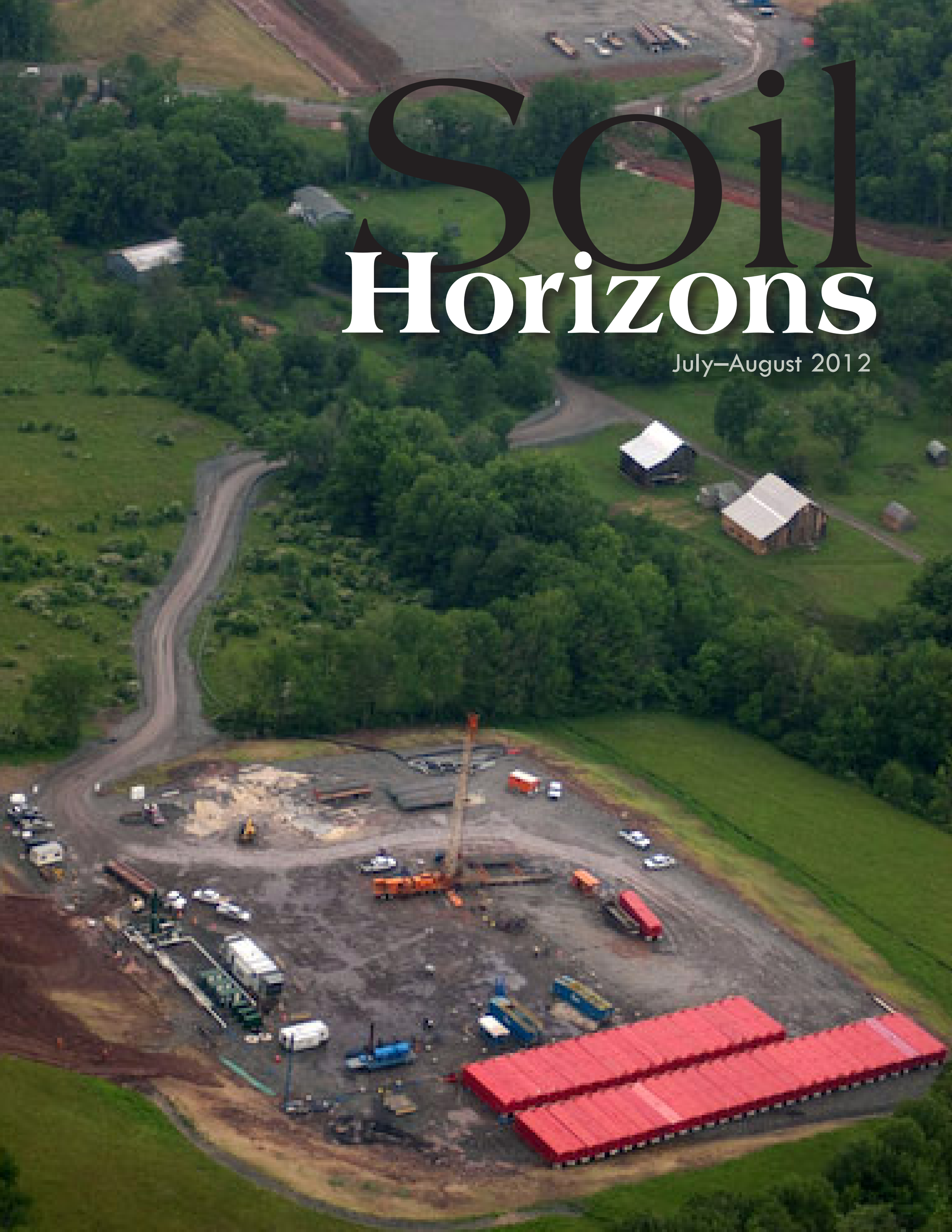
Soil Horizons

July–August 2012



Fracking's Footprint: Scientists Study Impact of Shale Gas Development on Pennsylvania's Forests

Madeline Fisher

Travel the length and breadth of Pennsylvania and you'll notice a divide that has defined the state from the start: The southeast is settled and wealthy farm country, while the less prosperous north and west have always depended on boom-and-bust cycles of resource extraction. Nearly all of Pennsylvania was clear-cut in the late 1800s and early 1900s, making it for a time the largest producer of lumber in the United States. Underground coal mining began even earlier, followed by surface strip-mining in the 20th century. Oil and gas production have also flourished here; since 1859, more than 325,000 wells have been drilled.

Now the latest boom is on. Thousands of feet below the surface are the Marcellus and Utica shales and their largely untapped reserves of natural gas.

For decades, geologists have known about the fuel stored in deep rock formations such as the Marcellus, which runs beneath Pennsylvania, New York, West Virginia, and other Appalachian states. But extracting it wasn't economical until the advent of horizontal drilling and the controversial technique known as hydraulic fracturing (view video here: http://marcellus.psu.edu/resources/drilling/index.php), or fracking. In the latter process, millions of gallons of pressurized water, sand, and chemicals are injected deep into the earth to fracture the shale and release the trapped gas.

Since 2004, nearly 3,000 shale gas wells have been drilled in Pennsylvania, which is still just a tiny fraction of the state's conventional oil and gas wells. But because shale gas is so deep and extracting it means handling massive amounts of water, much more infrastructure is involved than in conventional drilling—creating a much bigger footprint as a result, says Pennsylvania State University assistant soil science professor Patrick Drohan.

"I could see right away when I saw my first Marcellus gas pad," he says, "that this would be something that would change Pennsylvania's landscape unlike anything the state has seen in well over 50 years."

To support the drilling of a 5,000-foot-deep well and the fracking process that follows, engineers must build a raised, gravel pad of three to five acres in size and a stormwater system to handle the resulting runoff. New roads to the drill pad are needed, as are compressor stations for pumping the gas and pipelines to carry it away. And because most of the pressurized water comes back up once hydraulic fracturing is finished, flowback water storage ponds and treatment facilities must be constructed, as well.

A gas pad in Pennsylvania.

Pad access road in Pennsylvania.

Pipeline construction in Pennsylvania.

But the vast landscape changes produced by shale gas development are poorly understood, which is why Drohan, Penn State wildlife ecologist Margaret Brittingham, and others are now working to shed some much-needed scientific light on the process. Their first goal has been to char-

Madeline Fisher, associate editor–magazines, Soil Science Society of America, Madison, WI.

doi:10.2136/sh2012-53-4-lf
Published in *Soil Horizons* (2012).

acterize the Pennsylvanian landscapes where development is occurring: where the activity is concentrated, what the topography and soils are like, whether the land cover is agriculture or forest.

They then hope their data can inform the siting of future wells, pipelines, and roads so this infrastructure causes the least disturbance in the short term and eases the way toward bringing back farmland and forest later on.

Pennsylvania's Pine Creek Gorge.

Some of the most beloved forests in the state are found in and around Pine Creek Gorge (http://www.dcnr.state.pa.us/forestry/oldgrowth/pinecreek.aspx), known as the Grand Canyon of Pennsylvania. The site's expanse of trees is also among the last unbroken, "core" forest in the state and across the entire northeastern United States, as well.

It may not remain so, however. Drohan and Brittingham's work suggests that nearly 25% of Pennsylvania gas pads are being built in core forest areas, including those near Pine Creek, where at least one well rig now towers above the hills and trees. All told, some 1,700 acres of core forest could be lost to gas development, according to the scientists' study published this spring in *Environmental Management*. "That's still a very small part of the state," Drohan says. "But it's a very significant part of the state's forest."

Core forest is significant, in part, because of the birds that depend on it for their livelihood and survival, especially neotropical migrants, such as warblers, thrushes, and tanagers, which over-winter in Central and South America and then fly north in the summer to breed. Roughly 20% of the world's population of scarlet tanagers, for example, breeds in Pennsylvania.

The forest edge next to a gas pad.

The problem for these birds is that construction of pads, roads, pipelines, and other infrastructure opens up the canopy and creates new forest edges—essentially carving large, continuous blocks of forest habitat into smaller, patchier ones. As this occurs, Brittingham predicts that tanagers and other forest birds will be replaced by chickadees, woodpeckers, and other "generalist" species that thrive in smaller woodlots. And the same is true of plants, mammals, and amphibians.

"Basically, any species that can do well around people or across a range of habitats will tend to benefit" from the changes, she says. "And ones that are very specialized on a certain type of habitat and are sensitive to disturbance—you lose those."

Just as important is the loss of the ecological roles they play. Neo-tropical migrants, for instance, "are the insect-eating machines of the forest," Brittingham says, keeping down mosquitoes and forest pests. "They've evolved with the forest," she says, "and the forest has evolved with them."

Gas development in Bradford County, PA, in the Susquehanna River basin.

As forest is cleared and soils are removed or covered over to create pads and roads, land managers and scientists also want to prevent sediment erosion and nutrient runoff into downstream waterways. Of particular concern is shale gas development in the Susquehanna River basin—the source of more than half of the freshwater flowing into the embattled Chesapeake Bay.

Not only does this basin contain more pads than any of Pennsylvania's other major river basins (60% of existing pads and 54% of future, permitted ones), Drohan says, but 25% of these pads are in core forest, as well. Roughly 145 miles of new roads could also be built in the basin—an amount that is 10 to 100 times greater than in any other.

What this all means is that shale gas development poses a substantial new risk to the water quality of Chesapeake Bay, which people have already been struggling for decades to improve.

Plantings of trees and ground vegetation in a shale gas drilling area.

There is an urgent need, in other words, for a regional, landscape approach to siting drilling infrastructure, Drohan says, and on this front some progress is already being made. The Pennsylvania Department of Conservation and Natural Resources (DCNR), for example, is trying to get drillers to share pipeline corridors on state lands, rather than letting each cut its own pipeline path through the forest. Drohan also recently received a grant from the DCNR to model the locations of the wettest, most vulnerable soils on state forests so that the agency can work with the shale gas industry to protect these areas.

At the same time, 90% of Pennsylvania shale gas development is happening on private land today, according to his analysis with Brittingham, meaning that no single agency or organization has the final say on where drilling can take place or in what manner. Nor, for that matter, can any one group decide that people in economically depressed areas of Pennsylvania can't take advantage of the new opportunity.

Thus, the key to doing things right—or as right as possible—is for scientists, companies, landowners, local governments, and the public to keep on talking, Drohan says.

"I think one thing people need to be careful about is polarizing the issue. Once you do that, you're going to shut the door on any potential compromise," he says. "And at the end of the day, no entity is going to get its way. Some compromise will have to occur."

Editor's note: Unless otherwise noted, the images in this story come from the Penn State Extension Marcellus Electronic Field Guide (http://marcellusfieldguide.org/index.php), a resource for landowners on management topics ranging from preparing for shale gas development to restoring vegetation and wildlife habitat once drilling is finished. Interested in this topic? Check out the full-length version in the July issue of CSA News magazine (https://www.soils.org/publications/csa-news/).

My Thirty Years with Ground-Penetrating Radar

Jim Doolittle

It all began for me in Florida in the late 1970s when a USDA Soil Conservation Service (SCS) soil scientist became friends with a NASA engineer at the Kennedy Space Center. The soil scientist recognized that manual and mechanical augers and probes provide highly needed and detailed soil information but were also slow and tedious to use, thus limiting the number of observations that could be made. The soil scientist and NASA engineer wanted a faster and less labor-intensive tool that could be used to increase the quality and quantity of soil information. In 1979, in a cooperative project, USDA-SCS, NASA, and the Florida Department of Transportation studied the use of resistivity and ground-penetrating radar (GPR) in soil survey (Benson and Glaccum, 1979; Johnson et al., 1979). After reviewing the existing literature, the group decided that GPR would offer the greatest possibility.

Working with a geophysical company (Technos, Inc., Miami, FL), more than 12 km of continuous radar data were collected at sites in Polk and Hardee Counties, Florida. A conclusion drawn from this study was that GPR provides a means of obtaining a large quantity of detailed soil information in a relatively short time (Johnson et al., 1979). Furthermore, these researchers observed that "borings are needed to establish ground truth for [radar] signatures" and that once correlations between borings and radar imagery have been developed, "lateral extension of information can be made with a high degree of accuracy without additional borings" (Johnson et al., 1979).

Shortly after the study by Johnson et al. (1979), a brief article about it appeared in a newsletter by USDA-SCS (1980). At that time, I was a soil scientist in North Dakota. When I read the article, I remember saying to my soil survey party members, "Those turkeys in Florida think that they can map soils with radar." Shortly after the article was written, a GPR unit was purchased, and a vacancy announcement for a GPR operator in Florida was issued. Well, at that time, I thought that I had too many North Dakota winters and needed to get back East. No one in Florida seemed to want the job, and I had some experience with a different type of radar in the Navy, and so began one of the most rewarding and enjoyable rides of my life.

Shortly after arriving in Florida, I was sent to New Hampshire for radar training at Geophysical Surveys System, Inc. (GSSI). I was accompanied by Dr. Ron Patezold, a soil physicist with SCS, who was then assigned to a USDA Agricultural Research Service (ARS) facility in Beltsville, MD. Ron was interested in using GPR to assess variations in soil moisture content. Ron and I would take turns either operating the radar control unit or pulling the radar antenna across a test area. In order to make the best interpretation, Ron would "over gain" while I tended to "under gain" the radar signal. Less rather than more information provided me with a better image on which to make my interpretation, and for Ron, it was the opposite. There is no *cookbook* setting with GPR, and so the lesson learned was that GPR results depend on the interpreter.

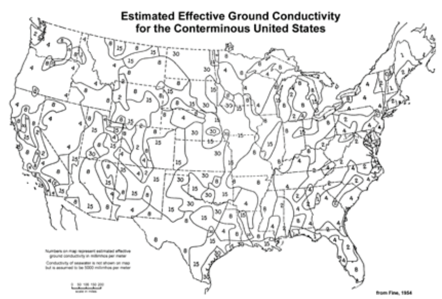
Guest columnist Jim Doolittle, USDA-NRCS National Soil Survey Center, looks back at his 30 years of working with ground-penetrating radar, which he describes as an "enjoyable ride."

While attending classroom sessions at GSSI, my attention was often distracted by a large map on a wall that showed the effective ground conductivity for the conterminous USA. This map was developed by the Federal Communication Commission in 1954. The performance of GPR depends on the electrical conductivity of soils. Soils having high electrical conductivity rapidly attenuate radar energy, restrict penetration depths, and severely limit the effectiveness of GPR. The FCC map (Fine, 1954) provided general guidance as to suspected rates of signal attenuation, penetration depths, and relative suitability of GPR within different areas of the United States. Because this map was prepared at a small scale (1:2,500,000) and from a limited sample population (7,000 ray paths and 127 soil samples), broad generalizations were naturally made. While I didn't know it at the time, this map would play a major role in my GPR career. Often times, I would get

Jim Doolittle, USDA-NRCS National Soil Survey Center, 11 Campus Blvd., Suite 200 Newtown Square, PA 19073 (jim.doolittle@lin.usda.gov).

doi:10.2136/sh2012-53-4-lgc
Published in *Soil Horizons* (2012).

a call asking if GPR would work in a specific soil or area of the country. I would look at a copy of this map, which was hung over my desk, and answer "yes" or "no" based on the observed radar performance for the effective conductivity values given for Florida and in other areas that I had worked with GPR. As far as the property or target in the soil that the radar was going to be used to detect, I had no clue unless I had already tried to identify it in Florida.

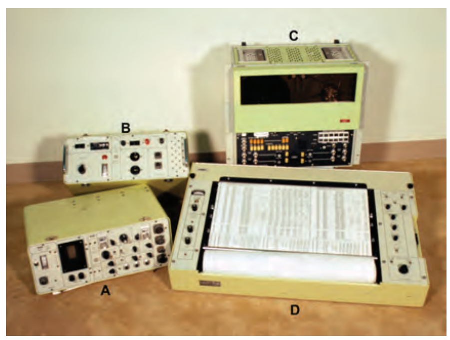


This map of effective ground conductivity provided early guidance as to the use of GPR for soil investigations in different parts of the USA.

In my early GPR days, little was known about the performance of GPR in different soils. Ground-penetrating radar was a relatively new technology, and very little was known or written about its use. The first commercially available GPR had only been marketed in the mid-1970s. In one of the earlier references on GPR, the dielectric permittivity for "average soil" was listed as 16 (Morey, 1974). This "average" soil would elude me throughout my GPR career. Soils are too spatially and temporally variable for an "average" value to have significance.

My First Radar Unit

My first radar unit was extremely bulky and cumbersome. Typically, in relatively open areas, the control and recording units were housed in a vehicle with an antenna towed in a sled behind this mobile platform. The unit was powered by the vehicle's battery. In more inaccessible areas, the unit was carried into a site with either a generator or a set of marine batteries for a power source. In many inhospitable terrains (e.g., steeply forested, densely vegetated), this was a most onerous task that I never looked forward to. The transmission line, which connected the control unit with the antenna, was 30 m long. As a result, an area with this radius could be surveyed around the control and recording units before these components needed to be repositioned. Radar data were displayed on an oscilloscope and strip charts. Interpretations were made directly from raw data on strip charts. There was a tape recorder, but it was not intended for field use and never worked well. Available signal-processing techniques were extremely primitive and largely borrowed from the seismic community.



The first radar unit that was purchased by USDA consisted of a control unit (A), power distribution unit (B), tape recorder (C), and graphic recorder (D). Three antennas were also purchased with this unit, operating at a center frequency of 80, 120, and 300 MHz.

Florida possesses optimal soil conditions for the use of GPR: extensive areas of electrically resistive sands. My first venture out of Florida was in 1983 to Texas and Oklahoma for both soil and engineering GPR studies. My first location was near Hondo, TX. I still can recall the scene as I drove up to the site along the highway. The SCS state soil scientist had gathered a very large crowd of highway department officials, SCS soil scientists and engineers, and university faculty and students to witness the radar chart the depth to bedrock. That was one of the longest days of my career. Texas is not the sand pile that Florida is, especially along the highway northeast of Hondo. With the GPR, I never saw the bedrock until it was exposed at the surface. Well, that day, I learned to appreciate soils with high clay contents and expansive clay mineralogy. The lesson learned was that GPR results are site specific and soil dependent.

Early radar units were bulky and cumbersome. In relatively open areas, mobile surveys were conducted towing the antenna behind a vehicle (A). In more inaccessible areas, the GPR unit had to be carried in and powered off a generator with the antenna limited to a 30 m search radius (B).

By the mid 1980s, the reality that many soils were unfavorable to GPR began to temper the initial excitement and expectation for this technology (Annan, 2002). However, the director of the Soil Survey Division wanted me on the national staff in order to facilitate the use of this technology across the USA. In 1985, I was assigned to the Northeast National Technical Center (NENTC) in Chester, PA. In 1987, I was reassigned to the National Soil Survey Center in Lincoln, NE, but stationed at the NENTC.

The use of GPR gradually expanded in soil science and agriculture. In 1986, a small group of soil scientists representing USDA-SCS, USDA-ARS, and the University of Florida got together in Tifton, GA to discuss GPR and the challenges that they were facing. They were joined by geophysicists from the USA and other countries. In 1988, the University of Florida and USDA-SCS hosted the Second International Symposium on Geotechnical Applications of Ground-Penetrating Radar in Gainesville, FL. Following these meetings, an international conference on GPR has been held every two years in countries around the world. Presently, the 14th International Conference on GPR (GPR2012) is being hosted by Tongji University, in Shanghai, China. It is always a pleasurable thought that these conferences were begun by a small group of soil scientists wanting to know more about GPR.

'Dog and Pony Show' Days

During my first 10 years with GPR, this geophysical method was on a wide variety of soils in different physiographic regions throughout the USA. These were the "dog-and-pony show" days of my career: Ground-penetrating radar was a novel tool in soil survey, and many soil scientists wanted to see it demonstrated on their soils. More often than not, soils that were unfavorable for GPR were selected and results were disappointing. However, knowledge in the form of a geographic perspective into the soil properties that influence GPR did come out of these setbacks. It must be said that in many studies, GPR did provide accurate and detailed information. During this period, it was principally used to evaluate soil properties and estimate the variability and the taxonomic composition of soil map units. In this capacity, GPR was repeatedly used to chart the lateral extent and depth of soil horizons; delineate pans, water tables, and bedrock and stratigraphic surfaces; assess soil compaction and plow pan development; and infer variations in soil texture, organic matter content, humification, and cementation.

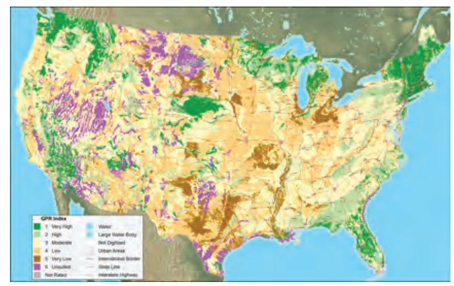
I always felt that GPR is a relatively expensive tool that must be kept in use and in the field rather than sitting on a shelf. In addition, I always felt a need to seek out new avenues of application and provide service to all potential customers. In the late 1980s, after completing back-to-back assignments using GPR to non-destructively detect brown rot and hollows in standing trees in Mississippi and to map the distribution of pocket gopher burrows in Kansas, my supervisor referred to me as a "loaded, misdirected cannon." I missed the point and considered his statement as a compliment.

In the mid-1990s, GPR transitioned from analog to digital systems. Radar units became increasingly smaller, lighter weight, and less expensive. Each new unit provided increased capabilities. Pedestrian surveys, with the GPR control and recording unit attached to a harness worn by the operator, became the standard field protocol.

In the last 15 years, significant advances have occurred and at an accelerated rate in GPR technology. My first radar unit was a subsurface interface radar (SIR)-8 system, which I used for 15 years. In the last 15 years, I have gone through three different radar systems: SIR-2, SIR-2000, and SIR-3000. All of these succeeding units provided increased capabilities and advantages for soil investigations.

