhe at Indiana University. Ruhe's geology graduate students at Indiana took extensive training in soil science at the Agronomy Department of Purdue University.

"Soils occupy a niche that gives them a dynamic character and a subtle memory. The organic content of surface soil can change rapidly (in as little as 10 to 100 years) in response to climatic and ecological changes or land management practices. In contrast, extensive weathering of a soil's mineral content requires much more time. Soils thus acquire their basic attributes at very different rates. They reflect both the present and the past, recording how they have changed in response to recent events while they document changes (like weathering) that have occurred over tens of thousands of years." This elegant quote from University of Wisconsin soil scientists Kevin McSweeney and John Norman (1996) sums up the central role of soils in biogeochemistry. Indeed, the field has its roots in the 1926 treatise "The Biosphere" by Russian soil scientist Vladimir I. Vernadsky. Research on cycling of nutrients such as carbon, nitrogen, sulfur, and phosphorous, and of contaminant elements such as arsenic, is underway in many soil science departments today.

Soil scientists have a long history at the U.S. Geological Survey (USGS). Examples of their investigations are shown in Table 1. Because of its importance as an environment for waste disposal, major research efforts have focused on the unsaturated zone; the USGS hosts an unsaturated zone interest group at http://mn.water.usgs.gov/uzig/about.htm. The most requested data set in the USGS National Geochemical Database consists of analyses of 1300 surface soils collected from non-cultivated fields with native vegetation in the conterminous United States during the 1960s and 1970s; this data is widely used to establish baseline concentrations of metals and other elements. The USGS and NRCS are currently conducting pilot studies for a joint, major expansion and upgrading of the national-scale soil geochemical database (Smith and others, 2003). In the USGS today, where topics such as pesticide-, nutrient- and pathogen-transport, carbon storage, and rangeland quality are now commonplace, research opportunities for soil scientists and geologists with training in soil science, are growing.

In its recent report, *Basic Research Opportunities in Earth Science*, the National Research Council (2001) noted the need for more studies of the earth's near-surface environment in order to better understand and assess human impacts in this "critical zone". Soil science and the study of coastal zone processes were singled out as requiring greater attention and funding by National Science Foundation's (NSF) Division of Earth Sciences.

A recognition of the importance of soils is not limited to the basic science community. Geologists and engineers are increasingly dealing with soil-contamination cleanups and wetland delineation. Demand for housing and commercial space in the United States has led to the rapid expansion of suburban communities in areas beyond the reach of existing sewer systems. More than 37 percent of new development in the nation uses on-site wastewater disposal systems (Dix, 2001). This has created an increasing need for expertise in soil suitability for the safe disposal of wastewater using septic fields and alternative technologies. Environmental health specialists, engineers and geologists who are called upon to make these siting decisions look to soil scientists for guidance on issues such as soil structure and redox status as indicators of suitable soils. Natural Resources Conservation Service (NRCS; the former Soil Conservation Service) soil scientists at regional offices spend considerable time on such efforts (Ed Redmond, NRCS-Mt. Vernon, Ohio; oral communication, September 29, 2001). The Soil Science Department at North Carolina State University has pioneered training efforts in this area. Its efforts clearly recognized the needed links to geologic expertise, and among its early instructors was USGS hydrogeologist Ralph Heath. The program is now sponsored jointly with the Department of Geology at East Carolina University.

K-12 EDUCATION

I recently visited the New Mexico State Science Fair and was impressed by the number of projects at the middle school level within the earth science section that focused on soils. Many projects at the science fair used the book *A Study of Soil Science* by Henry D. Foth (1970) as a resource. Foth, a professor of soil science at Michigan State University who died in 1994, was active in bringing a soils component into the American Geological Institute's (AGI) Earth Science Curriculum Project (ESCP) of the late 1960s – early 1970s. He co-authored a field guide to soils and contributed to the ESCP text *Investigating the Earth*. The impact of these efforts, three decades ago, to bring soil science into the K-12 earth-science curriculum is still clearly evident today.