In the late-1990s, signal processing matured, opening new windows of opportunity for GPR. Today, advanced signal-processing techniques are routinely used in many applications, and processing has become the "key" to modern GPR interpretations. The use of advanced processing techniques has greatly improved the characterization of some subsurface features.

It was becoming evident at this time that the map prepared for the FCC was too coarse and inaccurate to guide GPR applications. In 2002, collaborative work by soil scientists and GIS specialists from the USDA-NRCS National Cartography and Geospatial Center, National Soil Survey Center, and National Geospatial Management Center resulted in the development of the Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States. This thematic map, as well as state GPR soil suitability maps, has largely replaced the 1954 FCC map as a guide for projecting the relative suitability of soils to GPR.



The Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States shows that only 22% of the soils (colored green) are considered well suited to GPR. Thirty-six and seven percent of the soils are considered poorly and unsuited to GPR (colored brown and purple), respectively.

During the past decade, the union of GPR with GPS has permitted the collection of georeferenced GPR data sets, which can be manipulated and displayed in GIS or other imaging software. This synergy has greatly improved the utility of GPR in soil investigations. In addition, newly developed interactive interpretation modules provide for the rapid, semi-automatic "picking" of subsurface features. This has expedited interpretations and has resulted in the compilation of large data sets that are automatically transcribed into layer files, which can be imported into GIS or Excel spreadsheets for analysis.

Ground-penetrating radar has changed considerably over the years. Present GPR systems are well suited to soil investigations. Within USDA-NRCS, the number of radar operators has expanded greatly in this century. Presently there are 15 radar units located in 12 states [AR, CA, CT, FL (3), GA (2), MA, RI, PA, NC, NJ, WI, and WV]. Many universities have GPR systems and are using them in a wide variety of research activities. As many new radar operators are recent college graduates, they have introduced new and more contemporary skill sets. Using advanced analysis and display formats, they are exploiting the full digital data and analysis capabilities of modern GPR systems.

Rapidly advancing and often leapfrogging technologies have changed the way GPR soil investigations are being conducted. Present GPR systems are intergraded with GPS, and results are often displayed in GIS.

Over the years, GPR has been able to adjust to new areas of emphasis. In recent years, it has been successfully used to characterize and map subaqueous and anthropogenic soils. It has also been extensively used in hydropedological and hydrogeophysical investigations. Here, it is being used to characterize soil, stratigraphic, and lithologic structures that influence the movement of water in both the saturated and unsaturated zones at scales ranging from several meters to watersheds.

A Firm Foundation for GPR

Today, GPR rests on a firm foundation in soils and agriculture. Younger minds, exploring new areas of application, are continually putting out new additions onto this foundation. These younger, more innovative minds are finding new ways to process and archive radar data so that they will not be lost as has been the case in the past. They are open to the use of different technologies with GPR and seek new avenues for its use. For those interested in learning more about GPR, there have been numerous dissertations and articles written on its theory and application. Several books have been written expressly on GPR (e.g., Daniels, 2004; Jol, 2009; Miller et al., 2010) while others have chapters devoted to GPR (e.g., Allred et al., 2008; Rubin and Hubbard, 2006). International conferences are held specifically for GPR, while others have papers presented on the topic. In addition, several focus groups have been established in professional organizations devoted to near-surface geophysics.

Looking back on the last thirty years, I am pleased with the modest advancements that have been made with GPR in soils and agriculture and the even greater progress that has been made in system design and signal-processing procedures. I am confident that, in the future, GPR will have an expanded role to play in both soil and agriculture research and applications. My journey with GPR is almost over, and it has been a most enjoyable ride.

References

Allred, B.J., J.J. Daniels, and M.R. Ehsani. 2008. Handbook of agricultural geophysics. CRC Press, Boca Raton, FL.

Annan, A.P. 2002. GPR—History, trends, and future developments. Subsurf. Sens. Technol. Appl. 3(4):253–270.

Benson, R., and R. Glaccum. 1979. The application of ground-penetrating radar to soil surveying. Final Report NASA, Cape Kennedy Space Center, FL. Technos, Inc., Miami, FL.

Daniels, D.J. 2004. Ground penetrating radar. 2nd edition. The Institute of Electrical Engineers, London, United Kingdom.

Fine, H. 1954. An effective ground conductivity map for continental United States. Proc. Inst. Radio Eng. 42:1405–1408.

Johnson, R.W., R. Glaccum, and R. Wojtasinski. 1979. Application of ground-penetrating radar to soil survey. Proc. Soil Crop Sci. Soc. Fla. 39:68–72.

Jol, H. 2009. Ground penetrating radar: Theory and applications. Elsevier Science, Amsterdam, The Netherlands.

Miller, R.D., J.H. Bradford, and K. Hollinger, 2010. Advances in near-surface seismology and ground-penetrating radar. Geophysical Development Series No. 15. American Geophysical Union, Washington, DC and the Environment and Engineering Geophysics Society, Denver, CO.

Morey, R.M. 1974. Continuous subsurface profiling by impulse radar. p. 212–232 *In* Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, Henniker, NH, 11 to 16 August 1974.

Rubin, Y., and S.S. Hubbard. 2006. Hydrogeophysics. Water Science and Technology Library Vol. 50. Springer, The Netherlands.

USDA-SCS. 1980. Scientist test use of ground penetrating radar as a soil survey tool. *Soil and Water Conservation News.* August 1980, page 4.

A Tale of Dirty Legislation

Gary Elsner, PSS, CPSS, and CPSC

"Legislation is like sausage … You never want to know what went in to it"—Anonymous

After years of waiting in the soil pits and trenches of rural and urban Minnesota, the soil scientists of the Minnesota Association of Professional Soil Scientists (MAPSS) were able to negotiate the legislative mine fields to establish an official Minnesota state soil. This is the tale of MAPSS's efforts to guide (push, pull, and pry) to have the legislation passed. Read on for an explanation of the title of the article.

The effort started in 1985 when MAPSS formed a State Soil Committee, which was charged with finding a shining example of a soil series worthy of becoming Minnesota's official state soil. The committee and members worked for a year compiling a recommendation as to the merits of naming a state soil, and at the MAPSS annual meeting in 1986, they reported that four essential criteria should be used by the members for selecting the state soil. The criteria were that the soil must: (1) have its type location in Minnesota, (2) be extensive, (3) be economically important, and (4) be photogenic (teachable). Seven soils were nominated, but one was eliminated because it was a Michigan soil.

Brief presentations were made by each soil's sponsor, including a presentation made by a member dressed as the French explorer Pierre-Charles Le Sueur (his nominated soil was Le Sueur). Following the presentations, 51 members voted for their choice (ballots were not reviewed during the meeting), and a motion was made and passed to form two committees: (1) a Legislative Committee and (2) an Education Committee.

The vote tallies were presented at the MAPSS Executive Committee (EC) meeting in May of 1987. The Lester series received 37% of the votes (the majority) and was given final approval as the MAPSS state soil of Minnesota. During the 1987 MAPSS annual meeting, the State Soil Committee reported that the EC had approved Lester as our MAPSS state soil. Now the goal was "simply" to introduce legislation in February of 1988 to establish Lester as the official Minnesota state soil. All the members thought their wild enthusiasm would carry any bill through the Minnesota House and Senate. How naïve we were. Now the often silent, but herculean, effort began.

In a special meeting called in March of 1988, the EC learned that before the legislative session that there was actually considerable interest from key legislators to establish a state soil. It seemed there was a good chance we could get a state soil approved during this short session of the legislature. However, as the session started, problems arose which made it difficult to get the state soil approved.

Lester was officially recognized this year as Minnesota's state soil, 25 years after it was first proposed.

State Soil or State Muffin?

The blueberry growers of Minnesota proposed the blueberry muffin as the "state muffin." A group of grade school children also proposed the giant beaver (*Castoroides ohioensis*) as the state fossil. With this being an election year, there was concern that a state soil may seem trivial if introduced with a "state muffin" and a "state fossil." Besides, how could a group of field-hardened soil scientists compete with cute grade school children and a luscious vision of a "blueberry muffin?"

There was also a peat mining organization that wanted an organic soil as the state soil. Hmmm, how happy would we be with "Bullwinkle" as the state soil? Our legislative supporters strongly urged us to wait until after the elections in the fall, so a decision was made not to introduce the state soil bill in 1988. The state muffin passed, but the state fossil did not pass and was criticized by the legislature because the word "Ohio" was part of the scientific name. Happily, Bullwinkle remained in Frostbite Falls, MN.

At the December 1988 MAPSS annual meeting, there was a presentation made about hiring a lobbyist for the state soil

Gary Elsner, Minnesota Association of Professional Soil Scientists, Blain MN (gelsner@juno.com).

doi:10.2136/sh2012-53-4-ltp
Published in *Soil Horizons* (2012).

effort and options for the 1989 session. There was considerable discussion on whether or not MAPSS should hire a lobbyist to promote Lester as our state soil. Consensus of the group seemed to favor increasing publicity of the need for a state soil. Following the annual meeting, the EC met and passed a motion to table hiring a lobbyist and instead work to build coalitions and educate citizens and legislators. Some old curmudgeons in our group grumbled that this decision was based on the habitual "thriftiness" of our profession.

The state soil promotional efforts were placed on the back burner in the early to mid-1990s due to the MAPSS soil science licensing effort. In May of 1995, the Minnesota governor signed the Geoscience Licensing legislation. Rule writing and other licensing-related efforts continued through the rest of the decade. Another decade slipped by, we became grayer and somewhat wiser, and yet Lester remained in cold storage. A gleam of light and a happy convergence of events were to occur to change this sad condition of the beleaguered MAPSS state soil.

A Perfect Storm

At the 2010 annual meeting, it became apparent that several soils-related events were converging, including the SSSA 75th anniversary; the 100th anniversary of the University of Minnesota Department of Soil, Water, and Climate; and the MAPSS 40th anniversary. A few of the old back benchers at the meeting suggested that these events might be the perfect opportunity to get the state soil legislation passed. An article for the spring 2011 newsletter, titled "A Perfect Storm," was written to outline our opportunity. The Lester state soil flag was once more raised by a few dedicated MAPSS members seeing a once-in-a-lifetime opportunity. Some of the MAPSS members had no idea the "state soil team" had been waiting in the pit all this time.

The article on the "Perfect Storm" was discussed during the 2011 MAPSS Summer Tour. A motion was made and passed to form a "Perfect Storm Committee" (PSC). The PSC drafted a handout and made a presentation at the 2011 Annual Meeting, and members, many who were not born during the original nomination of Lester, gave the committee permission to begin pursuing the various PSC events. Prior to the PSC presentation, Dr. Carl Rosen, head of the University of Minnesota, Department of Soil, Water, and Climate, gave a presentation about the upcoming 100th Anniversary of the department and its desire to work with MAPSS on the upcoming events.

As a follow-up to the annual meeting, the PSC met with Dr. Rosen to discuss the upcoming events. At this meeting, it was learned that the Smithsonian Soil Exhibit "Dig It!" was probably coming to the Bell Museum in November of 2012. Dr. Rosen suggested that MAPSS should pursue designation of Lester as the Minnesota state soil in conjunction with the coming of the "Dig It!" exhibit. After some initial resistance to parting with any spare change, the PSC was given permission to contact a lobbyist about pursuing the state soil. The PSC contacted the lobbyist who immediately recognized that all of the soil-related events represented a significant case for establishing a state soil by the legislature.

In the January 2012, the PSC and EC decided to proceed with the state soil legislation and hire a lobbyist. The PSC suggested the following to pay for the costs: (1) asking for donations from the membership, (2), using existing professional development fund dollars, and (3) putting on some additional soil workshops. An outline for lobbying services and a cost proposal were provided to MAPSS, and the EC gave the PSC permission to proceed on Jan. 31, 2012. The state soil bill was drawn up and provided to MAPSS on Feb. 4, 2012. Now there was only three months left to make our case to the Minnesota legislators. If the small PSC group had any wits about them, they may have blanched; however, blind faith in the importance of soil ruled the day, and the legislative battle was on.

The PSC then began working with the lobbyist to find authors. Criteria for selecting authors were finding: (1) a Republican, since that was the majority party, preferably one in the House and one in the Senate Government Operations committees, which is where the bill would be heard first; and (2) someone who was in one of our member's districts. Many potential sponsors had been approached, and initially, they blustered excuses about the frivolity of the effort. However, Senator Gen Olson had the vision to see the importance of soil and agreed to be our primary author. Senator Olson was the chair of the Senate Education Committee, and out of the sheer force of the perfect storm, she told us of her experience as a soil judger in 4H. Senator Olson became our soil-enlightened advocate. The Senate bill was introduced on Mar. 5, 2012 and referred to the State Government Innovation and Veterans Committee. The House version of the bill was introduced on Mar. 15, 2012 and referred to the Agricultural and Rural Development Finance Committee.

Eaten by the 'Sausage Machine'

The Senate heard and passed the bill in committee on Mar. 12, 2012. There was also a bill heard right after the state soil bill, sponsored by a first-grade class, to designate the black bear as the state mammal. Again, it seemed difficult for the hard-bitten soil scientists, now 25 years older, to compete with the shining faces of youth. This bill passed as well. Neither bill received a hearing in the House, which meant we had not made the committee deadline in both houses and so the bill was dead. The PSC group was almost silent and lost, and rumor was we were eaten by the legislative "sausage machine."

However, our lobbyist and Senate sponsor knew better and conjured legislative magic. Plan B was revealed, which would amend the state soil language to the Senate version of the Agricultural Omnibus bill. The amendment was proposed and passed on the Senate floor on

Apr. 4, 2012 with one Senator commenting during testimony on the floor: "Maybe now we can stop treating our soil like dirt." The addition of this language to the Agricultural Omnibus bill gave Lester new life. On Apr. 20, 2012, the state soil language was amended to the House version of the Omnibus bill in conference committee (the vote was 10–0).

The House adopted the conference committee report on Apr. 24, 2012 and the Senate did the same 66–0 later in the day. The members of these committees recognized the importance of soil, where food comes from, and where jobs in Minnesota originate. So, 25 years after Lester was selected by the MAPSS membership, Minnesota Governor Mark Dayton signed the bill on Apr. 28, 2012, making Lester the Minnesota state soil. But we were not done yet.

In the print and internet press, until the bill was signed by the governor, the effort was universally panned. After we missed our deadline for a hearing in the house, a teacher in northern Minnesota wrote an editorial critical of the state soil effort and the legislature for not passing the state mammal legislation. A local reporter wrote not only about the state soil amendment but about the black bear. The title of the article was "Dirty Legislation." The reporter criticized the legislators for passing the state soil bill but not passing any "other" significant legislation. Not only were the legislators chastised for adding the state soil language, but also for not passing the black bear legislation.

Then, almost immediately after the bill was added to the Agricultural Omnibus bill on the Senate floor, a local political reporter began Tweeting about it and was on the radio at least a couple of times that afternoon complaining about the waste of time recognizing soil as an icon of a state economy dominated by agriculture and forestry. Further complaints were heard in the local press from parents of the school children claiming that the soil legislation was only passed because MAPSS hired a lobbyist. MAPSS did respond to this criticism via an email from me directly to the first grade teacher who was working on the state mammal legislation. She called me that same day, and at the end of the conversation, she congratulated us on our success.

Generally speaking, the legislators we worked with were very supportive. Yes, many wanted to know why this was important to the state, but as we moved through the process, our explanations were heard, recognized, and praised. My advice to anyone considering state soil legislation would be to find a passionate sponsor and be ready to convince everyone that recognizing and celebrating soil is important for the citizens of your state.

I am happy to note that a reporter contacted us after the bill was signed, and so I did an interview with her for almost half an hour. The result was a very well-written, positive article about our new state soil. We delivered plaques to six legislators who were the most supportive of our effort. The plaque for Senator Olson named her an Honorary Soil Scientist and the others were for Outstanding Service to MAPSS. We had a large group of soil scientists present at the capitol to make the presentations and take photos. The legislators appreciated them and were all looking forward to hearing more about our educational efforts highlighting Lester, the Minnesota state soil. Now our band of Lester supporters is awaiting the further celebrations of "Dig It!" and soil anniversaries as well as a well-deserved rest away from the legislative trenches.

Senator Olson received a plaque from the Minnesota Association of Professional Soil Scientists naming her "Honorary Soil Scientist" for her work to get Lester recognized as the state's official soil.

Do you have a tale you'd like to share—good or bad—about life as a soil scientist or an experience you've had in the field? If so, email it to Dawn Ferris at dferris@sciencesocieties.org. You may remain anonymous if you like.

1987

One of a Kind

Francis Hole was a pedologist at the University of Wisconsin–Madison. He started in Soil Science but eventually held a joint appointment with Geography. He was well known for his unique teaching style (which included songs he wrote about soils and self accompaniment on his violin), his many years of field work in Wisconsin, his soil mapping, and his training of generations of pedologists and geographers. Key publications include *The Soils of Wisconsin* and of *Soil Genesis and Classification*, the classic pedology textbook he co-authored that has been through multiple editions. But, he was perhaps most proud of establishing a State Soil for Wisconsin (one of the first state soils in the United States), the Antigo Silt Loam (for which Francis, of course, wrote a song!). Photo taken in the John Day Badlands of Oregon during a conference/field trip on paleosols sponsored by the Geological Society of America, September, 1987.

Photo and description by Vance Holliday (University of Arizona, Tucson).

1960s–2012

World Class Soil Mineralogist

Warren Lynn received his Ph.D. in 1964 from the University of California at Davis. His Ph.D. research was on mineral transformation on oxidation of wet soils containing sulfides. He retained a long interest in the subject, as well as in the physical nature of organic soils. He started work for the Soil Conservation Service (later the Natural Resources Conservation Service) in 1963. He was stationed in the regional Soil Survey Laboratory in Lincoln, Nebraska, which in 1975 was combined with the other two regional laboratories to form the National Soil Survey Laboratory, part of the National Soil Survey Center. He was in charge of clay mineralogy in the Lincoln regional laboratory, which he pursued with thoroughness. Instead of a mineral code for clay mineral abundance he assigned adjectival words, which perhaps was better because it connoted the uncertainty. He continued his scientific contributions to clay mineralogy after 1975 in the National Soil Survey Laboratory. In the regional laboratory, he wrote two papers about use of the electron micro-probe to observe soil fabric, working at facilities at the University of Nebraska. During his tenure in the National Soil Survey Laboratory he developed a world-class reputation in both clay and soil mineralogy, coauthoring a chapter entitled "Carbonate, Halide, Sulfate, and Sulfide Minerals" in *Minerals in Soil Environments*, published by Soil Science Society America in 1977. Dr. Lynn died in Lincoln, NE on March 18, 2012 at the age of 76.

Submitted by Dr. Robert B. Grossman and Dr. Wiley D. Nettleton, Research Soil Scientists, Retired, Waverly and Lincoln, NE.

1920s

Early Soil Inspectors

Macy Lapham (middle) and UC Berkeley Professor Charles Shaw describe a soil profile along a road cut while working on the Series 1925 Soil Survey of The Salinas Area, California. Macy was a pioneering figure for nearly 45 years as a Senior Soil Scientist Inspector with the USDA Division of Soil Survey. Macy Lapham's name as Inspector appears in almost all soil surveys published during the first 50 years of soil surveys in the western part of the United States. His classic 1949 book *Crisscross Trails—Narrative of a Soil Surveyor* details his professional career, which began in 1899, the same year as the Soil Survey. Charles E. Kellogg, Chief, USDA Division of Soil Survey stated in the Forward of Macy's book: "The West, Macy, and the Soil Survey grew up together. None would have been quite the same without the others."

Photo courtesy of Dr. Stanley W. Cosby Photo Collection. Information courtesy of Kerry Arroues, NRCS, Hanford, CA.

Submit items for Profiles in History to Associate Editor Sam Indorante (Sam.indorante@il.usda.gov).

doi:10.2136/sh2012-53-4-pih
Published in *Soil Horizons* (2012).

Soils and Climate Change: Gas Fluxes and Soil Processes

Eric C. Brevik

According to the Intergovernmental Panel on Climate Change, global temperatures are expected to increase 1.1 to 6.4°C during the 21st century, and precipitation patterns will be altered by climate change. Soils are intricately linked to the atmospheric–climate system through the carbon, nitrogen, and hydrologic cycles. Altered climate will, therefore, have an effect on soil processes and properties, and at the same time, the soils themselves will have an effect on climate. Study of the effects of climate change on soil processes and properties is still nascent, but has revealed that climate change will impact soil organic matter dynamics, including soil organisms and the multiple soil properties that are tied to organic matter, soil water, and soil erosion. The exact direction and magnitude of those impacts will be dependent on the amount of change in atmospheric gases, temperature, and precipitation amounts and patterns. Recent studies give reason to believe at least some soils may become net sources of atmospheric carbon as temperatures rise and that this is particularly true of high latitude regions with currently permanently frozen soils. Soil erosion by both wind and water is also likely to increase. However, there are still many things we need to know more about. How climate change will affect the nitrogen cycle and, in turn, how the nitrogen cycle will affect carbon sequestration in soils is a major research need, as is a better understanding of soil water–CO_2 level–temperature relationships. Knowledge of the response of plants to elevated atmospheric CO_2 given limitations in nutrients like nitrogen and phosphorus and associated effects on soil organic matter dynamics is a critical need. There is also a great need for a better understanding of how soil organisms will respond to climate change because those organisms are incredibly important in a number of soil processes, including the carbon and nitrogen cycles.

The most recent report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the average global temperature will probably rise between 1.1 and 6.4°C by 2090–2099, as compared to 1980–1999 temperatures, with the most likely rise being between 1.8 and 4.0°C (IPCC, 2007a). The idea that the Earth's climate is changing is now almost universally accepted in the scientific community (Cooney, 2010; Corfee-Morlot et al., 2007), and even many scientists who dispute that climate change is anthropogenic are in agreement that it is happening (i.e., Kutílek, 2011; Carter, 2007; Bluemle et al., 1999). Therefore, even if we can't agree on why climate change is happening, it should be possible to agree that it is happening, and with climate change happening, there will be effects on the environment, including the soil.