"How far down does the dirt go?" — this is the kind of question kids ask (Schneiderman, 2001). There is an inherent fascination with this material underfoot everywhere, making soils a natural entrée to the world of earth science. In the minds of pre-college students, the identity of soil science as an earth science is clear. College-level geology curricula that ignore or minimize

Ion exchange, and origin of permanent and pH-dependent charges on minerals.
Concept of bioavailable nutrients. Use of plant-available soil testing procedures and other selective extraction procedures (in contrast to total element measurements).
Bulk density, soil structure, and their effects on water flow.
Soil (and rock) color description using the Munsell charts. Use of soil color to identify redox conditions in soil profiles and implications for land use management.
Concepts of plant-available water holding capacity, and use of the soil moisture retention curve to calculate available water.
Five factors of soil formation.
Soil Taxonomy (Brevik, 2002); its nomenclature and diagnostic criteria.
Soil micromorphology, and use of soil thin sections (Stoops, 2003; accompanying CD contains hundreds of thin section images).
Indices of soil quality (Langley-Turnbaugh and Evans, 2001).
Role of microorganisms in cycling of carbon, nitrogen, sulfur and iron.

Table 2. Possible soils topics for inclusion in undergraduate geology courses.

teaching about soils truncate this student interest by establishing impediments or dead-ends to a natural progression from early interests. Every effort should be made to avoid this.

Recent efforts to improve the teaching of soils at the middle school level have been undertaken by AGI as part of its inquiry-based Investigating Earth Systems curriculum (http://www.agiweb.org/ies/soil.html). NASA soil scientist Elissa Levine hosts a comprehensive K-12 soil science education homepage (part of NASA's GLOBE Program) at http://www.globe.gov/fsl /welcome.html. Among the advanced topics covered are ion exchange, thin sections, making soil monoliths, and soil characterization protocols. A major exhibit on soils at the Smithsonian Institution's National Museum of Natural History in Washington, DC is presently in the planning stage (www.soils.org/smithsonian).

COLLEGE & UNIVERSITY LEVEL

Introductory geology classes and textbooks must cover a wide range of topics. Soils and weathering generally receive one-chapter treatment. The focus in most introductory texts is on the soil profile. The modern system of soil classification used in the United States is generally ignored in favor of the old "podzol-pedalfer-pedocal-laterite" system. The new system, with its 11 soil orders, is an elegant scheme, developed over several decades, based on observable and measurable soil features, and using nomenclature with information-filled prefixes and suffixes. Its inclusion in introductory geology classes is recommended. For supplementary topics, instructors may want to include some discussion of the dynamic properties of soils— *e.g.*, ion exchange, nutrient cycling, shrink-swell behavior, and water movement. With the current popularity of the television show "CSI: Crime Scene Investigation", another supplementary topic of likely broad interest is the application of soils information in forensic studies. An excellent source of material on this topic is *Forensic Geology: Earth Sciences and Criminal Investigation* by geologist Raymond C. Murray and soil scientist John C. F. Tedrow (1975). Alfred R. Conklin, Professor of Agriculture and Chemistry at Wilmington College (Ohio), writes a series of short articles on basic concepts in soil science (*e.g.*, soil microorganisms, soil pores, infiltration and percolation, and soil and sediment) suitable for use in introductory classes for the magazine *Contaminated Soil Sediment and Water*, and available at http://www.aehsmag.com/issues.htm. Suggested topics for inclusion in undergraduate geology courses are given in Table 2.

Introductory and, in some cases, advanced soil science classes are presently being taught in a rapidly expanding number of earth and environmental science departments [e.g., Carleton College, City College of New York, Dartmouth College, Hamilton College, Harvard University (in their landscape architecture program), Minot State University, New Mexico Institute of Mining and Technology, Portland State University, Richard Stockton College of New Jersey, San Francisco State University, Southeast Missouri State University, Stanford University, State University of New York at Plattsburgh, University of Akron, University of Oklahoma (these last two in geography departments), University of Southern Maine, University of Texas at San Antonio, University of Virginia, Valdosta State University, Vassar College, Yale University].

Activities such as a workshop held at the College of Wooster in September 2001 on *Soils and the Undergraduate Curriculum*, sponsored by the Soil Science Society of America (SSSA), the Keck Geology Consortium, NRCS and USGS have been aimed at encouraging the teaching of soil science in geoscience departments. Fifteen geology faculty members (plus one person each from departments of geography and archaeology) from non-land grant institutions participated. The three-day workshop featured lectures on soil mapping, micromorpholgy, chemistry, fertility, physics, and microbiology; visits to soils research facilities operated by Ohio State University and the USDA Agricultural Research Service; and several mapping exercises in glaciated and unglaciated terrains. Proactive steps by professional societies and others are helping to break down historical and institutional boundaries between the two communities.

Movement across traditional academic boundaries is growing. For example, at California Polytechnic State University-San Luis Obispo, a geology minor is offered in conjunction with the Earth and Soil Sciences Department (College of Agriculture); geology faculty (housed here in the Physics Department of the College of Science and Mathematics) teach these courses. Among full-time geology faculty at a variety of institutions, one now sees soil scientists or geologists with graduate or post-doctoral training in soil science. An informal survey of position-available advertisements in *Geotime*s, *EOS*, and the newsletter of the SSSA over the past two years shows a variety of new faculty positions that integrate soil science and the other geosciences. These trends are also apparent in graduate student-, postdoctoral- and research support staff-recruitment and hiring.

Cross-disciplinary training and hiring is a reality for soil scientists, as well as for geologists. For example, the undergraduate soil science program at Pennsylvania State University now requires a course in hydrogeology. Students from soil science with interests in paleosols and

Soil survey opportunities may exist within the Natural Resources Conservation Service; local contact information is available on the web at

http://offices.usda.gov/scripts/ndISAPI.dll/oip_public/USA_map.

Advanced undergraduates interested in biogeochemistry, surface and colloid chemistry, biodegradation of soil contaminants, and soil-water movement can get research experience (with a stipend to cover living expenses) at various campuses under the NSF-funded Integrative Graduate Education, Research, and Training (IGERT) program:

Washington State University, Center for Multiphase Environmental Research
http://www.cmer.wsu.edu/Igert.htm
Pennsylvania State University, Biogeochemical Research Initiative for Education
http://www.ems.psu.edu/BRIE/
University of California - Davis, NEAT (Nanophases in the Environment, Agriculture, and Technology)
http://neat.ucdavis.edu/index.htm

Table 3. Summer internship opportunities in soil science.

saturated zone hydrology may opt for graduate training in geology departments. Tackling ground water vulnerability-, soil contamination-, land use- and other issues being dealt with by regulatory agencies and environmental consulting companies requires a breadth of earth-science expertise; as a result, employment opportunities for students with cross-disciplinary training in soils and geology can be expected to grow in coming years.

For undergraduate geoscience students who wish to explore possible specialization in soil science, summer jobs and internships may be valuable experiences (Table 3). The IGERT centers noted in Table 3 are also bringing geology and soil science faculty, postdocs, and graduate students together on research projects. In Europe, similar interactions across earth science disciplines are being stimulated by the Marie Curie Training Sites (MCTS) such as the MCTS Postgraduate Centre for Biogeochemistry at the University of Newcastle upon Tyne (http://nrg.ncl.ac.uk/mariecurie/mariecurie2.html), and the MCTS in Analytical, Computational and Experimental Studies in Earth Sciences at the University of Bristol (http://mcts.gly.bris.ac.uk/geochem.html).

Other summer undergraduate research opportunities in soil-related investigations exist under the NSF - Research Experiences for Undergraduates (REU) program. (For a general description of the REU program, see http://www.nsf.gov/home/crssprgm/reu/start.htm; soil science opportunities may be listed under either earth sciences or biological sciences. For an example of a specific project, see the interdisciplinary ecosystem research program at the Altona Flat Rock jack pine barrens in northeastern New York. http://faculty.plattsburgh.edu/david.franzi/PSURP/PSURPindex.htm).

PROFESSIONAL SOCIETY ACTIVITIES

The Soil Science Society of America (SSSA) is the major soil science professional society in the United States with some 5,700 members. In 1993, SSSA became a member of the AGI. Soil Science departments are now listed in the AGI Directory of Geoscience Departments, and the field of soil science and its subfields (soil physics, soil chemistry and mineralogy pedology, forest soils/rangelands/wetlands, soil biology and biochemistry, and paleopedology) are noted here as geoscience-specialty identifiers for individuals. The SSSA has an active outreach program whose goals are to spread soil science knowledge to other fields of science, and to heighten the awareness of soil science as an earth science discipline. Its sponsorship of the 2001 Wooster workshop noted above was a recent step in that direction. In 2008, SSSA and the Geological Society of America (GSA) will hold a joint annual meeting.