Eric C. Brevik, Dep. of Natural Sciences and Agriculture and Technical Studies, Dickinson State Univ., Dickinson, ND 58601. *Corresponding author (Eric.Brevik@dickinsonstate.edu).

doi:10.2136/sh12-04-0012
Published in Soil Horizons (2012).
Received 5 Apr. 2012

Studies into the effects climate change will have on soils are in their early stages; therefore, there is still much more to be learned in this area. However, through the results of the studies that have been done and our understanding of soil processes and properties it is possible to provide some insight into the expected effects of climate change. For example, we know that changing climates will influence the carbon and nitrogen cycles, which will in turn affect soil processes and fertility (Hungate et al., 2003; Gorissen et al., 2004; Davidson and Janssens, 2006; Wan et al., 2011). Climate change will also influence soil moisture levels (Chiew et al., 1995; Backlund et al., 2008; Kirkham, 2011). Soil erosion by water is expected to increase as climate changes (Favis-Mortlock and Boardman, 1995; Ravi et al., 2010), and aeolian erosion of soils is expected to increase in dryland regions (Ravi et al., 2010). This brief discussion serves as an opening into the study of the effects of climate change on soils. Moreover, this paper will assess what we currently know about gas fluxes in soil related to climate change, as well as some of the potential effects of climate change on soil processes and properties.

Gas Fluxes and Soils

In 2004 carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) made up most of the anthropogenic greenhouse gas emissions (IPCC, 2007b). These three gases are also the most important of the long-lived greenhouse gases (Hansen et al.,

Abbreviations: IPCC, Intergovernmental Panel on Climate Change.

2007). These gases are a part of the global carbon and nitrogen cycles (Fig. 1 and 2). Before the Industrial Revolution, the global carbon and nitrogen cycles were in balance, with inputs approximately equaling outputs. Burning of fossil fuels, tilling of soil, and other human activities have altered the natural balance such that we are now releasing more carbon and nitrogen into the atmosphere each year than is taken up by global sinks (Pierzynski et al., 2009).

Because soils are part of the carbon and nitrogen cycles, it is possible to influence atmospheric levels of carbon- and nitrogen-based gases through soil management (Lal, 2007; Hobbs and Govaerts, 2010; Wagner-Riddle and Weersink, 2011). A fourth group of greenhouse gases, the halocarbons, will not be discussed here. However, halocarbons can be created naturally, and halocarbon formation has been documented in the soil (Hoekstra et al., 1999; Keene et al., 1999; Gribble, 2003). It should also be noted that the discussions of CO_2, CH_4, and N_2O presented here are brief and are only meant to demonstrate that ties exist between these gases, the soil system, and the atmosphere and to provide some examples of how human management can influence those relationships. Readers are referred to the references cited for more complete discussion of the topics covered.

Soils and Carbon Dioxide

The largest active terrestrial carbon pool is in soil, which contains an estimated 2500 Pg of carbon, compared to 620 Pg of carbon in terrestrial biota and detritus and 780 Pg of carbon in the atmosphere (Fig. 3) (Lal, 2010). In addition to these pools, there are approximately 90,000,000 Pg of carbon in the geological formations of Earth's crust, 38,000 Pg of carbon in the ocean as dissolved carbonates, 10,000 Pg of carbon sequestered as gas hydrates, and 4000 Pg of carbon in fossil fuels (Rustad et al., 2000). While the Earth's crust, the ocean, and the gas hydrates are much larger carbon pools than the soil, humans are not able to easily manipulate conditions that influence carbon exchange in these pools. We could reduce carbon emissions sharply by ceasing the use of fossil fuels, but this would require the development of alternative fuel sources. Therefore, we are left looking for other ways to manage ever-growing levels of CO_2 in our atmosphere. One of the potential ways that is readily available to mitigate CO_2 additions to the atmosphere is carbon sequestration by soils using the soil–plant system. Plants remove CO_2 from the atmosphere during photosynthesis and create carbohydrates, some of which are incorporated into plant tissues. As plants or plant parts die, some of the plant tissues are incorporated into the soil as soil organic matter (Lal et al., 1998). Given the

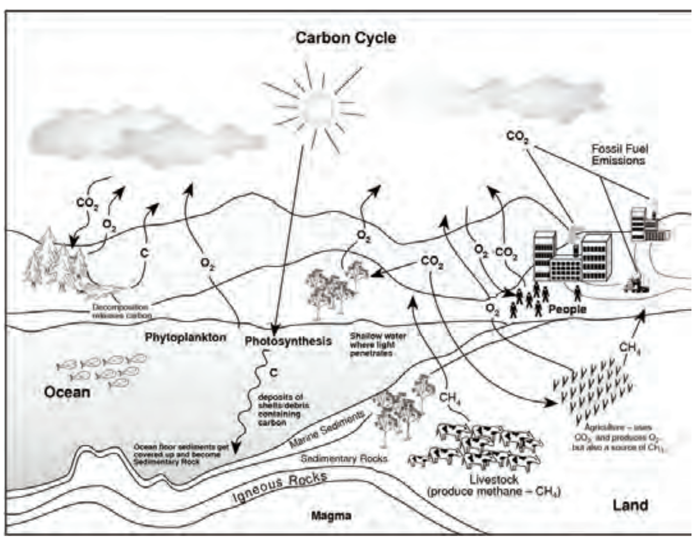


Fig. 1. The main components of the global carbon cycle. Carbon is able to move between different pools within the cycle. For example, burning of fossil fuels or decomposition of soil organic matter sends carbon gases into the atmosphere, while photosynthesis locks atmospheric carbon up in plant tissues and deposition of organic-rich sediments on the ocean floor locks carbon up in geologic rocks and sediments. (Courtesy of NASA.)

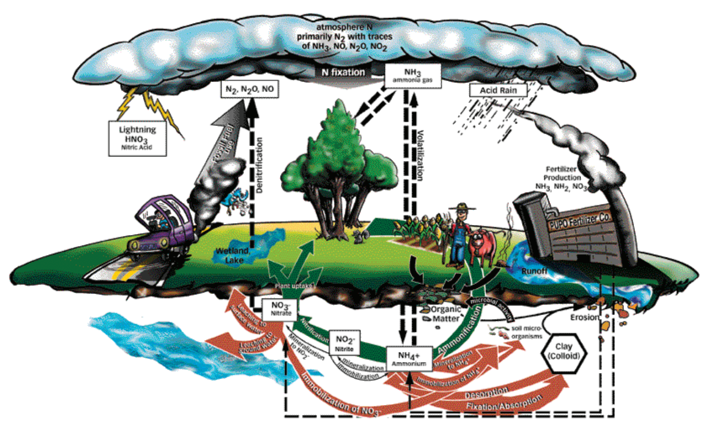


Fig. 2. The main components of the global nitrogen cycle. As with the carbon cycle, nitrogen is able to move between pools in its cycle, including the soil pool. Some processes put gases such as N_2O into the atmosphere, while other processes remove those gases from the atmosphere and transfer them into other pools. (Courtesy of NASA.)

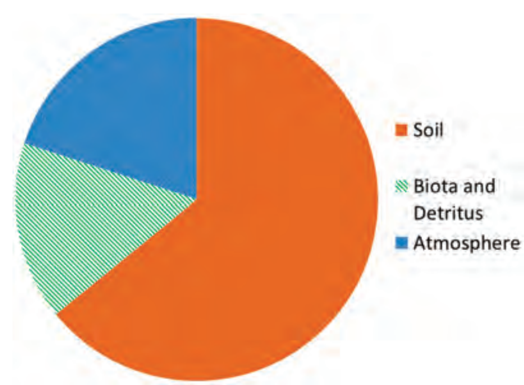


Fig. 3. Relative size of the active terrestrial carbon pools. The size of the soil carbon pool relative to the biological and atmospheric pools demonstrates the importance of soils in the carbon cycle. Data from Lal (2010).

proper conditions, some soils can become net carbon sinks, effectively removing CO_2 from the atmosphere (Fig. 4) (Mosier, 1998). Because of this capability of the soil–plant system, carbon sequestration by soils as a potential means of mitigating climate change has received a considerable amount of research interest.

Carbon can potentially be sequestered in any soil, but humanity has the greatest potential control over sequestration in intensively managed systems such as agricultural and agroforestry soils. Soil management techniques such as no-till systems often result in lower CO_2 emissions from the soil and greater carbon sequestration in the soil as compared to management systems based on intensive tillage (Fig. 5) (Post et al., 2004; Lokupitiya and Paustian, 2006; Steinback and Alvarez, 2006; Hobbs and Govaerts, 2010), as do changes such as using cover crops, crop rotations instead of monocropping, and reducing or eliminating fallow periods (Post et al., 2004; Álvaro-Fuentes and Paustian, 2011). The use of reduced or no-till systems has the added benefit of using less fuel for working the soil, which reduces CO_2 emissions by agricultural machinery (Schneider and Smith, 2009; Hobbs and Govaerts, 2010; Wagner-Riddle and Weersink, 2011); fuel savings of around 32.7 L ha^{-1} (3.5 gallons per acre) have been estimated for no-till versus conventional tillage systems in cotton (*Gossypium hirsutum* L.) farming (Wolf and Snyder, 2003). Returning land from agricultural use to native forest or grassland can also lead to significant carbon sequestration in soils (Post and Kwon, 2000; Silver et al., 2000). Sequestration of carbon tends to be rapid initially, with declining rates over time (Fig. 5) (Neill et al., 1998; Silver et al., 2000; Dixon-Coppage et al., 2005). Maximizing carbon sequestration in soils requires adequate nitrogen to allow carbon accumulation. Hungate et al. (2003) questioned whether or not there will be enough nitrogen available to maximize carbon sequestration as climate change occurs.

Management decisions can restrict the ability of a soil to sequester carbon as well. For example, the extensive use of heavy equipment in modern production agriculture has made soil compaction a major problem that has been shown to limit carbon sequestration (Brevik, 2000; Brevik et al., 2002; Dixon-Coppage et al., 2005). Organic soils can be a particular carbon management challenge as they typically form in wet conditions and have to be drained for agricultural uses. This drainage changes the soil environment from anaerobic to aerobic, which speeds decomposition of the organic matter in the soil and releases greenhouse gases into the atmosphere. A study in Finland on the effect of crops on greenhouse gas fluxes from soils showed that the organic soils were a net source of CO_2 for all cropping systems studied (Martikainen et al., 2002).

Most agricultural soils only sequester carbon for about 50 to 150 yr following management changes before they reach carbon saturation (Mosier, 1998; Lal, 2010), putting a limit on the ultimate effectiveness of soils in mitigating CO_2 additions to the atmosphere. The IPCC estimates that 0.4 to 0.8 Pg C yr^{-1} (the

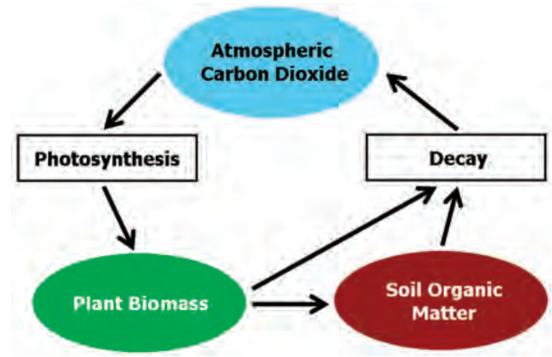


Fig. 4. The concept of carbon sequestration by soils. Atmospheric CO_2 is utilized during photosynthesis and transformed into plant biomass. As the biomass enters the soil and decays, some of it is transferred into soil organic matter and some returns to the atmosphere as CO_2. Soil organic matter also decays and releases CO_2 to the atmosphere. If more plant biomass is added to the soil than decays, the total amount of soil organic matter increases, resulting in carbon sequestration.

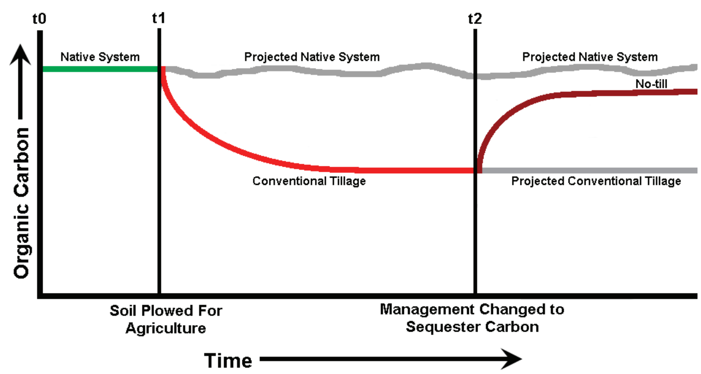


Fig. 5. Typical changes in soil organic carbon with time under different soil management. Time t0 to t1 represents the soils under a native ecosystem. At t1, the soil was broken for agricultural production using conventional tillage, leading to a decline in soil organic matter. The "Projected Native System" is the expected soil organic matter content if the native ecosystem had not been disturbed. At t2, management was changed to sequester carbon in the soil. The "Projected Conventional Tillage" is the expected soil organic matter content if conventional tillage had been maintained. Note that changes in organic carbon content are rapid immediately following management changes but rates of change decrease and then stop as the soil reaches carbon equilibrium.

equivalent of 1.4–2.9 Pg of CO_2 yr^{-1}) could be sequestered globally in agricultural soils, with soil carbon saturation occurring after 50 to 100 yr (Smith et al., 2007). Estimated anthropogenic CO_2 emissions to the atmosphere in 2004 totaled about 38 PgC yr^{-1} (IPCC, 2007b), and natural carbon sinks have taken about 45% of anthropogenic CO_2 emissions out of the atmosphere since 1959 (Denman et al., 2007), meaning about 21 Pg yr^{-1} of anthropogenic C remained in the atmosphere for the long term in 2004. Using the numbers above, carbon sequestration by agricultural soils would be able to remove about 2 to 4% of the annual anthropogenic additions of carbon to the atmosphere for the next 50 to

100 yr. While this is not a large amount, there are other reasons to sequester carbon in agricultural soils, including rehabilitation of degraded soils and overall improvement of soil quality, which can lead to increased crop production and enhanced food security (Brevik, 2009; Lal, 2010).

Intensely managed soils have received the most attention in carbon sequestration research, but there are other soils that have potential for significant carbon sequestration as well. Coastal wetland soils have the ability to sequester carbon at higher rates than most agricultural soils (Brevik and Homburg, 2004; Hussein et al., 2004; Jespersen and Osher, 2007; Johnson et al., 2007). Coastal wetland soils can sequester carbon over hundreds or thousands of years rather than the decades possible with agricultural soils. In addition, they can sequester carbon to depths of several meters as opposed to the typical single meter depth measured for agricultural soils, making coastal wetland soils more efficient at sequestering carbon than most agricultural soils on a per unit area basis (Brevik and Homburg, 2004; Hussein et al., 2004; Johnson et al., 2007). Coastal wetlands also release much lower levels of CH_4 and N_2O than freshwater wetlands (DeLaune et al., 1990; Bartlett and Harris, 1993), a distinct advantage when considering carbon sequestration as a means of potentially mitigating greenhouse gas–driven climate change. Findings such as these indicate that the conservation and restoration of coastal wetlands would be well advised (Brevik and Homburg, 2004; Zedler and Kercher, 2005). However, the current global trend is a rapid reduction of coastal wetlands through natural activities such as erosion due to rising sea levels. Human activities also lead to the loss of wetlands as they are drained and filled in or otherwise modified for uses such as agriculture, urban development, petroleum extraction, and salt production (Titus, 1991; Steyer and Stewart, 1992; Tsihrintzis et al., 1996; White and Morton, 1997). Significant carbon sequestration is also possible in other nonagricultural soils, including some abandoned mine and quarry sites (Akala and Lal, 2001; Dixon-Coppage et al., 2005; Sperow, 2006).

While we have the ability to sequester carbon in the soil, management decisions can also release carbon from the soil, making those soils a net source of greenhouse gases. Plowing native soils for agricultural production (Fig. 5), introducing more aggressive forms of tillage to an agricultural management system, and draining wetlands are examples of management changes that increase CO_2 emissions from soils. It is also true that carbon that has been sequestered can be returned to the atmosphere at a future time if the management changes that led to its sequestration are altered. In short, managed soils can be either net sinks or net sources of CO_2 depending on their management (Schlesinger, 1995; Mosier, 1998).

Arctic soils are of particular concern in terms of the release of carbon to the atmosphere. Due to the cold conditions under which they form, microbial activity and decomposition rates tend to be low in Arctic soils; thus, soil organic carbon reaches high levels (Barber et al., 2008). However, warming these soils can switch them from a carbon sink to a carbon source (Oechel and Vourlitis, 1995; Welker et al., 1999; Bliss and Maursetter, 2010), with well-drained soils releasing CO_2 to the atmosphere (Sjögersten et al., 2006; Barber et al., 2008). This is of particular concern because Arctic soils contain about 30% of the world's soil carbon (Oechel and Vourlitis, 1995; Chapin et al., 2004) and thus have the potential to release large quantities of greenhouse gases into the atmosphere as they thaw (Chapin et al., 2004).

Soils and Methane

Methane concentrations in the atmosphere did not increase between 1998 and 2005, but were more than 2.5 times higher than in 1800 (Forster et al., 2007). Agriculture accounts for about 47% of annual global anthropogenic emissions of CH_4 (Smith et al., 2007). Production of CH_4 in the soil is associated with the anaerobic decomposition of organic matter. Because of this, the main anthropogenic source of soil-derived methane is rice (*Oryza sativa* L.) production, while natural soil-derived methane comes primarily from wetlands (Fig. 6) (Heilig, 1994; Stępniewski et al., 2011). Termites (*Termitoidae*) are also a major natural source of methane (Heilig, 1994). A significant portion of the CH_4 produced in soil is oxidized by soil microorganisms aerobically (Schütz et al., 1990; Mosier, 1998; Stępniewski et al., 2011) into products including CO_2 (Fig. 6) (Heilig, 1994). Increasing soil temperatures lead to increased CH_4 production in rice paddy soils and wetlands, which is a concern with rising global temperatures (Schütz et al., 1990; Stępniewski et al., 2011). The melting of soils that have been permanently frozen (permafrost) (Fig. 7) is also becoming a major source of atmospheric CH_4 (Barber et al., 2008).

Management makes a difference in CH_4 fluxes in soil. The presence of ammonium ions in the soil from nitrogen fertilization has been shown to inhibit the ability of agricultural soils to

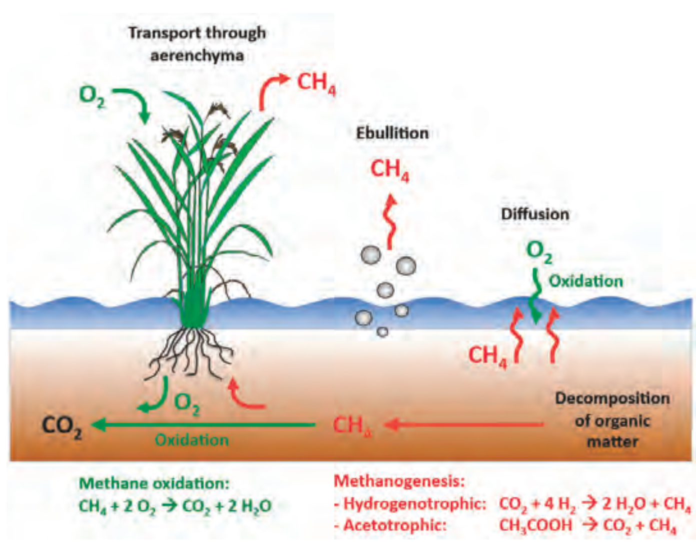


Fig. 6. Generation and emission of methane from wet soils. (Courtesy of Josef Zeyer, ETH Zurich, Switzerland.)

serve as a CH_4 sink (Stępniewski et al., 2011). Different vegetation growing on the same soil will also cause differences in CH_4 emission or consumption. In a study by Hu et al. (2001), a soil under forest vegetation acted as a net sink of CH_4, while the same soil in a nearby field planted with maize (*Zea mays* L.) was essentially CH_4 neutral, and a third field of the same soil planted with grass (Poaceane family) cover was a net source of CH_4 to the atmosphere.

Rice production management has the greatest potential to reduce anthropogenic additions of soil-derived CH_4 (Neue, 1992). Dryland tillage and dry seeding or other means of reducing the period of soil saturation leads to less CH_4 production (Neue, 1992; Stępniewski et al., 2011). However, the production of CH_4 and N_2O are inversely related in rice soils; managing soil moisture levels to prevent the generation of one tends to encourage generation of the other (Neue, 1992). Since both are greenhouse gases, the balance between them must be carefully assessed. Adding organic amendments such as manure to flooded soils as a nutrient source increases CH_4 emissions (Wassmann et al., 1993; Stępniewski et al., 2011; Zhang et al., 2011). Fertilizer experiments have produced some mixed results (Neue, 1992). Wassmann et al. (1993) found no mineral fertilizer effect on methane generation in rice paddy soils when adding potassium fertilizers, but Lu et al. (1999) found that phosphorus fertilizers decreased CH_4 emissions. Lu et al. (1999) attributed this to increased root exudates in phosphorus-deficient soils as the plant tried to manipulate the soil environment to increase phosphorus uptake. Stępniewski et al. (2011) noted that adding oxidizing mineral fertilizers can reduce CH_4 emissions by 20 to 70%. Zhang et al. (2011) also noted that a mixed management system that incorporated ducks (Anatidae family) into the rice system decreased methane emissions.

Soils and Nitrous Oxide

Agriculture accounts for about 58% of anthropogenic N_2O emissions (Smith et al., 2007). From a soil perspective, N_2O is created when soil water contents approach field capacity and biological reactions in the soil convert NO_3^- to NO, N_2O, or N_2 (Mullen, 2011). Enhanced microbial production in expanding agricultural lands that are amended with fertilizers and manure is believed to be the primary driver behind increased atmospheric N_2O levels (Lokupitiya and Paustian, 2006; Forster et al., 2007). Well over one-half of the global emissions of N_2O appear to come from the equator to 30° N and S (Forster et al., 2007), with 13 to 37% of global N_2O emissions coming from tropical forest soils (Melillo et al., 2001). Nitrous oxide emissions typically increase with increasing soil clay content when other factors are held constant (Chatskikh et al., 2005). There are also some indications that warming of cold-region soils could lead to increased N_2O emissions from those soils (Brooks et al., 1997; Williams et al., 1998).

Agricultural management is a major factor in N_2O emissions. As nitrogen fertilizer applications increase, denitrification and the generation of N_2O in the soil also increases (Fig. 8) (Grant et al., 2006; Mullen, 2011; Stępniewski et al., 2011). Emissions of N_2O are usually lower in organic farming systems than in conventional systems (Stępniewski et al., 2011). Some studies have found higher N_2O emissions from tilled soils than from no-till soils (Steinbach and Alvarez, 2006; Stępniewski et al., 2011; Wagner-Riddle and Weersink, 2011), but this is not true in all cases (Grandy et al., 2006). The conversion of tropical forest to pasture led to an initial increase in N_2O emissions followed by a decline in emissions relative to the original forest in a Brazilian study (Melillo et al., 2001); however, conversion of tropical forest to fertilized crop production in Borneo led to an order of magnitude increase in N_2O emissions from the agricultural soils as compared to the forest soils (Hall et al., 2004).

Fig. 7. The projected shift of the permafrost boundary in northern Asia by 2100 due to climate change (Cruz et al., 2007).

Gas Fluxes and Soils Summary

In summary, human management can have a profound impact on processes that emit or consume CO_2, CH_4, and N_2O in the soil. Current soil carbon estimates for soils of the world are given in

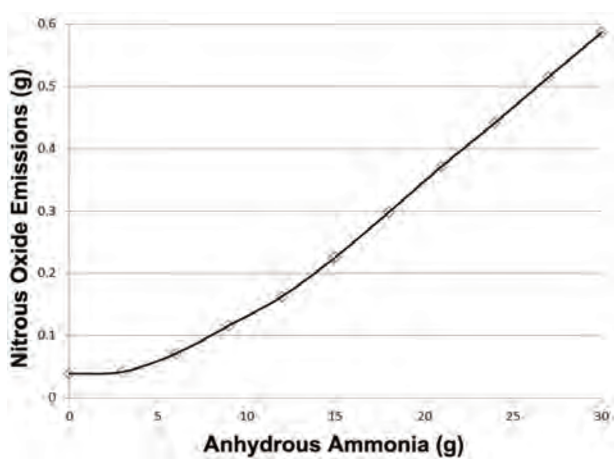


Fig. 8. Modeled nitrous oxide emissions per square meter at various application rates of anhydrous ammonia fertilizer. Data from Grant et al. (2006).

Table 1. Any land management changes that lead to reduced production (i.e., the use of oxidizing mineral fertilizers or decreased flood times to reduce CH_4 emissions from rice fields) or increased sequestration (i.e., converting to a no-till system with cover crops to sequester carbon) of greenhouse gases in the soil system have the overall effect of reducing atmospheric greenhouse gases. However, soils can also serve as a source of greenhouse gases. In fact, soils are a major source of anthropogenic non-CO_2 emissions from agriculture. Nitrous oxide emissions from soils constituted 38% and CH_4 emissions from rice production 11% of the total non-CO_2 greenhouse gas emissions from agriculture in 2005 (Smith et al., 2007). Additionally, increasing soil temperatures have been shown to lead to increased CH_4 production in rice paddies and wetlands (Schütz et al., 1990; Stępniewski et al., 2011). However, soils are not currently considered to be a major net source of CO_2. While agricultural soils produce large quantities of CO_2 each year, they also take up large quantities, such that agricultural soils are estimated to contribute less than 1% of net global anthropogenic CO_2 emissions (Smith et al., 2007).

Climate Change and Soil Processes

Climate change is expected to have several effects on the soil system. Changes in atmospheric concentrations of CO_2, temperature, and precipitation amounts and patterns will modify the soil–plant system and influence decomposition rates, which will have impacts on soil organic carbon levels. Organic carbon in turn has a significant influence on soil structure, soil fertility, microbial processes and populations in the soil, and other important soil properties. The challenge in figuring out how climate change will influence soil properties and processes is in working out the complex interactions that take place as conditions change.

Soil Organic Carbon

Early expectations were that increased atmospheric CO_2 would lead to increased plant productivity coupled with increased carbon sequestration by soil, with the implication that increased plant growth and the soil–plant system would help offset increasing atmospheric CO_2 levels (Coughenour and Chen, 1997; Hättenschwiler et al., 2002). This increase in plant growth is known as the CO_2 fertilization effect. However, recent studies indicate the CO_2 fertilization effect may not be as large as originally thought (Poorter and Navas, 2003; Zavaleta et al., 2003; Long et al., 2005; Körner, 2006; Jarvis et al., 2010; Zaehle et al., 2010). Increasing levels of ozone may actually counteract the CO_2 fertilization effect, leading to reduced plant growth under elevated CO_2 (Long et al., 2005), and the negative effects of increased temperatures on plant growth may also cancel out any CO_2 fertilization effect that does take place (Jarvis et al., 2010). Nitrogen limitations may negatively affect plant growth (Hungate et al., 2003), and modeling of carbon dynamics as influenced by nitrogen indicates less carbon sequestration by soil than originally expected given CO_2 fertilization (Zaehle et al., 2010). A long-term elevated CO_2 experiment in a grasslands ecosystem indicated that nitrogen and phosphorus became limiting after a time, again limiting plant biomass response to elevated CO_2 (Niklaus and Körner, 2004). Niklaus and Körner (2004) concluded that the increases in plant productivity they did see were primarily due to soil moisture status as opposed to a CO_2 fertilization effect. Experiments looking at the decomposition of plant

Table 1. Soil organic and total carbon for soils of the world and carbon per square meter to a depth of 1 m. Organic and total carbon data for each order are from Eswaran et al. (1995), and total area of ice-free land is from Blum and Eswaran (2004). The average organic and total carbon per square meter for each order is calculated using the data from Eswaran et al. (1995) and Blum and Eswaran (2004).

Order†	Organic C	Total C	Ice-free land surface	Organic C	Total C
	Pg		km^2	kg m^{-2}	
Alfisols	136	236	12,620,000	10.8	18.7
Andisols	69	70	912,000	75.7	76.8
Aridisols	110	1154	15,700,000	7.0	73.5
Entisols	106	223	23,390,000	4.5	9.5
Histosols	390	390	3780,000	103.2	103.2
Inceptisols	267	552	15,110,000	17.7	36.5
Mollisols	72	211	11,260,000	6.4	18.7
Oxisols	150	150	9810,000	15.3	15.3
Spodosols	98	98	5600,000	17.5	17.5
Ultisols	101	101	11,050,000	9.1	9.1
Vertisols	38	63	3160,000	12.0	19.9
Misc. land‡	18	18	18,400,000	1.0	1.0

† Eswaran et al. (1995) was published before the Gelisols order was established in 1998. Before 1998, most of the soils currently classified as Gelisols were classified in the Entisols, Inceptisols, Histosols, Mollisols, and Spodosols orders (Buol et al., 2003). For the purposes of this table, the Gelisols area has been split equally among these soil orders.

‡ Ice-free land without soil cover.

tissues grown under elevated atmospheric CO_2 also indicate that increased levels of CO_2 are emitted during that decomposition (Kirkham, 2011), and Carney et al. (2007) observed soil organic carbon levels declining under increased atmospheric CO_2 levels due to increased microbial activity. Therefore, elevated CO_2 levels will not necessarily lead to increased soil carbon sequestration, but may instead result in more carbon turnover (Eglin et al., 2011).

Increased temperature is likely to have a negative effect on carbon allocation to the soil, leading to reductions in soil organic carbon and creating a positive-feedback in the global carbon cycle as global temperature rise (Gorissen et al., 2004; Wan et al., 2011). Link et al. (2003) observed that soil warming and drying led to a 32% reduction in soil carbon during a 5-yr time period. Modeling of carbon responses to climate change in Canada predicted small increases in aboveground biomass in forest and tundra ecosystems, but larger decreases in soil and litter pools, for an overall increase in atmospheric carbon (Price et al., 1999). Another modeling study predicted decreases in soil organic carbon of 2.0 to 11.5% in the north-central United States (Grace et al., 2006). Niklińska et al. (1999) measured humus respiration rates under increased temperatures in samples from European Scots pine stands and concluded that the ecosystems studied would switch from net sinks to net sources of atmospheric carbon with global warming.

What this all means from a soils perspective is that soils cannot necessarily be expected to become massive carbon sinks as atmospheric CO_2 levels rise. The actual impact of elevated atmospheric CO_2 on carbon storage in soils is very difficult to predict. However, if the results of the studies above are representative of what does occur, soils may actually lose organic matter as atmospheric CO_2 levels and global temperatures increase, creating a positive feedback system that could push temperatures even higher. If too much organic matter is lost that will also have negative impacts on soil physical, chemical, and biological properties (Wolf and Snyder, 2003; Brevik, 2009).

Soil Nitrogen

When CO_2 enrichment increases the soil C/N ratio, decomposing organisms in the soil need more nitrogen, which can reduce nitrogen mineralization (Gill et al., 2002; Hungate et al., 2003; Reich et al., 2006a). Mineralization is an essential step in supplying nitrogen to plants (Pierzynski et al., 2009; Mullen, 2011). Therefore, if nitrogen mineralization is reduced, it would be expected that plant-available nitrogen levels in the soil would also be reduced, and plant productivity would be negatively affected. Holland (2011) reported that nitrogen limitation of CO_2 fertilized plants is consistent with the results reported by Hungate et al. (2003), but that increased temperatures stimulate nitrogen availability in the soil, enhancing terrestrial carbon uptake relative to the results of Hungate et al. (2003). However, the stimulated carbon uptake is not enough to offset the nitrogen limitation, and the net result is still an increase in atmospheric CO_2 and an overall reduction in soil carbon levels (Holland, 2011).

It should be noted that nitrogen supplements (i.e., fertilizer) can alter these results (Reich et al., 2006a). Fertilization occurs much more often on agricultural soils than on forest or grassland soils. However, Mulvaney et al. (2009) reported that adding synthetic nitrogen fertilizers in excess of crop needs has the long-term effect of decreasing both soil organic carbon and total soil nitrogen, negatively impacting soil productivity and agronomic efficiency. Therefore, nitrogen fertilization needs to be used carefully.

Some researchers have reported that increasing temperatures increase nitrogen mineralization (Norby and Luo, 2004; Joshi et al., 2006; Reich et al., 2006b), which could have a positive effect on plant growth. However, a warming study by An et al. (2005) showed that nitrogen mineralization was stimulated in the first year but depressed afterward. Szukics et al. (2010) studied the effects of increasing temperature (5–25°C) and soil water (30, 55, and 70% water-filled pore space) on the activity of microorganisms responsible for nitrification and denitrification. They found that increasing soil temperature from 5 to 25°C induced a rapid stimulation of nitrogen cycling rates. The nitrification rate and NO_3^- concentration increased most rapidly at the 55% water content. In the 70% water content soils, the NO_3^- pool was increasingly depleted as soil temperature increased, and was almost completely depleted at 25°C. The depletion in hot, wet soils was attributed to complete denitrification and the release of nitrogen gases into the atmosphere. Nitric oxide was the primary nitrogen gas released from the 30% water content soils, and N_2O emissions were highest from the 55% water content soils. This research demonstrates that increased emissions of N gases into the atmosphere from soils are possible as global temperatures warm.

Symbiotic biological N_2 fixation often increases with elevated CO_2 levels, but usually only in experiments where phosphorus, potassium, and/or other non-nitrogen nutrients were added (Reich et al., 2006b). In experiments where increases in N_2 fixation were observed without the addition of non-nitrogen nutrients they tended to be short-term responses to elevated CO_2 levels that declined with time (Reich et al., 2006b). Free-living and associate N_2-fixing organisms appear to be unresponsive to elevated CO_2 levels in the limited long-term field experiments that have been conducted (Reich et al., 2006b). Therefore, it is unlikely that increased rates of atmospheric nitrogen fixation can be relied on to ensure that nitrogen does not become a limiting factor to carbon sequestration by soils in a warmer world.

The relationships between climate change and soil nitrogen and how that relationship will affect carbon sequestration by soils are among the more controversial issues being addressed right now in the study of soil science and climate change, and more study is needed to resolve it (Holland, 2011; Reich et al., 2006b). Understanding these carbon–nitrogen interactions is critical to determine whether soil organic matter levels will increase or decline under elevated CO_2 levels.

Soil Water

Water content in soils of semiarid grassland systems is expected to be higher under elevated atmospheric CO_2, a condition attributed to reduced transpiration due to increased stomatal resistance (Kirkham, 2011). An experiment in a desert scrub ecosystem did not find increased soil water content under elevated CO_2 levels (Nowak et al., 2004), presumably because the stomata of desert plants already act to reduce transpiration. However, another study in an irrigated desert agroecosystem showed a trend toward higher soil water contents under elevated CO_2 as compared to ambient CO_2 (Kirkham, 2011). In short, different parts of the world will be impacted differently in terms of soil water (Kang et al., 2009).

Doubling atmospheric CO_2 has been shown to reduce seasonal evapotranspiration by 8% in wheat (*Triticum aestivum* L.) and cotton and by 9% in soybean [*Glycine max* (L.) Merr.] grown under day/night temperatures of 28/18°C (Hatfield, 2011). However, the reduction in transpiration by soybeans was eliminated if the plants were grown under temperatures of 40/30°C (Hatfield, 2011). In a study on rice doubling CO_2 decreased evapotranspiration by 15% at 26°C but increased evapotranspiration at 29.5°C (Hatfield, 2011). Elevated CO_2 levels increase the water use efficiency and decrease evapotransporation rates of many plants. However, evapotranspiration rates appear to be temperature dependent, meaning the water benefits of increased atmospheric CO_2 could be reduced or lost in areas where temperatures rise too high.

Erosion

Through climate change and anthropogenic activities, many of our world's soils have or are expected to become more susceptible to erosion by wind and/or water (Zhang et al., 2004; Ravi et al., 2010; Sivakumar, 2011). Simulations ran for Australia showed that increased rainfall due to climate change could lead to significant increases in runoff, with amplification greater in arid areas (up to five times more runoff than the percentage increase in rainfall) than in wet and temperate areas (twice as much runoff as the percentage change in rainfall) (Chiew et al., 1995). Greater runoff would be expected to cause increased erosion. Water erosion models in the United Kingdom predicted that a 10% increase in winter rainfall could increase annual soil erosion by as much as 150% during wet years, but that long-term averages of soil erosion would show a modest increase over current conditions (Favis-Mortlock and Boardman, 1995). Li et al. (2011) predicted changes in water erosion of −5 to 195% for conventional tillage and 26 to 77% for conservation tillage in China's Loess Plateau region, while Zhang et al. (2004) predicted increased erosion in Oklahoma, USA of 19 and 40% under conservation and conventional tillage, respectively.

The negative effects of soil erosion on crop yields and food production are well established (Fig. 9) (Poudel et al., 1999; Sparovek and Schnug, 2001; Pimentel, 2006; Bakker et al., 2007). During their study of a semiarid Mediterranean ecosystem in Spain, García-Fayos and Bochet (2009) found strong correlations between climate change and soil erosion and negative impacts on aggregate stability, bulk density, water-holding capacity, pH, organic matter content, total nitrogen, and soluble phosphorus in the soil. Therefore, it can be stated that if climate change increases soil erosion, it will also damage soil properties that are important in the production of food and fiber resources needed by humans.

Soil Organisms

Soil organisms are essential to create a well-functioning soil (Wolf and Snyder, 2003; Brevik, 2009). Some soil organisms break down fresh organic matter added to the soil, releasing nutrients that can be used by plants and cycling nutrients through the soil system. Other soil organisms fix atmospheric nitrogen, making it available to plants. During organic matter decomposition soil organisms create organic "glues" that help arrange individual sand, silt, and clay particles in the soil into peds. Pores between the peds serve as pathways for the movement of water, air, and roots through the soil, and pores within the peds act to store water between rain events. The role of soil organisms in decomposing organic matter means they are an integral part of the global carbon and nitrogen cycles, which influence the concentrations of greenhouse gases in the atmosphere.

The effect of climate change on soil organisms is not easy to determine. Soil organisms respond to a wide array of soil conditions, including temperature, water content, pH, nutrient

Fig. 9. Erosion of topsoil from this hilltop has led to reduced crop production in the eroded areas. (Photo by Gene Alexander, USDA-NRCS.)

levels, oxygen status, and the presence or absence of other soil organisms (Brady and Weil, 2008). It is very difficult if not impossible to predict how all these variables will change at any single location given changes in global climate. Therefore, studies in this area tend to look at how changes in one or two variables, temperature and/or rainfall, for example, would influence soil organisms at a given location. The results of some of those studies are summarized here.

Briones et al. (1997) conducted an experiment with intact soil cores, raising the average annual temperature of those cores by 2.5°C. They tracked Enchytraeidae, Tardigrada, and Diptera responses and determined that some species were tolerant to the new, higher temperatures and would increase their numbers, some species would migrate to deeper layers of the soil, and some would go dormant or extinct. Briones et al. (1997) concluded that predicted global temperature changes would have significant effects on the soil ecosystem that would have important implications for organic matter decomposition and nutrient cycling.

Kardol et al. (2011) looked at the influence of CO_2 level, temperature, and precipitation on microarthropods. They found that the community composition shifted in response to the treatments, with most of the composition shift attributed to the effects of precipitation and temperature and how those two variables affected soil water content. They concluded that climate change can affect the structure of soil microarthropod communities, which could in turn have an impact on ecosystem functions such as soil organic matter decomposition.

Drennan and Nobel (1996) performed a study to look at the effects of elevated CO_2 concentrations and temperature on the root systems of three desert plants, *Encelia farinosa* A. Gray ex Torr. (a C_3 plant), *Pleuraphis rigida* Thurb. (C_4), and *Agave deserti* Engelm. (CAM). They found that *A. deserti* increased its average daily root elongation under elevated CO_2, but there was no root elongation effect on the other two species. They also found that shading of the soil reduced daily variations in soil temperature and altered root distribution and elongation patterns.

While this brief discussion of climate change effects on soil organisms does not definitively answer how soil organisms will change in response to climate change, it does indicate that soil ecosystems will change as a result of climate change and that some very important processes involving soil organisms, like organic matter decomposition and nutrient cycling, will also likely change. This conclusion differs substantially from the assumption by some early in the study of soil organisms and climate change that predicted temperature changes would likely produce little response from the soil ecosystem except in response to shifts in vegetation (Whitford, 1992).

Conclusions

The Earth's climate system is changing—of that we are certain. Beyond that, most of what is covered in this paper is less certain. There are still many things we need to know more about. How climate change will affect the nitrogen cycle and, in turn, how the nitrogen cycle will affect carbon sequestration in soils constitute a major research need, as is a better understanding of soil water–CO_2 level–temperature relationships. Knowledge of the response of plants to elevated atmospheric CO_2 given potential limitations in nutrients like nitrogen and phosphorus and how that affects soil organic matter dynamics is a critical need. There is also a great need for a better understanding of how soil organisms will respond to climate change because those organisms are incredibly important in a number of soil processes, including the carbon and nitrogen cycles.

All of these questions involve highly complex and interconnected systems that make it difficult to isolate a single variable, such as temperature or precipitation patterns, to reach meaningful conclusions about how a change in that single variable affects the system being studied. However, we do know that there is the potential for some undesirable things to occur as a result of climate change. There is the possibility that soils could contribute increasing amounts of greenhouse gases to the atmosphere, losing their ability to act as a sink for carbon as global temperatures increase, and there is the chance that we will see negative impacts on the physical and chemical properties of our soils that are essential for the production of food and fiber products. Therefore, it is critical that continued research into these areas be supported, with the particular goal of understanding the complex interactions that take place in the natural environment.

References

Akala, V.A., and R. Lal. 2001. Soil organic carbon pools and sequestration rates in reclaimed minesoils in Ohio. J. Environ. Qual. 30:2098–2104. doi:10.2134/jeq2001.2098

Álvaro-Fuentes, J., and K. Paustian. 2011. Potential soil carbon sequestration in a semiarid Mediterranean agroecosystem under climate change: Quantifying management and climate effects. Plant Soil 338:261–272. doi:10.1007/s11104-010-0304-7

An, Y., S. Wan, X. Zhou, A.A. Subedar, L.A. Wallace, and Y. Luo. 2005. Plant nitrogen concentration, use efficiency, and contents in a tallgrass prairie ecosystem under experimental warming. Glob. Change Biol. 11:1733–1744. doi:10.1111/j.1365-2486.2005.01030.x

Backlund, P., A. Janetos, D.S. Schimel, J. Hatfield, M.G. Ryan, S.R. Archer, and D. Lettenmaier. 2008. Executive Summary. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC., USA. p. 1–10.

Bakker, M.M., G. Govers, R.A. Jones, and M.D.A. Rounsevell. 2007. The effect of soil erosion on Europe's crop yields. Ecosystems 10:1209–1219. doi:10.1007/s10021-007-9090-3

Barber, D.G., J.V. Lukovich, J. Keogak, S. Baryluk, L. Fortier, and G.H.R. Henry. 2008. The changing climate of the Arctic. Arctic 61:7–26.