The SSSA website (www.soils.org) has an Internet glossary of soil science terms that is handy for instructors and students. The following symposia from recent SSSA annual meetings show just some of the topics of interest to other earth scientists:

- Deep regolith: Exploring the lower reaches of the soil,
- Landscape hydrology and the movement of nutrients through the soil,
- Interpreting water table data for land use decisions,
- Restoration of alluvial tailings deposits in Leadville, Colorado.

The SSSA also has an extensive publication program. It publishes the *Soil Science Society of America Journal*, the *Journal of Environmental Quality*, and a new electronic *Vadose Zone Journal* (published in cooperation with GSA). Among its book publications is the classic, four-volume *Methods of Soil Analysis*, covering physical, chemical, microbiological and mineralogical methods. Other earth science professional societies in which a good mix of soil scientists and geologists exists include Friends of the Pleistocene, the Hydrology Section of the American Geophysical Union, and the Clay Minerals Society. Informal one-on-one interactions within these societies have had a major role in helping to integrate the disciplines.

CONCLUSION

In the late 1880s and early 1890s, John Wesley Powell, the second director of the USGS and a strong supporter of soil surveys, pressed to have the agency moved from the Department of the Interior to the newly formed Department of Agriculture (Amundson and Yaalon, 1995). Such were the ties between geology and soil science a century ago. We are now at another interesting crossroad. The modern societal and scientific perception of soils has been extended beyond soil as solely a medium for plant growth. Soil is now also viewed as a natural body, a structural mantle, a water transmitting mantle, and an ecosystem component (Smith and Hudson, 2002). Clear links exist from these perspectives of soils to geomorphology, engineering geology, hydrology, and biogeochemistry. This is an exciting time to be working at the soil science/geology interface. Hydrogeologists are investigating macropore flow, a phenomenon first studied by soil physicists, as a possible aquifer recharge mechanism in semi-arid regions (Wood and others, 1997). At the same time, we have soil scientists using acoustic bathymetry data collected by the National Oceanic and Atmospheric Administration to help map subaqueous soils (Bradley and Stolt, 2002).

Within the geological and geographical sciences there has been a recent emergence of many subspecialty and hybrid fields in which a knowledge of the properties and behavior of soils, and an appreciation of their spatial heterogeneity and temporal dynamics is critical. These include:

Ecohydrology—the study of plant-water interactions; of the effects of hydrological processes on the distribution, structure and function of ecosystems; and of the effect of biological processes on components of the hydrological cycle (Eagleson, 2002; Newman and others, 2003).

Ethnopedology—the study of the perception, classification, appraisal, use and management of soils by indigenous people (WinklerPrins and Sandor, 2003).

Hydrogeophysics—the application of geophysical techniques for hydrogeological characterization of the shallow subsurface (Hubbard and Rubin, 2002; Müller, 2003).

Hydropedology—the bridging of traditional pedology with hydrology, geostatistics, and soil physics for application in soil-landscape modeling (Lin, 2003).

Nanogeoscience—the study of geological processes (typically near-surface) involving particles smaller than 100 nanometers (National Science Foundation, 2002).

Neogeomorphology—the study of the change of the earth's surface as a result of human activity (Haff, 2002).

While today there are many cross-cutting issues in geology and soil science—such as carbon sequestration, water quality, and vadose zone hydrology and contamination—there are also differences in perception, training, and institutional affiliations that tend to keep the disciplines and individual geologists and soil scientists apart. The realities of dealing with complex environmental problems and the action of professional societies are helping to bridge these gaps. Exposure of geology undergraduate students to an in-depth examination of the nature and properties of soils will be of benefit to their professional development and later work experience. Graduate training in a soil science department should be viewed as viable option for undergraduate geology students with interests in the surficial environment, and as a continuum of their development as geoscientists. Such departments offer unique opportunities for training, with a disciplinary depth not generally available elsewhere, in pedology, soil physics, soil chemistry and mineralogy, and soil microbiology.

ACKNOWLEDGMENTS

The views expressed here are those of the author, and do not reflect official policy of the U.S. Geological Survey. The author thanks Jill Schneiderman of Vassar University, Robert Ridky of the U.S. Geological Survey, Walter Parham of the China Tropical Lands Project, Annabelle Foos of the University of Akron, and Michele Hluchy of Alfred University for their review of the manuscript.