Bartlett, K.H., and R.C. Harris. 1993. Review and assessment of methane emissions from wetlands. Chemosphere 26:261–320. doi:10.1016/0045-6535(93)90427-7

Bliss, N.B., and J. Maursetter. 2010. Soil organic carbon stocks in Alaska estimated with spatial and pedon data. Soil Sci. Soc. Am. J. 74:565–579. doi:10.2136/sssaj2008.0404

Bluemle, J.P., J.M. Sabel, and W. Karlén. 1999. Rate and magnitude of past global climate changes. Environ. Geosci. 6:63–75. doi:10.1046/j.1526-0984.1999.08036.x

Blum, W.E.H., and H. Eswaran. 2004. Soils for sustaining global food production. J. Food Sci. 69:37–42.

Brady, N.C., and R.R. Weil. 2008. The nature and properties of soils. 14th ed. Pearson Prentice Hall, Upper Saddle River, NJ.

Brevik, E.C. 2000. A comparison of soil properties in compacted versus non-compacted Bryant soil series twenty-five years after compaction ceased. Soil Surv. Horiz. 41:52–58.

Brevik, E.C. 2009. Soil health and productivity. In: W. Verheye, editor, Soils, plant growth and crop production. Encyclopedia of Life Support Systems (EOLSS), UNESCO, EOLSS Publishers, Oxford, UK.

Brevik, E.C., T. Fenton, and L. Moran. 2002. Effect of soil compaction on organic carbon amounts and distribution, south-central Iowa. Environ. Pollut. 116:S137–S141. doi:10.1016/S0269-7491(01)00266-4

Brevik, E.C., and J.A. Homburg. 2004. A 5000 year record of carbon sequestration from a coastal lagoon and wetland complex, Southern California, USA. Catena 57:221–232. doi:10.1016/j.catena.2003.12.001

Briones, M.J.I., P. Ineson, and T.G. Piearce. 1997. Effects of climate change on soil fauna; responses of enchytraeids, Diptera larvae, and tardigards in a transplant experiment. Appl. Soil Ecol. 6:117–134. doi:10.1016/S0929-1393(97)00004-8

Brooks, P.D., S.K. Schmidt, and M.W. Williams. 1997. Winter production of CO_2 and N_2O from alpine tundra: Environmental controls and relationship to inter-system C and N fluxes. Oecologia 110:403–413.

Buol, S.W., R.J. Southard, R.C. Graham, and P.A. McDaniel. 2003. Soil genesis and classification. 5th ed. Iowa State Univ. Press, Ames.

Carney, K.M., B.A. Hungate, B.G. Drake, and J.P. Megonigal. 2007. Altered soil microbial community at elevated CO_2 leads to loss of soil carbon. Proc. Natl. Acad. Sci. USA 104:4990–4995. doi:10.1073/pnas.0610045104

Carter, R.M. 2007. The myth of dangerous human-caused climate change. In: Proceedings of the Australasian Institute of Mining & Metallurgy New Leaders Conference, 2–3 May 2007, Brisbane. p. 61–74.

Chapin, F.S., III, G. Peterson, F. Berkes, T.V. Callaghan, P. Angelstam, M. Apps, C. Beier, Y. Bergeron, A.-S. Crépin, K. Danell, T. Elmqvist, C. Folke, B. Forbes, N. Fresco, G. Juday, J. Niemelä, A. Shvidenko, and G. Whiteman. 2004. Resilience and vulnerability of northern regions to social and environmental change. Ambio 33:344–349.

Chatskikh, D., J.E. Olesen, J. Berntsen, K. Regina, and S. Yamulki. 2005. Simulation of effects of soils, climate, and management on N_2O emission from grasslands. Biogeochemistry 76:395–419. doi:10.1007/s10533-005-6996-8

Chiew, F.H.S., P.H. Whetton, T.A. McMahon, and A.B. Pittock. 1995. Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. J. Hydrol. 167:121–147. doi:10.1016/0022-1694(94)02649-V

Cooney, C.M. 2010. The perception factor: Climate change gets personal. Environ. Health Perspect. 118(11):A484–A489. doi:10.1289/ehp.118-a484

Corfee-Morlot, J., M. Maslin, and J. Burgess. 2007. Global warming in the public sphere. Philos. Trans. R. Soc. London. Ser. A 365:2741–2776.

Coughenour, M.B., and D.-X. Chen. 1997. Assessment of grassland ecosystem responses to atmospheric change using linked plant-soil process models. Ecol. Appl. 7:802–827.

Cruz, R.V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, and N. Huu Ninh. 2007. Asia. In: M.L. Parry et al., editors, Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 469–506.

Davidson, E.A., and I.A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173. doi:10.1038/nature04514

DeLaune, R.D., W.H. Patrick, C.W. Lindau, and C.J. Smith. 1990. Nitrous oxide and methane emission from Gulf Coast wetlands. In: A.F. Bouwman, editor, Soils and the greenhouse effect. John Wiley and Sons, New York. p. 497–502.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, and X. Zhang. 2007. Couplings between changes in the climate system and biogeochemistry. In: S. Solomon et al., editors, Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 499–587.

Dixon-Coppage, T.L., G.L. Davis, T. Couch, E.C. Brevik, C.I. Barineau, and P.C. Vincent. 2005. A forty-year record of carbon sequestration in an abandoned borrow-pit, Lowndes County, GA. Proc. Soil Crop Sci. Soc. Fl. 64:8–15.

Drennan, P.M., and P.S. Nobel. 1996. Temperature influences on root growth for *Encelia farinosa* (Asteraceae), *Pleuraphis rigida* (Poaceae), and *Agave deserti* (Agavaceae) under current and doubled CO_2 concentrations. Am. J. Bot. 83:133–139. doi:10.2307/2445929

Eglin, T., P. Ciasis, S.L. Piao, P. Barré, V. Belassen, P. Cadule, C. Chenu, T. Gasser, M. Reichstein, and P. Smith. 2011. Overview on response of global soil carbon pools to climate and land-use changes. In: T.J. Sauer, J.M. Norman, and M.V.K. Sivakumar, editors, Sustaining soil productivity in response to global climate change: Science, policy, and ethics. John Wiley and Sons, Oxford, UK. p. 183–199.

Eswaran, H., E. Van den Berg, P. Reich, and J. Kimble. 1995. Global soil carbon resources. In: R. Lal et al., editors, Soil processes and the carbon cycle. CRC Press, Boca Raton, FL. p. 27–43.

Favis-Mortlock, D., and J. Boardman. 1995. Nonlinear responses of soil erosion to climate change: A modeling study on the UK South Downs. Catena 25:365–387. doi:10.1016/0341-8162(95)00018-N

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland. 2007. Changes in atmospheric constituents and in radiative forcing. In: S. Solomon et al., editors, Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 129–234.

García-Fayos, P., and E. Bochet. 2009. Indication of antagonistic interaction between climate change and erosion on plant species richness and soil properties in semiarid Mediterranean ecosystems. Glob. Change Biol. 15:306–318. doi:10.1111/j.1365-2486.2008.01738.x

Gill, R.A., H.W. Polley, H.B. Johnson, L.J. Anderson, H. Maherali, and R.B. Jackson. 2002. Nonlinear grassland responses to past and future atmospheric CO_2. Nature 417:279–282. doi:10.1038/417279a

Gorissen, A., A. Tietema, N.N. Joosten, M. Estiarte, J. Peñuelas, A. Sowerby, B.A. Emmett, and C. Beier. 2004. Climate change affects carbon allocation to the soil in shrublands. Ecosystems 7:650–661. doi:10.1007/s10021-004-0218-4

Grace, P.R., M. Colunga-Garcia, S.H. Gage, G.P. Robertson, and G.R. Safir. 2006. The potential impact of agricultural management and climate change on soil organic carbon of the north central region of the United States. Ecosystems 9:816–827. doi:10.1007/s10021-004-0096-9

Grandy, A.S., T.D. Loecke, S. Parr, and G.P. Robertson. 2006. Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. J. Environ. Qual. 35:1487–1495. doi:10.2134/jeq2005.0166

Grant, R.F., E. Pattey, T.W. Goddard, L.M. Kryzanowski, and H. Puurveen. 2006. Modeling the effects of fertilizer application rate on nitrous oxide emissions. Soil Sci. Soc. Am. J. 70:235–248. doi:10.2136/sssaj2005.0104

Gribble, G.W. 2003. The diversity of naturally produced organohalogens. Chemosphere 52:289–297. doi:10.1016/S0045-6535(03)00207-8

Hall, S.J., G.P. Asner, and K. Kitayama. 2004. Substrate, climate, and land use controls over soil N dynamics and N-oxide emissions in Borneo. Biogeochemistry 70:27–58. doi:10.1023/B:BIOG.0000049335.68897.87

Hansen, J., M. Sato, P. Kharecha, G. Russell, D.W. Lea, and M. Siddall. 2007. Climate change and trace gases. Philos. Trans. R. Soc. London Ser. A 365:1925–1954. doi:10.1098/rsta.2007.2052

Hatfield, J.L. 2011. Soil management for increasing water use efficiency in field crops under changing climates. In: J.L. Hatfield and T.J. Sauer, editors, Soil management: Building a stable base for agriculture. SSSA, Madison, WI. p. 161–173.

Hättenschwiler, S., I.T. Handa, L. Egli, R. Asshoff, W. Ammann, and C. Körner. 2002. Atmospheric CO_2 enrichment of alpine treeline conifers. New Phytol. 156:363–375. doi:10.1046/j.1469-8137.2002.00537.x

Heilig, G.K. 1994. The greenhouse gas methane (CH4): Sources and sinks, the impact of population growth, possible interventions. Popul. Environ. 16:109–137. doi:10.1007/BF02208779

Hobbs, P.R., and B. Govaerts. 2010. How conservation agriculture can contribute to buffering climate change. In: M.P. Reynolds, editor, Climate change and crop production. CPI Antony Rowe, Chippenham, UK. p. 177–199.

Hoekstra, E.J., H. de Weerd, E.W.B. de Leer, and U.A.Th. Brinkman. 1999. Natural formation of chlorinated phenols, dibenzo-p-dioxins, and dibenzofurans in soil of a Douglas fir forest. Environ. Sci. Technol. 33:2543–2549. doi:10.1021/es9900104

Holland, E.A. 2011. The role of soils and biogeochemistry in the climate and Earth system. In: T.J. Sauer, J.M. Norman, and M.V.K. Sivakumar, editors, Sustaining soil productivity in response to global climate change: Science, policy, and ethics. John Wiley and Sons, Oxford, UK. p. 155–168.

Hu, R., K. Kusa, and R. Hatano. 2001. Soil respiration and methane flux in adjacent forest, grassland, and cornfield soils in Hokkaido, Japan. Soil Sci. Plant Nutr. 47:621–627. doi:10.1080/00380768.2001.10408425

Hungate, B.A., J.S. Dukes, M.R. Shaw, Y. Luo, and C.B. Field. 2003. Nitrogen and climate change. Science 302:1512–1513. doi:10.1126/science.1091390

Hussein, A.H., M.C. Rabenhorst, and M.L. Tucker. 2004. Modeling of carbon sequestration in coastal marsh soils. Soil Sci. Soc. Am. J. 68:1786–1795. doi:10.2136/sssaj2004.1786

IPCC. 2007a. Summary for policymakers. In: S. Solomon et al., editors, Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 1–18.

IPCC. 2007b. Climate change 2007 synthesis report. In: R.K. Pachauri and A. Reisinger, editors, Working group contributions to the fourth assessment report of the intergovernmental panel on climate change. Cambridge Univ. Press, Cambridge, UK. p. 23–73.

Jarvis, A., J. Ramirez, B. Anderson, C. Leibing, and P. Aggarwal. 2010. Scenarios of climate change within the context of agriculture. In: M.P. Reynolds, editor, Climate change and crop production. CPI Antony Rowe, Chippenham, UK. p. 9–37.

Jespersen, J.L., and L.J. Osher. 2007. Carbon storage in the soils of a mesotidal Gulf of Maine estuary. Soil Sci. Soc. Am. J. 71:372–379. doi:10.2136/sssaj2006.0225

Johnson, B.J., K.A. Moore, C. Lehmann, C. Bohlen, and T.A. Brown. 2007. Middle to Late Holocene fluctuations of C_3 and C_4 vegetation in a northern New England salt marsh, Sprague Marsh, Phippsburg Maine. Org. Geochem. 38:394–403. doi:10.1016/j.orggeochem.2006.06.006

Joshi, A.B., D.R. Vann, and A.H. Johnson. 2006. Litter quality and climate decouple nitrogen mineralization and productivity in Chilean temperate rainforests. Soil Sci. Soc. Am. J. 70:153–162. doi:10.2136/sssaj2004.0173

Kang, Y., S. Khan, and X. Ma. 2009. Climate change impacts on crop yield, crop water productivity, and food security—A review. Prog. Nat. Sci. 19:1665–1674. doi:10.1016/j.pnsc.2009.08.001

Kardol, P., W.N. Reynolds, R.J. Norby, and A.T. Classen. 2011. Climate change effects on soil microarthropod abundance and community. Appl. Soil Ecol. 47:37–44. doi:10.1016/j.apsoil.2010.11.001

Keene, W.C., M. Aslam, K. Khalil, D.J. Erickson III, A. McCulloch, T.E. Graedel, J.M. Lobert, M.L. Aucott, S.L. Gong, D.B. Harper, G. Kleiman, P. Midgley, R.M. Moore, C. Seuzaret, W.T. Sturges, C.M. Benkovitz, V. Koropalov, L.A. Barrie, and Y.F. Li. 1999. Composite global emissions of reactive chlorine from anthropogenic and natural sources: Reactive chlorine emissions inventory. J. Geophys. Res. 104(D7):8429–8440. doi:10.1029/1998JD100084

Kirkham, M.B. 2011. Elevated carbon dioxide. CRC Press, Boca Raton, FL.

Körner, C. 2006. Plant CO_2 responses: An issue of definition, time and resource supply. New Phytol. 172:393–411. doi:10.1111/j.1469-8137.2006.01886.x

Kutílek, M. 2011. Soils and climate change. Soil Tillage Res. 117:1–7. doi:10.1016/j.still.2011.08.009

Lal, R. 2007. Soil science and the carbon civilization. Soil Sci. Soc. Am. J. 71:1425–1437. doi:10.2136/sssaj2007.0001

Lal, R. 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience 60:708–721. doi:10.1525/bio.2010.60.9.8

Lal, R., J. Kimble, and R.F. Follett. 1998. Pedospheric processes and the carbon cycle. In: R. Lal et al., editors, Soil processes and the carbon cycle. CRC Press, Boca Raton, FL. p. 1–8.

Li, Z., W.-Z. Lui, X.-C. Zhang, and F.-L. Zheng. 2011. Assessing the site-specific impacts of climate change on hydrology, soil erosion, and crop yields in the Loess Plateau of China. Clim. Change 105:223–242. doi:10.1007/s10584-010-9875-9

Link, S.O., J.L. Smith, J.J. Halverson, and H. Bolton, Jr. 2003. A reciprocal transplant experiment within a climatic gradient in a semiarid shrub-steppe ecosystem: Effects on bunchgrass growth and reproduction, soil carbon, and soil nitrogen. Glob. Change Biol. 9:1097–1105. doi:10.1046/j.1365-2486.2003.00647.x

Lokupitiya, E., and K. Paustian. 2006. Agricultural soil greenhouse gas emissions: A review of national inventory methods. J. Environ. Qual. 35:1413–1427. doi:10.2134/jeq2005.0157

Long, S.P., E.A. Ainsworth, A.D.B. Leakey, and P.B. Morgan. 2005. Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. Philos. Trans. R. Soc. London Ser. B 360(1463):2011–2020. doi:10.1098/rstb.2005.1749

Lu, Y., R. Wassmann, H.-U. Neue, and C. Huang. 1999. Impact of phosphorus supply on root exudation, aerenchyma formation and methane emission of rice plants. Biogeochemistry 47:203–218.

Martikainen, P.J., K. Regina, E. Syväsalo, T. Laurila, A. Lohila, M. Aurela, J. Silvola, R. Kettunen, S. Saarnio, H. Koponen, T. Jaakkola, A. Pärnä, H. Silvennoinen, H. Lehtonen, J. Peltola, M. Sinkkonen, and M. Esala. 2002. Agricultural soils as a sink and source of greenhouse gases: A research consortium (AGROGAS). In: J. Käyhkö and L. Talve, editors, Understanding the global system, the Finnish perspective. Finnish Global Change Research Programme FIGARE, Turku, Finland. p. 55–68.

Melillo, J.M., P.A. Steudler, B.J. Feigl, C. Neill, D. Garcia, M.C. Piccolo, C.C. Cerri, and H. Tian. 2001. Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon. J. Geophys. Res. 106(D24):34179–34188. doi:10.1029/2000JD000036

Mosier, A.R. 1998. Soil processes and global change. Biol. Fertil. Soils 27:221–229. doi:10.1007/s003740050424

Mullen, R.W. 2011. Nutrient cycling in soils: Nitrogen. In: J.L. Hatfield and T.J. Sauer, editors, Soil management: Building a stable base for agriculture. SSSA, Madison, WI. p. 67–78.

Mulvaney, R.L., S.A. Khan, and T.R. Ellsworth. 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. J. Environ. Qual. 38:2295–2314. doi:10.2134/jeq2008.0527

Neill, C., C.C. Cern, J.M. Melillo, B.J. Feigl, P.A. Steudler, J.F.L. Moraes, and M.C. Piccolo. 1998. Stocks and dynamics of soil carbon following deforestation for pasture in Rondonia. In: R Lal et al., editors, Soil processes and the carbon cycle. CRC Press, Boca Raton, FL. p. 9–28.

Neue, H.-U. 1992. Agronomic practices affecting methane fluxes from rice cultivation. Ecol. Bull. 42:174–182.

Niklaus, P.A., and C. Körner. 2004. Synthesis of a six-year study of calcareous grassland responses to in situ CO_2 enrichment. Ecol. Monogr. 74:491–511. doi:10.1890/03-4047

Niklińska, M., M. Maryański, and R. Laskowski. 1999. Effect of temperature on humus respiration rate and nitrogen mineralization: Implications for global climate change. Biogeochemistry 44:239–257.

Norby, R.J., and Y. Luo. 2004. Evaluating ecosystem responses to rising atmospheric CO_2 and global warming in a multi-factor world. New Phytol. 162:281–293. doi:10.1111/j.1469-8137.2004.01047.x

Nowak, R.S., S.F. Zitzer, D. Babcock, V. Smith-Longozo, T.N. Charlet, J.S. Coleman, J.R. Seemann, and S.D. Smith. 2004. Elevated atmospheric CO_2 does not conserve soil water in the Mojave Desert. Ecology 85:93–99. doi:10.1890/03-3054

Oechel, W.C., and G.L. Vourlitis. 1995. Effects of global change on carbon storage in cold soils. In: R. Lal et al., editors, Soils and global change. CRC Press, Boca Raton, FL. p. 117–129.

Pierzynski, G.M., J.T. Sims, and G.F. Vance. 2009. Soils and environmental quality. 3rd ed. CRC Press, Boca Raton, FL.

Pimentel, D. 2006. Soil erosion: A food and environmental threat. Environ. Dev. Sustain. 8:119–137. doi:10.1007/s10668-005-1262-8

Poorter, H., and M.-L. Navas. 2003. Plant growth and competition at elevated CO_2: On winners, losers and functional groups. New Phytol. 157:175–198. doi:10.1046/j.1469-8137.2003.00680.x

Post, W.M., R.C. Izaurralde, J.D. Jastrow, B.A. McCarl, J.E. Amonette, V.L. Bailey, P.M. Jardine, T.O. West, and J. Zhou. 2004. Enhancement of carbon sequestration in US soils. Bioscience 54:895–908. doi:10.1641/0006-3568(2004)054[0895:EOCSIU]2.0.CO;2

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. Glob. Change Biol. 6:317–327. doi:10.1046/j.1365-2486.2000.00308.x

Poudel, D.D., D.J. Midmore, and L.T. West. 1999. Erosion and productivity of vegetable systems on sloping volcanic ash–derived Philippine soils. Soil Sci. Soc. Am. J. 63:1366–1376. doi:10.2136/sssaj1999.6351366x

Price, D.T., C.H. Peng, M.J. Apps, and D.H. Halliwell. 1999. Simulating effects of climate change on boreal ecosystem carbon pools in central Canada. J. Biogeogr. 26:1237–1248. doi:10.1046/j.1365-2699.1999.00332.x

Ravi, S., D.D. Breshears, T.E. Huxman, and P. D'Odorico. 2010. Land degradation in drylands: Interactions among hydraulic-aeolian erosion and vegetation dynamics. Geomorphology 116:236–245. doi:10.1016/j.geomorph.2009.11.023

Reich, P.B., S.E. Hobbie, T. Lee, D.S. Ellsworth, J.B. West, D. Tilman, J.M. Knops, S. Naeem, and J. Trost. 2006a. Nitrogen limitation constrains sustainability of ecosystem response to CO_2. Nature 440:922–925. doi:10.1038/nature04486

Reich, P.B., B.A. Hungate, and Y. Luo. 2006b. Carbon-nitrogen interactions in terrestrial ecosystems in response to rising atmospheric carbon dioxide. Annu. Rev. Ecol. Evol. Syst. 37:611–636. doi:10.1146/annurev.ecolsys.37.091305.110039

Rustad, L.E., T.G. Huntington, and R.D. Boone. 2000. Controls on soil respiration: Implications for climate change. Biogeochemistry 48:1–6. doi:10.1023/A:1006255431298

Schlesinger, W.H. 1995. An overview of the carbon cycle. In: R. Lal et al., editors, Soils and global change. CRC Press, Boca Raton, FL. p. 9–25.

Schneider, U.A., and P. Smith. 2009. Energy intensities and greenhouse gas emission mitigation in global agriculture. Energy Efficiency 2:195–206. doi:10.1007/s12053-008-9035-5

Schütz, H., W. Seiler, and R. Conrad. 1990. Influence of soil temperature on methane emission from rice paddy fields. Biogeochemistry 11:77–95. doi:10.1007/BF00002060

Silver, W.L., R. Osterlag, and A.E. Lugo. 2000. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. Restor. Ecol. 8:394–407. doi:10.1046/j.1526-100x.2000.80054.x

Sivakumar, M.V.K. 2011. Climate and land degradation. In: T.J. Sauer et al., editors, Sustaining soil productivity in response to global climate change: Science, policy, and ethics. John Wiley & Sons, Oxford, UK. p. 141–154.

Sjögersten, S., R. van der Wal, and S.J. Woodin. 2006. Small-scale hydrological variation determines landscape CO_2 fluxes in the high Arctic. Biogeochemistry 80:205–216. doi:10.1007/s10533-006-9018-6

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, and O. Sirotenko. 2007. Agriculture. In: B. Metz et al., editors, Climate change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 497–540.

Sparovek, G., and E. Schnug. 2001. Temporal erosion-induced soil degradation and yield loss. Soil Sci. Soc. Am. J. 65:1479–1486. doi:10.2136/sssaj2001.6551479x

Sperow, M. 2006. Carbon sequestration potential in reclaimed mine sites in seven east-central States. J. Environ. Qual. 35:1428–1438. doi:10.2134/jeq2005.0158

Steinbach, H.S., and R. Alvarez. 2006. Changes in soil organic carbon contents and nitrous oxide emissions after introduction of no-till in Pampean agroecosystems. J. Environ. Qual. 35:3–13. doi:10.2134/jeq2005.0050

Stępniewski, W., Z. Stępniewski, and A. Rożej. 2011. Gas exchange in soils. In J.L. Hatfield and T.J. Sauer, editors, Soil management: Building a stable base for agriculture. SSSA, Madison, WI. p. 117–144.

Steyer, G.D., and R.E. Stewart, Jr. 1992. Monitoring program for Coastal Wetlands Planning, Protection, and Restoration Act projects. U.S. Fish and Wildlife Service. National Wetlands Research Center Open File Rep. 93-01.

Szukics, U., G.C.J. Abell, V. Hödl, B. Mitter, A. Sessitsch, E. Hackl, and S. Zechmeister-Boltenstern. 2010. Nitrifiers and denitrifiers respond rapidly to changed moisture and increasing temperature in a pristine forest soil. FEMS Microbiol. Ecol. 72:395–406. doi:10.1111/j.1574-6941.2010.00853.x

Titus, J.G. 1991. Greenhouse effect and coastal wetland policy: How Americans could abandon an area the size of Massachusetts at minimum cost. Environ. Manage. 15:39–58. doi:10.1007/BF02393837

Tsihrintzis, V.A., G.M. Vasarhelyi, and J. Lipa. 1996. Ballona wetland: A multi-objective salt marsh restoration plan. Proc. ICE Water Maritime Energy 118:131–144.

Wagner-Riddle, C., and A. Weersink. 2011. Net agricultural greenhouse gases: Mitigation strategies and implications. In: T.J. Sauer, J.M. Norman, and M.V.K. Sivakumar, editors, Sustaining soil productivity in response to global climate change: Science, policy, and ethics. John Wiley and Sons, Oxford, UK. p. 169–182.

Wan, Y., E. Lin, W. Xiong, Y. Li, and L. Guo. 2011. Modeling the impact of climate change on soil organic carbon stock in upland soils in the 21st century in China. Agric. Ecosyst. Environ. 141:23–31. doi:10.1016/j.agee.2011.02.004

Wassmann, R., H. Schütz, H. Papen, H. Rennenberg, W. Seiler, D. Aiguo, S. Renxing, S. Xingjian, and W. Mingxing. 1993. Quantification of methane emissions from Chinese rice fields (Zhejiang province) as influenced by fertilizer treatment. Biogeochemistry 20:83–101. doi:10.1007/BF00004136

Welker, J.M., K.B. Brown, and J.T. Fahnestock. 1999. CO_2 flux in Arctic and alpine dry tundra: Comparative field responses under ambient and experimentally warmed conditions. Arct. Antarct. Alp. Res. 31:272–277. doi:10.2307/1552257

White, W.A., and R.A. Morton. 1997. Wetland losses related to fault movement and hydrocarbon production, southeastern Texas coast. J. Coast. Res. 13:1305–1320.

Whitford, W.G. 1992. Effects of climate change on soil biotic communities and soil processes. In: R.L. Peters and T.E. Lovejoy, editors, Global warming and biological diversity. Yale Univ. Press, New York. p. 124–136.

Williams, M.W., P.D. Brooks, and T. Seastedt. 1998. Nitrogen and carbon soil dynamics in response to climate change in a high-elevation ecosystem in the Rocky Mountains, USA. Arct. Alp. Res. 30:26–30. doi:10.2307/1551742

Wolf, B., and G.H. Snyder. 2003. Sustainable soils: The place of organic matter in sustaining soils and their productivity. Haworth Press, New York.

Zaehle, S., P. Friedlingstein, and A.D. Friend. 2010. Terrestrial nitrogen feedbacks may accelerate future climate change. Geophys. Res. Lett. 37:L01401. doi:10.1029/2009GL041345

Zavaleta, E.S., M.R. Shaw, N.R. Chiariello, B.D. Thomas, E.E. Cleland, C.B. Field, and H.A. Mooney. 2003. Grassland responses to three years of elevated temperature, CO_2, precipitation, and N deposition. Ecol. Monogr. 73:585–604. doi:10.1890/02-4053

Zedler, J.B., and S. Kercher. 2005. Wetland resources: Status, trends, ecosystem services, and restorability. Annu. Rev. Environ. Resour. 30:39–74. doi:10.1146/annurev.energy.30.050504.144248

Zhang, J.-E., Y. Ouyang, Z.-X. Huang, and G.-M. Quan. 2011. Dynamic emission of CH_4 from a rice-duck farming ecosystem. J. Environ. Protect. 2:537–544. doi:10.4236/jep.2011.25062

Zhang, X.C., M.A. Nearing, J.D. Garbrecht, and J.L. Steiner. 2004. Downscaling monthly forecasts to simulate impacts of climate change on soil erosion and wheat production. Soil Sci. Soc. Am. J. 68:1376–1385. doi:10.2136/sssaj2004.1376

Evaluating Salinity and Sodium Levels on Soils before Drain Tile Installation: A Case Study

David Hopkins,* Katrin Chambers, Andrew Fraase, Yangbo He, Kristine Larson, Lindsey Malum, Leif Sande, Jeff Schulte, Eva Sebesta, Dustin Strong, Eric Viall, and Rodney Utter

Soil salinity has emerged as one of the most serious and widespread consequences of the climatic wet period affecting the northern region of the American Midwest since 1993. Groundwater levels have increased, causing not only millions of hectares of prevented planting in the Dakotas, but also much higher levels of soil salinity on otherwise productive soils. A persistent comment from producers throughout eastern North Dakota during the wet cycle was that salinity had emerged in areas where it was never a problem before. Management techniques to reduce salinity effects include crop selection, use of cover crops after harvest, calcium chemical amendments for sodic soils, tillage changes to reduce upland recharge, and tile drainage to lower water tables. Soil data collected to establish background salinity and sodicity levels on a Nahon soil map unit (fine, smectitic, frigid Calcic Natrudolls) east of Wheatland, ND are presented with a broader interpretation regarding the need to perform soil chemical sampling for certain soils before installing tile drainage.

Rationale

From September through November 2010, students in the North Dakota State University Soil Genesis and Survey course (Soils 644) conducted a variety of tests on farmland 1.6 km east of Wheatland, ND. The clay-rich, sodium-affected soil, the Nahon series, which is found on about 40,500 ha in North Dakota and South Dakota was examined. Several other soil map units were present at the field site (Table 1), but the Nahon unit was predominant.

Students examined the Nahon soil to solve an interpretive riddle. A review of chemical characterization data revealed that a Cass County Nahon profile, sampled by Experiment Station soil scientists in the 1950s, was quite inconsistent with a larger set of four Nahon profiles sampled in Brown County, South Dakota, which include the Type Location.[1] The mean exchangeable sodium percentage (ESP) from average depths of 69 to 116 cm for the South Dakota pedons was 14.6. The Cass County profile has C horizon exchangeable sodium percentages (ESP) nearly twice as high as the mean of the four South Dakota soils (Table 2) and has measurably higher salinity at shallower depths (data not shown). The only Nahon profiles in the NRCS National Soil Characterization database are the South Dakota pedons (NRCS, 2011). Can valid comparative interpretations be made if North Dakota Nahon profiles have different chemistry?

Groundwater levels have increased, causing not only millions of hectares of prevented planting in the Dakotas (Agweek, 2011), but much higher levels of soil salinity on otherwise productive soils. Producers were considering tile drainage on the land near Wheatland because of salinity problems, and they wanted to know if student results could aid their decision making process. So the opportunity to evaluate deep soil chemistry gained even more significance because ESP values have a profound effect on water transmitting properties of soils. Additionally, tile drainage is rapidly expanding in eastern North Dakota.

Methods

Soil salinity was mapped with a Veris 3100 Soil EC mapping system, which records apparent soil salinity (ECa) from the 0- to 30- and 0- to 91-cm depths every second (Fig. 1). During the Veris survey, nine locations were identified to calibrate Veris machine readings to represent the range in ECa measured across the field. The sites were sampled in 0- to 30- and 0- to 91-cm increments. Soil samples were mixed in the field, dried, and ground to pass a 2-mm sieve. Veris calibration samples were evaluated for

David Hopkins, Katrin Chambers, Andrew Fraase, Yangbo He, Kristine Larson, Lindsey Malum, Leif Sande, Jeff Schulte, Eva Sebesta, Dustin Strong, Eric Viall, and Rodney Utter, North Dakota State Univ., Fargo, ND. *Corresponding author (david.hopkins@ndsu.edu).

doi:10.2136/sh12-02-0006
Published in Soil Horizons (2012).
Received 23 Feb. 2012.

Abbreviations: ECa, apparent soil salinity; ECe, electrical conductivity; ESP, exchangeable sodium percentage; DEM, digital elevation model; SAR, sodium adsorption ratio.

[1] The Nahon series was established in Pembina County, ND in 1973, but the Type Location is south of Aberdeen in Brown County, SD, (Lat: 45°22′9.00″ N, Long: 98°27′17.00″ W).

Table 1. Soil map units present at the field site and their proportionate extent.

Map unit name	Taxonomic class	Area
		%
Nahon silt loam, 0–2% slopes	fine, smectitic, frigid Calcic Natrudolls	87.7
Bearden silty clay loam, 0–1% slopes	fine-silty, mixed, superactive, frigid Aeric Calciaquolls	5.6
Bearden-Kindred silty clay loams, 0–2% slopes	fine-silty, mixed, superactive, frigid Aeric Calciaquolls fine-silty, mixed, superactive, frigid Typic Endoaquolls	3.7
Bearden silty clay loam, saline, 0–1% slopes	fine-silty, mixed, superactive, frigid Aeric Calciaquolls	2.8
Fargo silty clay loam, 0–1% slope	fine, smectitic, frigid Typic Epiaquerts	0.3

Table 2. Cation-exchange capacity (CEC), exchangeable sodium percentage (ESP) and electrical conductivity (EC) from a Nahon soil (fine, montmorillonitic, Udic Natriboroll) sampled in Cass County, ND, in 1957.†

Horizon	Depth	CEC	ESP‡	EC
	cm	$cmol_c\ kg^{-1}$	%	$dS\ m^{-1}$
Ap	0–23	18.4	2.2	0.4
E	23–33	10.7	5.6	0.6
Bw	33–48	35.2	12.2	1.4
BCk	48–91	26.8	25.4	9.5
C	91–127	28.3	27.6	11.8
Cyz	127–152	26.8	30.2	11.0

† Pedon S57ND-017–004, (Lat: 47°06′7.00″ N, Long: 97°14′25.00″ W) (unpublished North Dakota Agricultural Experiment Station data).

‡ Exchangeable sodium percentage (ESP) quantifies the degree of sodium adsorbed by the cation-exchange sites for a given soil; values ≥15 are used to classify sodium-affected soils (U.S. Salinity Laboratory Staff, 1954).

electrical conductivity (ECe) and sodium adsorption ratio (SAR) from saturation paste extracts.

Veris data were transferred into a GIS using ArcGIS 9 software (ESRI, 2005) to generate maps of shallow and deep apparent salinity. Using spatial patterns from the shallow and deep ECa maps, five ECa zones were selected for further chemical analysis. Three random sites were identified in each of the five zones, and coordinates transferred to a portable GPS unit to locate field sample sites, which are illustrated in Fig. 2.

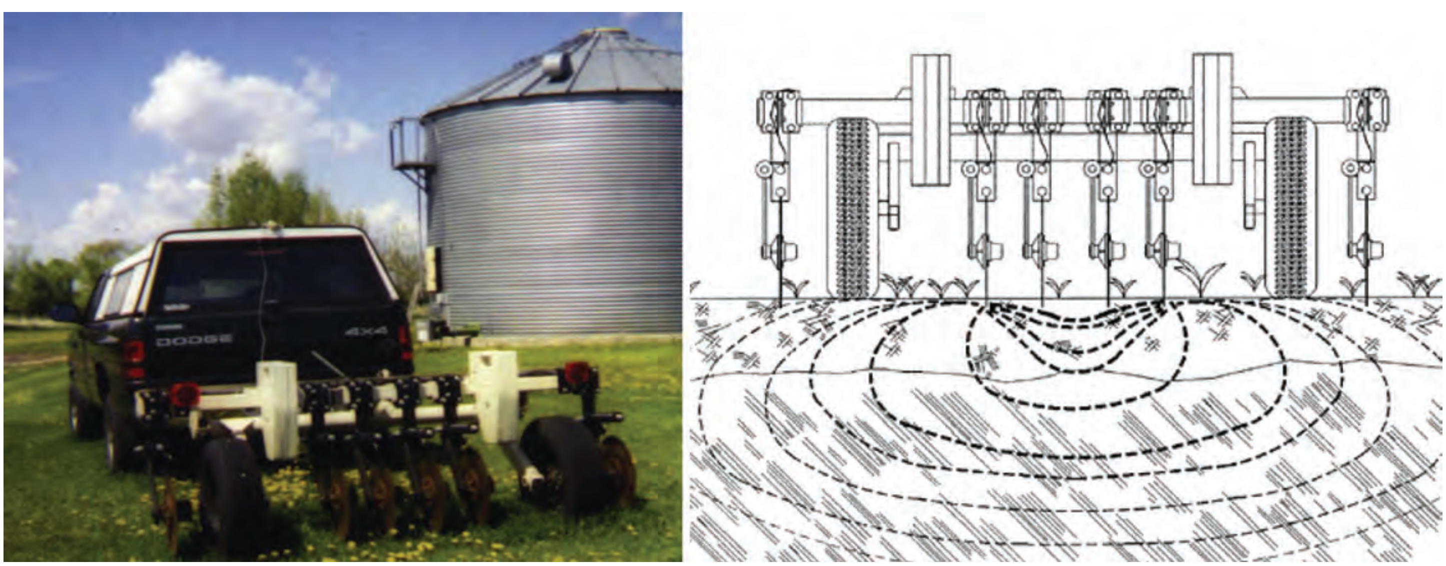


Fig. 1. A Veris 3100 Soil EC mapping system. Diagram illustrates the shallow apparent soil salinity (ECa) soil volume sensed by the four middle coulters and the deep ECa soil volume sensed by all six coulters (sketch courtesy of Veris Technologies, Salina, KS).

A core sample 122 cm deep was taken at each of the 15 sites, divided into 30-cm increments, dried, and ground to pass a 2-mm sieve. Samples from the five zones were also evaluated for ECe and SAR using saturated paste extracts. Chemical analysis procedures follow those of the NDSU Soil Testing Laboratory (NCR, 1988).

Students conducted several soil profile investigations in the field, made a surface elevation transect in the northwestern part of the field, contributed to the Veris survey, helped with hydraulic coring for Veris calibrations samples, and conducted all of the chemical analyses with technical supervision.

Statistical separation of means for the ECe and SAR data was performed using a Student *t* utility in JMP software (SAS Institute, 2007).

Results

Shallow and deep ECa ranged from 10 to above 500 mS m^{-1} (Fig. 2 and 3). The ECe of shallow Veris calibration samples ranged from 1.1 to 14.0 dS m^{-1}, and the deep samples ranged from 3.6 to 11.8 dS m^{-1} (Table 3).

The Veris salinity mapping system worked extremely well for this particular field, as shown by the linear relationship between Veris readings and laboratory measured electrical conductivity (Fig. 4). The coefficient of determination was slightly less robust for shallow readings (R^2 = 0.911, data not shown) than for the deeper samples illustrated in Fig. 4. Larger volumes of soil are represented by the deeper samples, and precipitation events and possible leaching would influence the surface layers more readily.

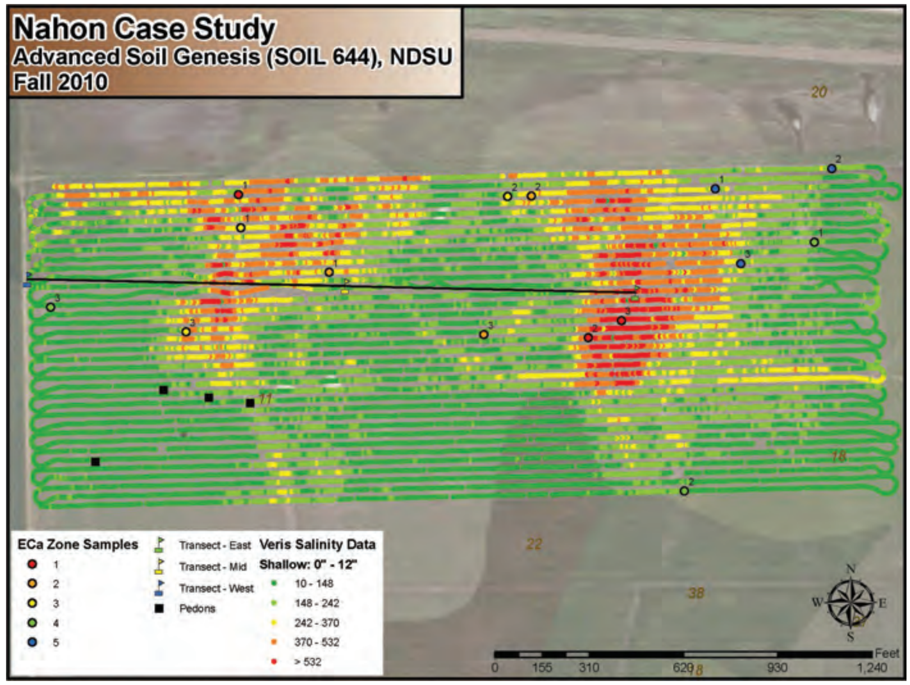


Fig. 2. Shallow apparent soil salinity at the field site imposed on a digital orthophotograph. Surface transect indicated shown in detail in Fig. 4. Units of apparent electrical conductivity are millisiemens per meter.

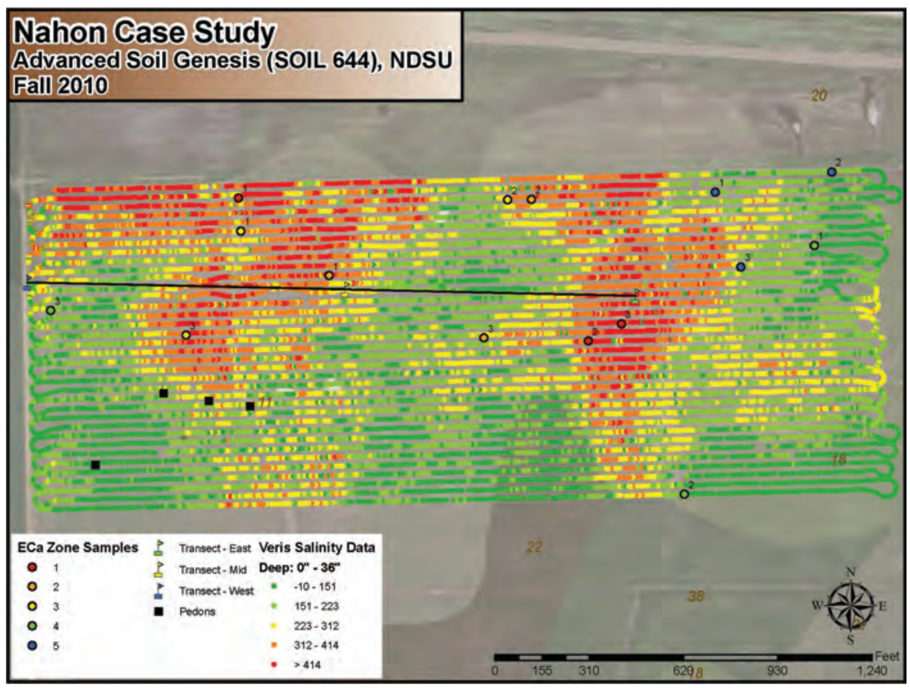


Fig. 3. Deep apparent soil salinity at the field site imposed on a digital soil survey map. Surface transect indicated shown in detail in Fig. 4. Units of apparent electrical conductivity are millisiemens per meter.