REFERENCES

Amundson, R., and Yaalon, D.H., 1995, E.W. Hilgard and John Wesley Powell: efforts for a joint agricultural and geological survey, Soil Science Society of America Journal, v. 63, p. 1485-1493.

Andraski, B.J., Sandstrom, M.W., Michel, R.L., Radyk, J.C., Stonestrom, D.A., Johnson, M.J., and Mayers, C.J., 2003, Plant and environmental interactions: Simplified method for detecting tritium contamination in plants and soil, Journal of Environmental Quality, v. 32, p. 988-995.

Birkeland, P.W., 1999, Soils and geomorphology (3ed ed.), New York, Oxford University Press, 430 p.

Bradley, M.P., and Stolt, M.H., 2002, Evaluating methods to create a base map for a subaqueous soil inventory, Soil Science, v. 167, p. 222-228.

Brevik, E.C., 1999, George Nelson Coffey: early American pedologist, Soil Science Society of America Journal, v. 59, p. 4-13.

Brevik, E.C., 2002, Problems and suggestions related to soil classification as presented in introduction to physical geology textbooks, Journal of Geoscience Education, v. 50, p. 539-543.

Chao, T.T., 1972, Selective dissolution of manganese oxides from soils and sediments with acidified hydroxylamine hydrochloride, Soil Science Society of America Proceedings, v. 36, p. 764-768.

Constantz, J., Tyler, S., and Kwicklis, E., 2003, Temperature-profile methods for estimating percolation rates in arid environments, Vadose Zone Journal, v. 2, p. 12-24.

Dix, S.P., 2001, Onsite wastewater treatment: a technology and management revolution: part 1, Water Engineering & Management, v. 148, p. 24-28.

Eagleson, P.S., 2002, Ecohydrology: Darwinian expression of vegetation form and function, Cambridge, Cambridge University Press, 443 p.

Eckhardt, D.A.V., and Stackelberg, P.E., 1995, Relation of ground-water quality to land use on Long Island, New York, Ground Water, v. 33, p. 1019-1033.

Foth, H.D., 1970, A study of soil science (2nd edition), Chestertown, Maryland, LaMotte Co., 48 p.

Haff, P.K., 2002, Neogeomorphology, Eos, Transactions, American Geophysical Union, v. 83, no. 29 (16 July 2002), p. 310, 317.

Harden, J.W., Sharpe, J.M., Parton, W.J., Ojima, D.S., Fries, T.L., Huntington, T.G., Dabney, S.M., 1999, Dynamic replacement and loss of soil carbon on eroding cropland, Global Biogeochemical Cycles, v. 13, p. 885-901.

Healy, R.W., Striegl, R.G., Russell, T.F., Hutchinson, G.L., and Livingston, G.P., 1996, Numerical evaluation of static-chamber measurements of soil-atmospheric gas exchange, Identification of physical processes: Soil Science Society of America Journal, v. 60, p. 740-747.

Hubbard, S., and Rubin, Y., 2002, Study institute assesses the state of hydrogeophysics, Eos, Transactions, American Geophysical Union, v. 83, no. 51 (17 December 2002), p. 602, 606.

Jackson, C.T., 1840, Report on the geological and agricultural survey of the state of Rhode-Island, made under the resolve of legislature in the year 1839, Providence, B. Cranston and Co., 312 p.

Jenne, E.A., 1977, Trace element sorption by sediments and soils—sites and processes, In Molybdenum in the environment (W.R. Chappell and K. K. Petersen, eds.); Proceedings of an International Symposium, New York, M. Dekker, v. 2, p. 425-553.

Krieger, R.A., Hatchett, J.L., Poole, J.L., 1957, Preliminary survey of the saline-water resources of the United States, USGS Water-Supply Paper 1374, 172 pp.

Landa, E.R., Phillips, E.J.P., and Lovley, D.R., 1991, Release of ^{226}Ra from uranium mill tailings by microbial Fe(III) reduction, Applied Geochemistry, v. 6, p. 647-652.

Langley-Turnbaugh, S.J., and Evans, C.V., 2001, A hierarchical evaluation of soil quality indicators in disturbed systems, Journal of Soil and Water Conservation, v. 56, p. 176-181.