According to the Cass County, ND Soil Survey, Nahon soils range from nonsaline (0–2 dS m^{-1}) in topsoils to moderately saline (4–16 dS m^{-1}) in the substratum (Prochnow et al., 1985). However, a significant portion of the study site is affected by surface salinity that is much higher than that typical for the Nahon series locally. The highest levels of apparent soil conductivity exist in even subtle depressions in this field, as shown by a comparison of the elevational transect (Fig. 5) with the Veris data shown in Fig. 3. The fact that depressions show the highest overall salinity is corroborated by a detailed digital elevation model (DEM) for this site (Fig. 6), which illustrates that a broad, deeper depression in the eastern part of the field is the center of the largest zone of elevated ECa readings. Generally in the Lake Agassiz plain, in complex landscapes, elevated microtopographic positions have the highest surface salinity due to evaporative discharge of groundwater (Skarie et al., 1986; Knuteson et al., 1989). In the case of the Nahon field site the lowest landscape positions have the highest levels of shallow ECa (Fig. 2), and the deep ECa survey reveals a wide distribution of subsoil salinity (Fig. 3). Surface drainage operations on this field are reflected in shallow ECa patterns as shown by a comparison of the linear features from the DEM (Fig. 6) and the shallow ECa map (Fig. 2). Soil removal may have accentuated salinity by stripping off surface soils with lower ECe.

Table 3. Electrical conductivity (ECe) and sodium adsorption ratio (SAR) values for nine Veris calibration samples taken on the field site.

Nahon field site	Veris readings		ECe		SAR	
	0–30 cm	0–91 cm	0–30 cm	0–91cm	0–30 cm	0–91 cm
	mS m^{-1}		dS m^{-1}			
1	140	340	3.1	9.3	5.1	8.0
2	440	400	7.9	9.4	5.6	6.1
3	540	486	14.0	11.8	9.0	0.2†
4	116	135	1.2	4.7	3.1	1.1
5	401	370	8.3	10.6	7.0	7.8
6	75	91	1.1	3.6	0.6	1.1
7	235	273	7.0	6.8	3.6	3.9
8	283	231	6.5	6.9	5.5	5.2
9	56	77	1.5	3.6	1.4	2.5

† The 0- to 91-cm depth SAR value for Site 3 is an analytical error: a clay soil with a topsoil SAR of 9 will certainly not have a 0–91 cm value of 0.2.

The Veris calibration samples show a few SAR values above 6 (Table 3), with one surface sample of 9 (Site 3). In most well-drained North Dakota soils SAR increases with depth (McClelland et al., 1959; Schroer, 1970), so there was an expectation that some deeper samples might have SAR levels above 13, the threshold criteria for sodium-affected soils. However, only ECa Zones 3 and 5 showed a slight increase in SAR at intermediate soil depths (60–91 cm) (Table 4), and even though the two ECa zones are statistically different at the α level of 0.05 (Table 5), the overall levels are rather low. These two zones were also the only ECa zones showing an increase in ECe with depth. The choice of five ECa zones to separate the salinity levels in the field worked fairly well. ECa zone 1 was statistically significantly different than the other four zones for both ECe and SAR (Table 5). Zones 2 and 3 were similar, as were zones 4 and 5 (Table 5). The average SAR ranged from 5 to less than 1 for the five ECa zones (Table 5). For this particular study site it is unlikely that sodium levels will interfere with soil hydraulic conductivity, which is a crucial factor in evaluating soils for tile drainage.

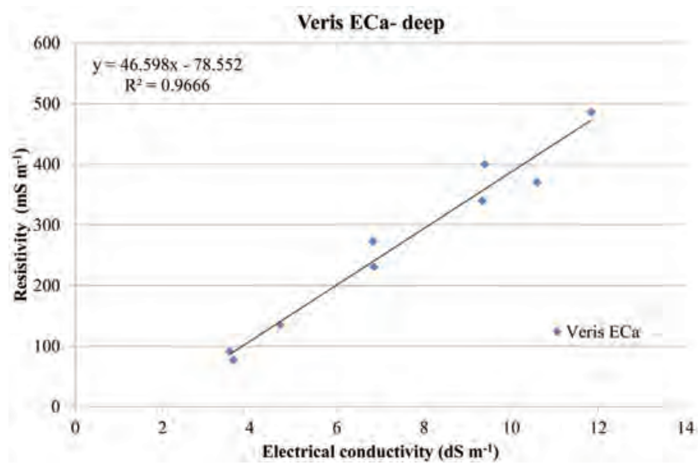


Fig. 4. Relation between deep (0–91 cm) Veris resistivity values and electrical conductivity for nine calibration samples.

Regional Implications

The fact that low SAR values were found in the case study is good news for the owners of this particular management unit dominated by the Nahon soil. However, some soils in the region do have elevated levels of sodium at depth, as verified in a recent USDA-ARS and NRCS regional study of salinity in the northern parts of the Red River Valley of the North (MLRA 56) (Lobell et al., 2010). Results of soil chemical data from the Walsh County, North Dakota area suggest a need for caution if considering tile drainage. The joint study was conducted in areas dominated by the Glyndon and Bearden series, both are silty, somewhat poorly drained soils that are widespread in the Glacial Lake Agassiz plain and regionally. Salinity and sodium levels were evaluated for 33 soils to 180 cm depth. More than 27% of the profiles had a mean saturated paste extract SAR greater than 13, the standard criteria to denote soils that experience sodium-induced dispersion (Fig. 7). Dispersive behavior destroys aggregates, induces crusting, reduces hydraulic conductivity, puddles the soils when wet, and generates very hard clods when dry (Brady, 1990). However, if solute concentration of the soil solution remains high enough, hydraulic conductivity will not decrease even with excess sodium on the clay exchange sites. When solution concentrations fall below a certain limit (i.e., the flocculation threshold),

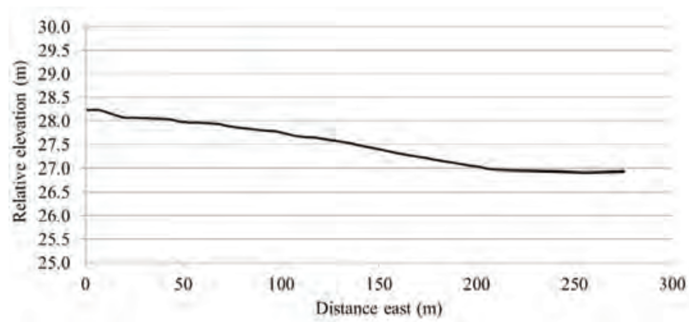


Fig. 5. Relative relief near transect in field site illustrating a relief of about 1.25 m.

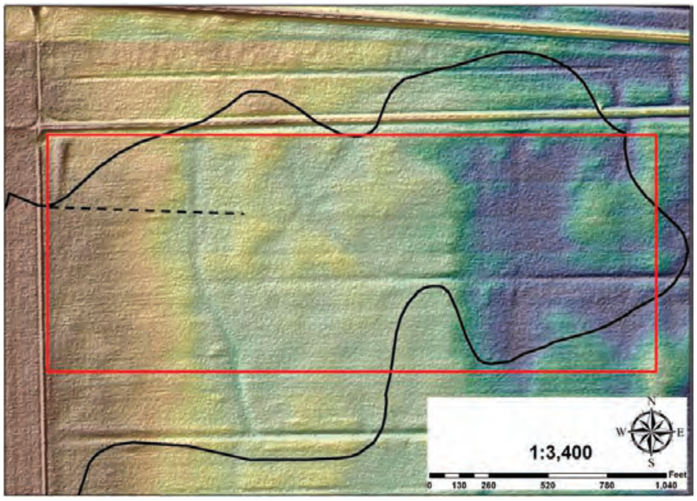


Fig. 6. Light detection and ranging (LiDAR) digital elevation model of the field site illustrating natural depressions (dark blue) and surface drainage patterns due to management. Area within the bold line is the Nahon soil map unit. Dashed line is surface transect shown in Fig. 5.

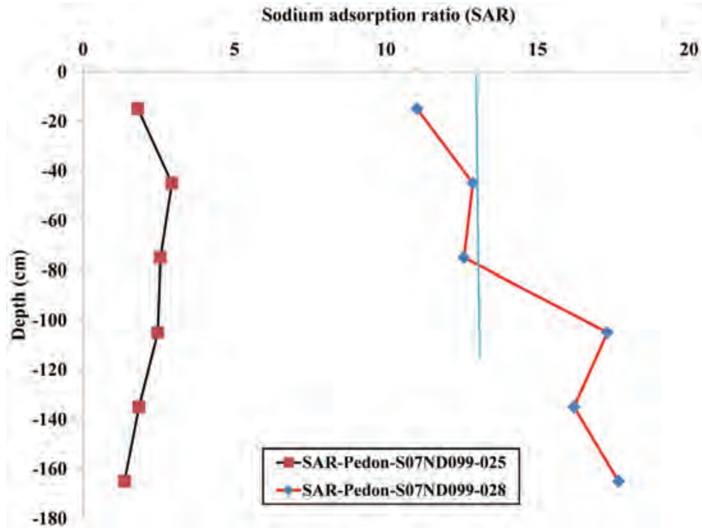


Fig. 7. Sodium adsorption ratio (SAR) of two Walsh County soils. Vertical line shows SAR threshold for sodic soil classification criteria. (Data from personal communication, Mr. Keith Anderson, Soil Survey Leader, MLRA 56, Fargo ND.)

Table 4. Apparent soil salinity (ECa) and sodium adsorption ratios (SAR) values of ECa zones for zone profiles per zone by depth class.

ECa Zone	Depth class†	ECe		SAR		*N*
		Mean	SD	Mean	SD	
1	1	11.3	1.2	6.0	0.8	3
	2	9.8	0.5	5.6	0.7	3
	3	8.3	1.3	4.6	1.2	3
	4	8.0	1.3	4.1	0.2	2
2	1	7.7	0.2	4.5	0.4	3
	2	7.6	1.1	4.4	0.8	3
	3	7.0	1.1	3.8	1.2	3
	4	5.7	1.5	3.5	1.2	3
3	1	5.7	1.6	3.4	1.1	3
	2	7.0	0.6	4.2	1.2	3
	3	7.3	0.8	3.9	0.4	3
	4	7.5	0.3	3.8	0.8	2
4	1	4.8	0.9	1.2	1.1	3
	2	4.8	1.9	1.4	1.5	3
	3	4.7	2.7	1.4	1.7	3
	4	2.4	0.9	0.4	0.2	2
5	1	2.5	1.1	0.3	0.1	3
	2	3.2	2.0	0.7	0.3	3
	3	4.4	0.9	1.2	0.5	3
	4	3.2	–	0.5	–	1

† Depth increments are based on 30-cm increments to a depth of 120 cm.

Table 5. Electrical conductivity of the saturation extract (ECe) and sodium adsorption ratio (SAR) averages for ECa Zones 1 through 5 identified in the Veris survey and means comparisons.†

Zone	ECe	SAR
	$dS\ m^{-1}$	
1	9.47 a‡	5.14 a
2	7.00 b	4.03 b
3	6.82 b	3.84 b
4	4.34 c	1.14 c
5	3.34 c	0.70 c

† Values are means of four 30-cm increments to 120 cm depth for three replications per zone.
‡ Means followed by different letters are statistically significant at an alpha level of 0.05.

hydraulic conductivity can be significantly reduced (Quirk and Schofield, 1955). The point is that when tile drainage reduces the soil solution electrical conductivity there is a chance that clay dispersion near the tiles will reduce efficiency of the drainage system. Producers need to be aware of these soil–water chemistry relationships before investing in tile drainage.

Acknowledgments

The generosity of McIntyre-Pyle Inc. toward fostering field-based experience for the NDSU students is greatly appreciated. The guidance given by Mr. Rodney Utter to graduate students in the field and Mr. Kevin Horsager's help and instruction in the laboratory analyses is also very much appreciated. Thanks are also due to Mr. Dave Zimmerman (NRCS MLRA 56 Soil Scientist) for the LiDAR image of the field site and to Mr. Jonathan Braski for his competent help with GIS illustrations. The evaluation and constructive comments of two anonymous reviewers are very much appreciated.

References

Agweek. 2011. Officials eye record prevented planting situations in ND, SD. 21 June 1011.

Brady, N.C. 1990. The nature and properties of soils. 10th ed. Macmillan Publ. Co., New York.

ESRI. 2005. ArcMap 9.1. ESRI, Inc., Redlands, CA.

Knuteson, J., L. Prunty, D. Patterson, and J. Richardson. 1989. Pedogenic carbonates in a calciaquoll associated with a recharge wetland. Soil Sci. Soc. Am. J. 53:495–499. doi:10.2136/sssaj1989.03615995005300020032x

Lobell, D., J. Doolittle, D. Potts, M. Baltes, M. Matos, D. Corwin, S. Lesch, K. Anderson, and M. Ulmer. 2010. Regional-scale assessment of soil salinity in the Red River Valley using multi-year MODIS EVI and NDVI. J. Environ. Qual. 39:35–41. doi:10.2134/jeq2009.0140

McClelland, J.E., C.A. Mogen, W.M. Johnson, F.W. Schroer, and J.S. Allen. 1959. Chernozems and associated soils of eastern North Dakota: Some properties and topographic relationships. Soil Sci. Soc. Am. Proc. 23:51–56. doi:10.2136/sssaj1959.03615995002300010022x

NCR. 1988. Recommended chemical soil test procedures for the North Central Region. W.C. Dahnke, editor, NCR Publ. 221 (rev). North Dakota Agric. Exp. Stn., Fargo.

NRCS. 2011. National Cooperative Soil Characterization Data. http://ssldata.nrcs.usda.gov/querypage.asp (accessed 13 April 2012).

Prochnow, N.D., N.J. Lunde, W.J. Terry, and D.P. Opdahl. 1985. Soil survey of Cass County area, North Dakota. SCS, U.S. Gov. Print. Office, Washington, DC.

Quirk, J.P., and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. Soil Sci. 6:163–178. doi:10.1111/j.1365-2389.1955.tb00841.x

SAS Institute. 2007. JMP statistics and graphics guide. Release 7. SAS Inst., Cary, NC.

Schroer, F.W. 1970. A study of the eddect of water quality and management on the physical and chemical properties of selected soils under irrigation. OWRR Proj. no. A-005-NDAK. North Dakota Water Resources Research Inst., North Dakota State Univ., Fargo.

Skarie, R.L., J.L. Richardson, A. Maianu, and G.K. Clambey. 1986. Soil and groundwater salinity along drainage ditches in eastern North Dakota. J. Environ. Qual. 15:335–340. doi:10.2134/jeq1986.00472425001500040004x

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. In: L.A. Richards, editor, Agric. Handb. 60. USDA, Washington, DC.

On the Soil in *Soil Survey Horizons* (1960–2009)

Alfred E. Hartemink,* H.D. Watson, and E.C. Brevik

Soil Survey Horizons was first published in 1960, and the 50th volume was published in 2009. Here we analyze what has been published in those 50 volumes (5575 pages). We classified 1080 contributions as to their focus (e.g., mapping, soil genesis), geographic origin, and what U.S. Soil Taxonomy order was described or studied. Almost 40% of all contributions focused on soil mapping. The number of soil mapping contributions had its peak in the mid-1980s and then gradually dropped but has been on the increase since 2005. Soil genesis, soil classification, and soil morphology were the focus of more than 150 contributions each. *Soil Survey Horizons* always has had a steady number of contributions, which we classified as "reflections on the discipline," and has published a number of ideas that were ahead of their time. Most of the contributions have come from the Central and Midwest part of the United States, and a considerable number of those have focused on Mollisols. Less than 10% of the contributions have been from outside the United States. In the past 50 years, *Soil Survey Horizons* has developed from a U.S. Midwest pedology and soil survey newsletter into a broader publication with research articles and reports.

"Do not fear to be eccentric in opinion, for every opinion now accepted was once eccentric."
Bertrand Russell (1872–1970)

Soil science is a rapidly evolving discipline with scientific insights, techniques, and projects in almost every corner of the globe. It has integrated and adapted tools, ideas, and techniques developed in other scientific disciplines, branched out into other scientific disciplines, and developed a number of thriving new subdisciplines. More than other disciplines, soil science has been at the forefront of discussions on environmental issues (e.g., acid rain, food production, sustainability, climate change), and soil scientists have always worked well in interdisciplinary projects and research teams (Bouma, 1975). Soil science evolved differently in different countries and continues to change with time—that seems to be the only constant.

There is some discussion on the direction of the soil science discipline, but overall it is vibrant, with a rapidly expanding knowledge base (Hartemink, 2012). Projections on its future are hard to make, but some ideas of where it is going can be induced from its past (e.g., the general can be inferred from the particular). There are many ways of inducing generalities of the past.

Alfred E. Hartemink and H.D. Watson, Univ. of Wisconsin–Madison, Dep. of Soil Science, F.D. Hole Soils Lab, 1525 Observatory Dr., Madison WI 53706; E.C. Brevik, Dep. of Natural Science and Agriculture and Technical Studies, Dickinson State Univ., Dickinson, ND 58601. *Corresponding author (hartemink@wisc.edu).

doi:10.2136/sh12-05-0017
Published in Soil Horizons (2012).
Received 7 May 2012.

One way of discovering how the discipline is evolving is a trend analysis of what has been published, and this has been done for a number of soil science journals like *Geoderma* (Hartemink et al., 2001) and *Pochvovedenie* (Ivanov and Lukovskaya, 2003).

In his paper "*Soil Survey Horizons*—50 Years of Communication," Eric Brevik traced the origin and developments of *Soil Survey Horizons* (Brevik, 2012). The beginning and purpose of the publication was described as an outlet for field observations and the field man's point of view, for which there was no place in the peer-reviewed literature and SCS soil survey reports. Brevik (2012) described how the publication became a SSSA publication, and how it has changed its publication format and policy. When in 1975 the first edition of *Soil Taxonomy* was published (Soil Survey Staff, 1975), *Soil Survey Horizons* was used to communicate and document changes in the classification system, and some years later consulting soil scientists were encouraged to publish articles on environmental topics, as were geologists. All of that was done to broaden the publication's audience (Brevik, 2012). The paper also analyzed the total items published, the number of pages, and the papers per published item.

Here we analyze what was published in the 50 volumes of *Soil Survey Horizons*. The aim is that the analysis of subjects tells us something about the soil science discipline, its focus and how it evolved over time.

Approach and Methods

We have literally browsed through all the issues of the 50 volumes of *Soil Survey Horizons* and classified all contributions except the obituaries, meeting announcements, and book reviews. In this paper, we have named published items "contributions" because some are just short descriptions of soil phenomena or observational notes and thus not papers in the classical sense. The contributions were classified based on the:

- soil science subdiscipline
- what soil order was described or studied using U.S. Soil Taxonomy (Soil Survey Staff, 2010)
- geographic origin (eight regions in the USA, seven global regions)

The following 11 soil science activities were used to classify the articles:

- soil genesis
- soil classification
- soil mapping
- soil morphology
- land evaluation
- pedometrics
- information systems
- astropedology
- soil education
- soil management
- reflections on the discipline

Contributions from the USA were grouped into the following eight regions:

- Pacific west (Alaska, California, Hawaii, Oregon, Washington)
- West (Arizona, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming)
- Central (Colorado, Kansas, Nebraska, North Dakota, Oklahoma, South Dakota, Texas)
- Mid-South (Arkansas, Kentucky, Louisiana, Mississippi, Missouri, Tennessee)
- Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, Wisconsin)
- Southeast (North Carolina, South Carolina, Alabama, Georgia, Florida, Puerto Rico)
- Mid-Atlantic (Delaware, Maryland, New Jersey, Pennsylvania, Virginia, West Virginia)
- Northeast (Connecticut, Maine, New Hampshire, New York, Rhode Island, Vermont).

Contributions from outside the USA were grouped as being from:

- Europe
- Latin America and the Caribbean
- Asia
- Africa
- Oceania
- The Middle East
- Global

Subject Analysis

More than 40% of all contributions in *Soil Survey Horizons* between 1960 and 2009 focused on soil mapping or discussed a soil mapping aspect (Fig. 1). The number of soil mapping contributions had its peak in the mid-1980s and then gradually dropped, but the number of contributions is on the increase since 2005. Currently, there are about 10 contributions each year that focus on soil mapping.

Soil genesis, soil classification, and soil morphology were the focus of more than 150 contributions each (Fig. 2). Soil morphology has been on the increase since the mid-1980s, and in the 2000s about six contributions per year focused on this important aspect of soil studies. Contributions on land evaluation have been fairly constant over the years, with on average about two contributions per year. Soil information systems were discussed

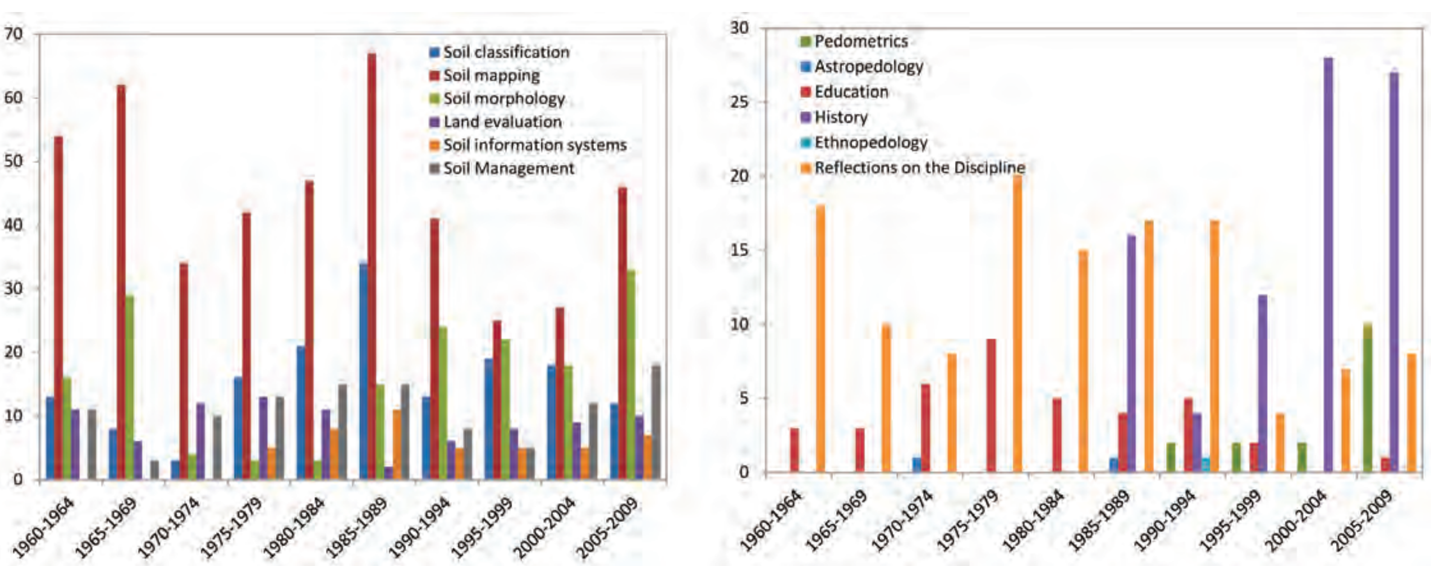


Fig. 1. Subject analysis in *Soil Survey Horizons* between 1960 and 2009. Bars are cumulative number of papers per topic in five year increments. Note difference in *y*-axis scale between left and right bar diagram.

in almost 50 contributions, but mostly in the late 1980s, which coincides with the development in database development and the availability of microcomputers. *Soil Survey Horizons* has had about two to three contributions each year on soil management, but it has never been one of the main pillars.