Leenheer, J.A., Wershaw, R.L., Brown, G.K., and Reddy, M.M., 2003, Characterization and diagenesis of strong-acid carboxyl groups in humic substances, Applied Geochemistry, v. 18, p. 471-482.

Lin, H., 2003, Hydropedology—bridging disciplines, scales, and data, Vadose Zone Journal, v. 2, p. 1-11.

Malcolm, R.L. and MacCarthy, P., 1986, Limitations of the use of commercial humic acids in water and soil research, Environmental Science and Technology, v. 20, p. 904-911.

McSweeney, K., and Norman, J.M., 1996, Soil land modeling: issues of scale, Geotimes, v. 41, no. 6, p. 22-24.

Müller, M., 2003, Opening doors for geophysics in soil sciences, Eos, Transactions, American Geophysical Union, v. 84, no. 26 (1 July 2003), p. 243.

Murray, R.C., and Tedrow, J.C.F., 1975, Forensic geology: earth sciences and criminal investigation, New Brunswick, New Jersey; Rutgers University Press, 217 p.

National Research Council (Board on Earth Sciences and Resources, Commission on Geosciences, Environment, and Resources), 2001, Basic research opportunities in earth science, Washington, D.C., National Academy Press, 154 p.

National Science Foundation, 2002, Report of the nanoscience workshop (Berkeley, California, June 14-16, 2002), available at http://www.nsf.gov/home/crssprgm/nano/geo_workshop.pdf .

Newman, B.D., Sala, O., and Wilcox, B.P., 2003, Conference promotes study of ecohydrology of semi-arid landscapes, Eos, Transactions, American Geophysical Union, v. 84, (14 January 2003), p. 13, 17.

Nimmo, J. R., Rubin, J., Hammermeister, D.P., 1987, Unsaturated flow in a centrifugal field, Measurement of hydraulic conductivity and testing of Darcy's law,Water Resources Research, v. 23, p. 124-134.

Rubin, J., 1983, Transport of reacting solutes in porous media: Relation between mathematical nature of problem formulation and chemical nature of reactions, Water Resources Research, v. 19, p. 1231-1252.

Schneiderman, J.S., 2001, How hot is the Sun, Daddy? And other simple questions your kid might ask, Esquire, v. 135, (March 2001), p. 182-185.

Severson, R.C., and Gough, L.P., 1979, Environmental implications of element emissions from phosphate-processing operations in southeastern Idaho, U.S. Geological Survey Professional Paper 1083; 20 p.

Smith, D.B., Goldhaber, M.B., Wilson, M.A., and Burt, R., 2003, A proposal for upgrading the National-Scale Soil Geochemical database for the United States. U.S. Geological Survey Fact Sheet FS-015-03, available at http://pubs.usgs.gov/fs/fs-015-03/

Smith, H., and Berman, B.D., 2002, The American soil survey in the twenty-first century, In Profiles in the History of the U.S. Soil Survey (D. Helms, A.B.W. Effland, and P.J. Durana, eds.), Ames, Iowa; Iowa State University Press, p. 303-313.

Stoops, G., 2003, Guidelines for analysis and description of soil and regolith thin sections, Madison, Wisconsin, Soil Science Society of America, 184 p.

Szabolcs, I., 1997, The First International Conference on Agrogeology, April 14-24, 1909, Budapest, Hungary. *In* History of Soil Science: international perspectives (Advances in Geoecology no. 29; D.H. Yaalon and S. Berkowicz, eds.), Reiskirchen, Germany; Catena Verlag GMBH, p. 67-78.

Tandarich, J.P., 1998, Agricultural chemistry: disciplinary history; Agricultural geology: disciplinary history, In Sciences of the earth: an encyclopedia of events, people, and phenomena (G. Good, ed.), New York, Garland Publishing, p. 19-23, 23-29.

Vernadsky, V.I., 1926, The Biosphere [translated to English and reprinted with commentary; 1998], New York, Copernicus (Springer-Verlag), 192 p.

WinklerPrins, A.M.G.A., and Sandor, J.A. eds., 2003, Ethnopedology (special issue), Geoderma, v. 111, no. 3-4.

Wood, W.W., Rainwater, K.A., and Thompson, D.B., 1997, Quantifying macropore recharge: examples from a semi-arid area, Ground Water, v. 35, p. 1097-1106.