The first pedometrics contributions came in the 1990s, and the number has grown to about two per year in the last couple of years. In the past 50 years less than a handful of contributions had astropedology or ethnopedology as their subject in *Soil Survey Horizons*.

Soil Survey Horizons always has had a steady number of contributions which we termed here *reflections on the discipline*. Often these were thought provoking and forward looking or debated some common practice or concept (e.g., Arnold, 2003; Bouma, 1975; Hunt, 1976; Jenny, 1965; Krusekopf, 1963; McCracken, 1993; Parker and Milfred, 1970; Peterson, 1981; Villars, 1990; Young, 1988). It is somewhat surprising that the international rise and fall of soil survey has received relatively little attention (Nachtergaele, 1990), but the subsequent revitalizing by the digital soil mapping paradigm also has not been widely discussed yet. Some of the reflective contributions harbor ideas that are as valid today as half a century ago when they were written; for example, "Soil science is a powerful tool for helping to find solutions to many of the problems confronting the modern world. However, the soil scientist realizes that he is only one of many scientists, and he is not so conceited as to believe, that his science can go it alone." (Fanning, 1961). All written when soil science was still a profession dominated by men, which is rapidly changing (Hartemink et al., 2008).

From the beginning *Soil Survey Horizons* contained entertaining bits, and here we shall give a few examples. One of the former *Soil Survey Horizon* editors, Don Franzmeier, proposed a new set of suborders, including *Poland* (Soil formed in volcanic ash in Central Europe), and *Xerox* (Very highly weathered soils in the Mediterranean climates. It is thought that this suborder will be widely used because of the ease with which pedon and map units descriptions can be produced) (Franzmeier, 1991). The Greywacke cover up on the pygmies forest in California taught us that CLORPT can also mean Classified Order to Restore Presidential Truth (Stella, 1998). In the 1960s several issues of *Soil Survey Horizons* contained cartoons, and Fig. 3, 4, and 5 show a few examples. There have also been soils-focused songs, several of these were by the editor F.D. Hole (e.g., Fig. 6).

Verses, poems, and personal reflections were all part of the early years and a song that appeared just after the 7th

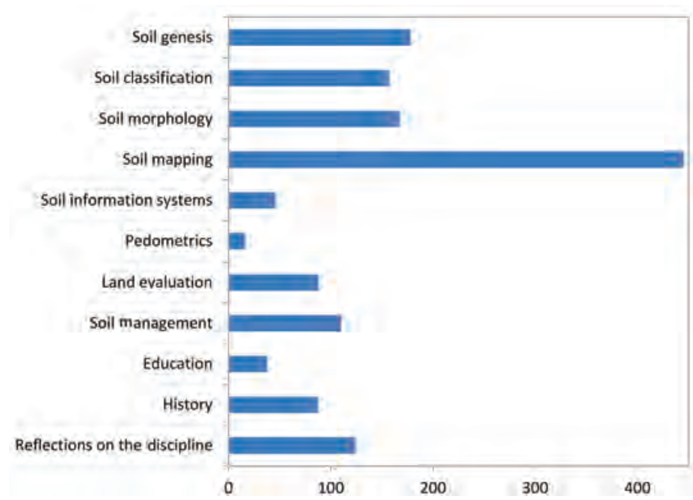


Fig. 2. Total number of contributions per soil science topic in *Soil Survey Horizons* between 1960 and 2009.

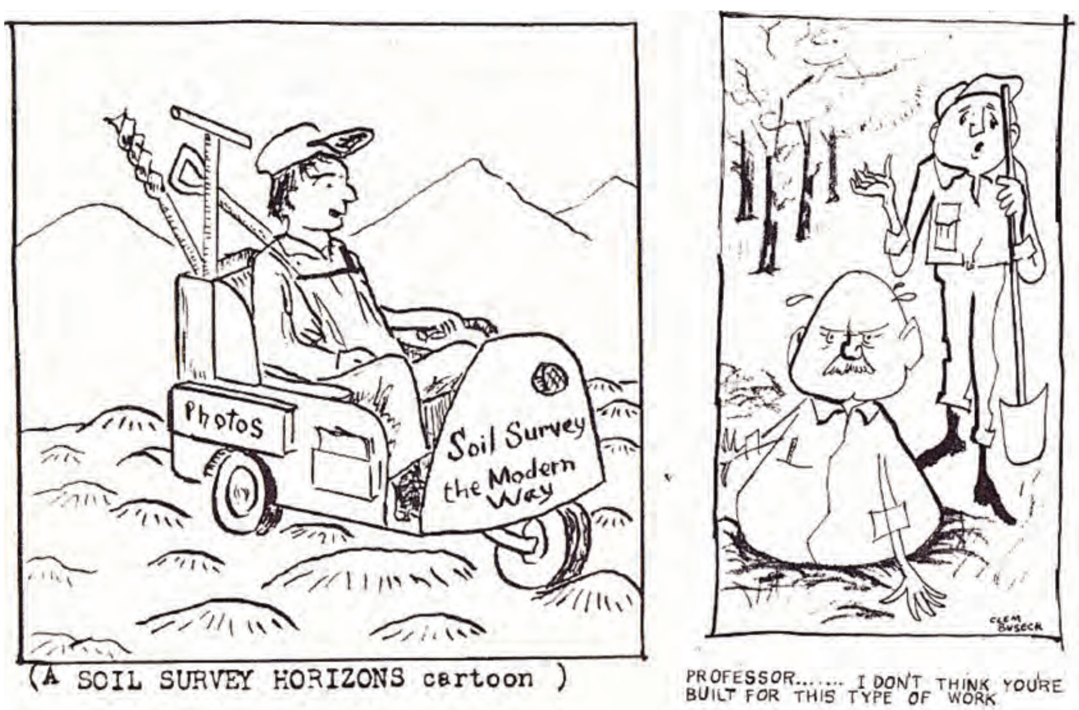


Fig. 3. Cartoons in *Soil Survey Horizons* (Soil Survey Horizons, 1962; Buseck, 1962). Soil survey the modern way was depicted in an electric car, and equipped with aerial photographs, augers, and spade.

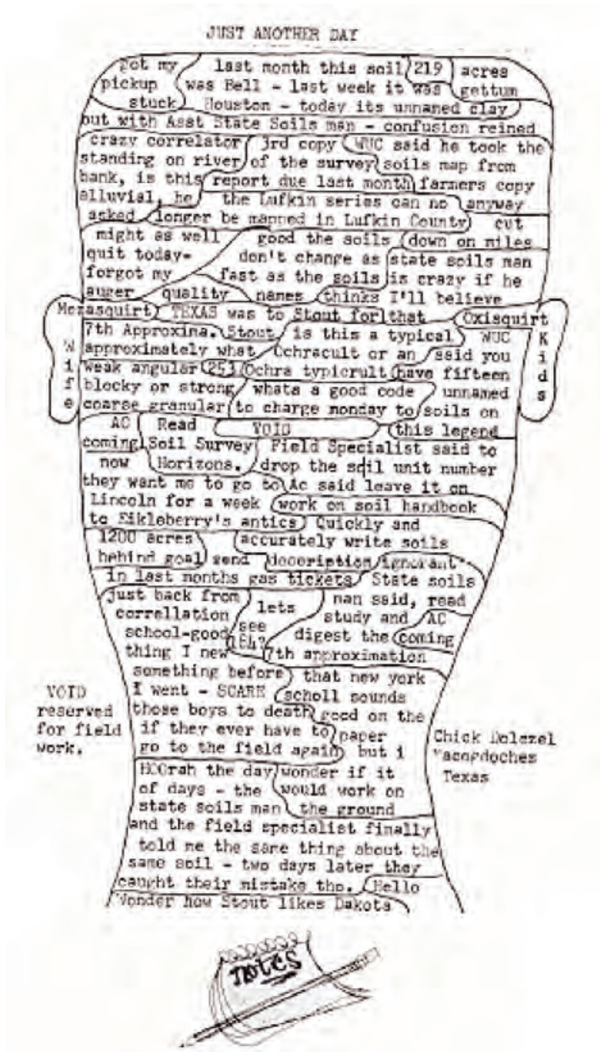


Fig. 4. Cartoon from *Soil Survey Horizons* (Dolezel, 1964).

Approximation (generally known as "the Brown Bible") was published in 1960 (Soil Survey Staff, 1960). This song was written by J.W. Hawley (1961) of the University of Illinois, and it is to the tune of "Jingle Bells":

Verse:

Brunizems are out; Podzols have to go
All such things are obsolete; Brown bible tells us so
Argudolls are in; Orthods steal the show
Fraglossudalfs and Natraqualfs, on and on they go

Chorus:
Oh! Haplaquol, Haplaquol, Hapla qoul the way
Oh what fun it is to be rid of Humic Gley-a!

(Repeat)

The forest soil scientist S.A. Wilde made the following contribution on soil classification: "Stonewall Jackson is said to have commented that as far as he was concerned there were two kinds of music:

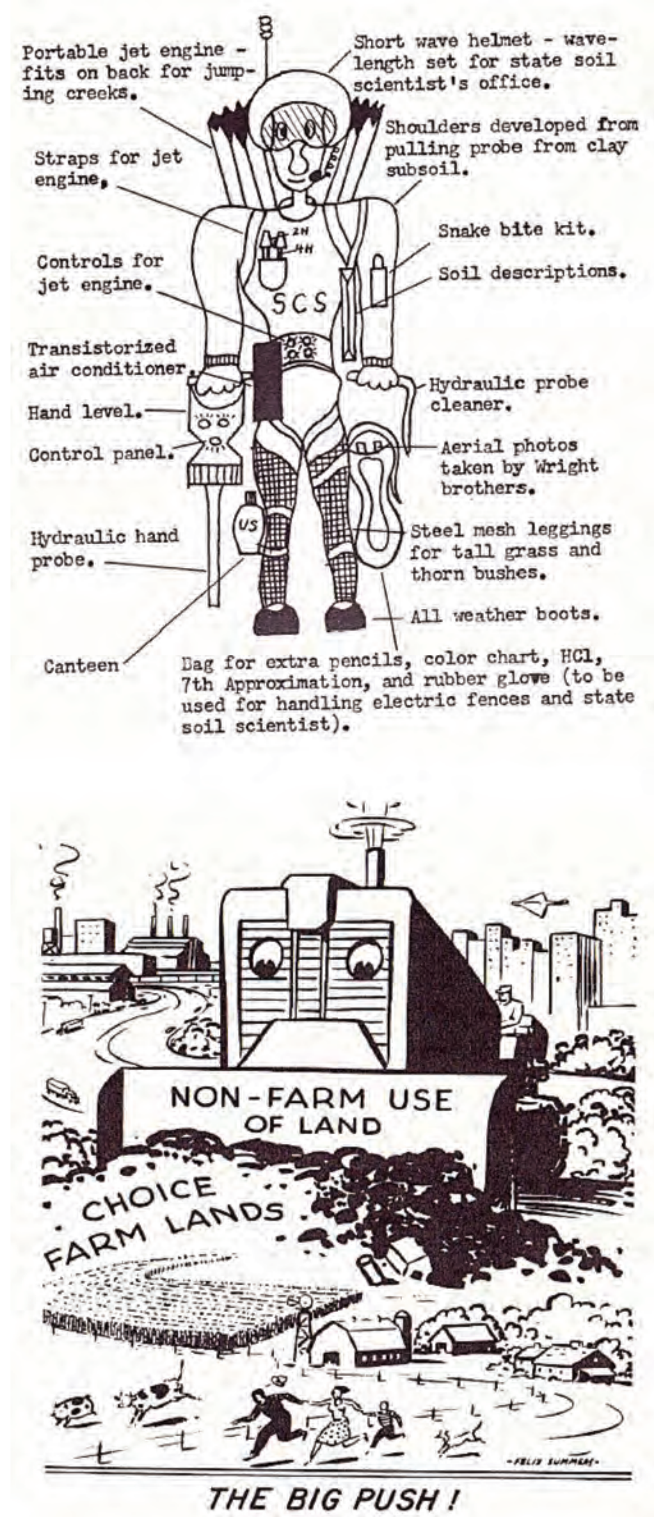


Fig. 5. Cartoons from *Soil Survey Horizons*: upper: soil scientist (Moore, 1966); lower: the big push.

Yankee Doodle and ain't. This may be taken as a blue print for a really simple soil classification: Podzols and ain't." (Wilde, 1968).

Fig. 6. "Some Think That Soil Is Dirt," by Francis Hole (1985).

In the mid-1980s the first historical contributions appeared, and considerable attention was given to the history of soil mapping in the United States by Roy Simonson. Various historical and biographical articles of American soil scientists have been published, including Milton Whitney, Curtis Marbut, George Coffey, Charles Kellogg, Roy Simonson, and Guy Smith. The history and the beginnings of *Soil Survey Horizons* has been given some attention (Buol, 1997; Buol, 2006; Wilson, 2006). The proposal for the state soils in the United States was also made in *Soil Survey Horizons* (Hole, 1976), and it was widely adopted by many states (Quandt and Watts, 1995; Watts et al., 1992), but a national soil was never embraced (Hole and Bidwell, 1989). Historical highlights continue with the *Profiles in History* series that was started by Sam Indorante with pictures of soil scientists in the field, at meetings, but most preferably: in the soil pit.

What Soil Order

Very few contributions in the 1960s made reference to a particular soil order (Fig. 7). This is not shocking as the 7th Approximation was launched at the World Congress of Soil Science in Madison in 1960, and *Soil Taxonomy* was only published in a finalized form in 1975 (Soil Survey Staff, 1975). Since then, references to all soil orders increased over time and peaked for most soil orders in the mid and late 1990s, after which references to soil orders decreased. From the 1980s onward, there have been about two papers per year with reference to Mollisols. In total almost one-half of all contributions in *Soil Survey Horizons* included a reference to a soil order. As the majority of the contributions were from the Midwest, it is not surprising that about 17% of the soils discussed were Mollisols (Fig. 8). Alfisols, Entisols, and Inceptisols were also each mentioned in about 60 contributions. The other soil orders were subjects in less than 30 contributions;

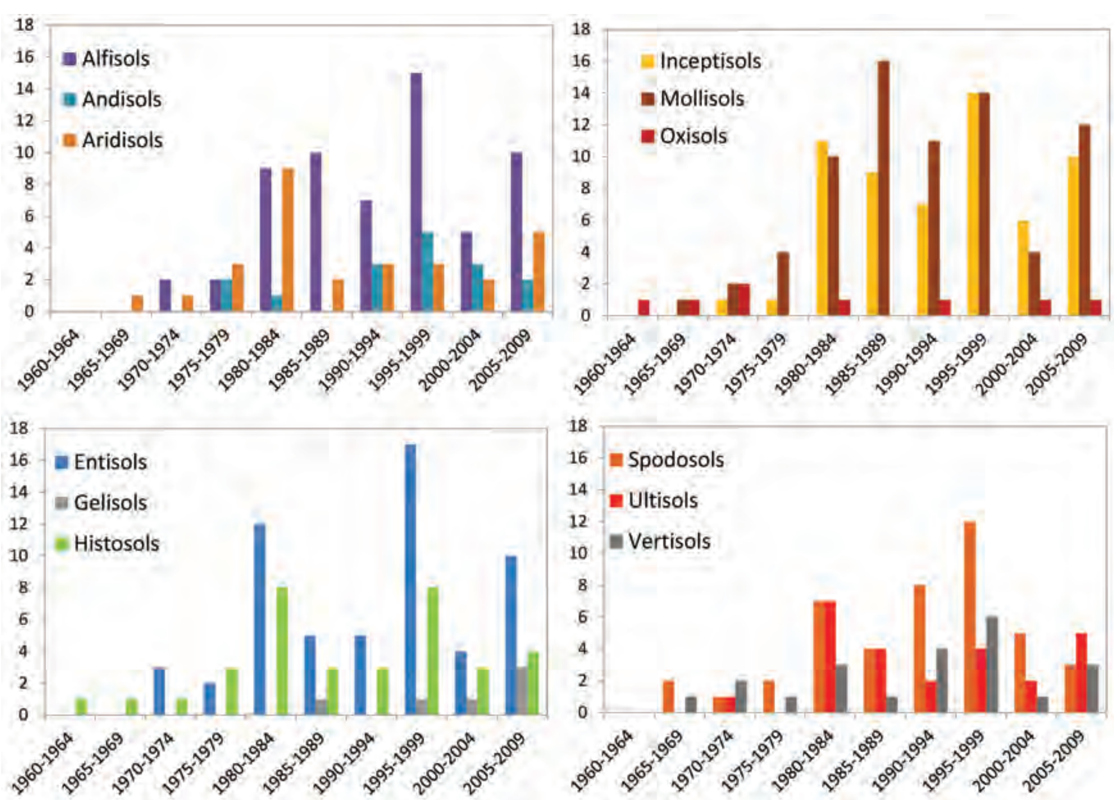


Fig. 7. Soil orders in *Soil Survey Horizons* between 1960 and 2009. Bars are cumulative number of papers per topic in 5 years.

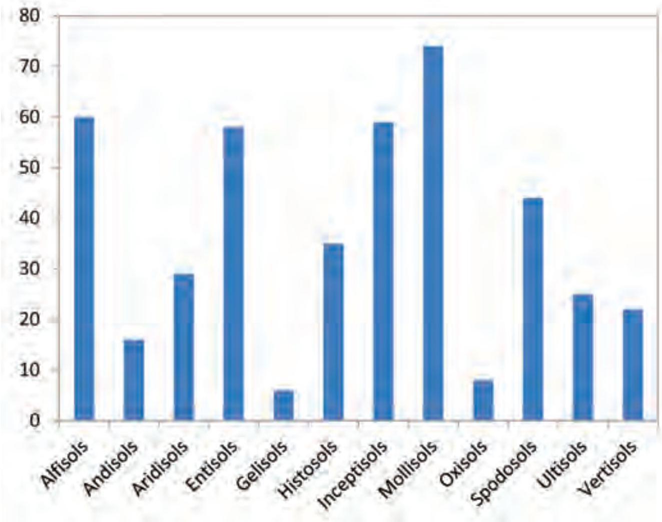


Fig. 8. Total number of contributions per Soil order in *Soil Survey Horizons* between 1960 and 2009.

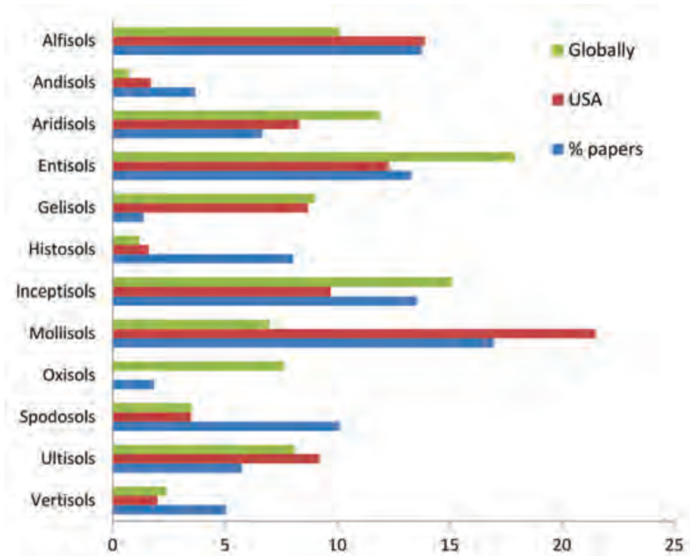


Fig. 9. Extent of the 12 soil orders globally, in the USA and the percentage of papers in *Soil Survey Horizons* (1960–2009) referring to each given soil order.

Gelisols (introduced in 1998) were lowest, along with Oxisols (not common in the USA).

Figure 9 compares the percentage of contributions on a particular soil order and the extent in the USA and globally for each soil order. Although the significance of this is limited, it shows that contributions on Gelisols and Ultisols are somewhat underrepresented, whereas contributions on Histosols, Andisols, Spodosols, and Vertisols are overrepresented relative to their land area in the United States.

Geographic Origin

Most of the contributions in the 1960s came from the Midwest and Central part of the USA (Fig. 10). There were a few papers from the West and Pacific West region, although the number slightly increased with time. From the other regions, only one to two contributions per year were published.

A little more than10% of the contributions have come from outside the USA, and most were from Asia and Africa (Fig. 11 and 12). Only five contributions have been published from Canada.

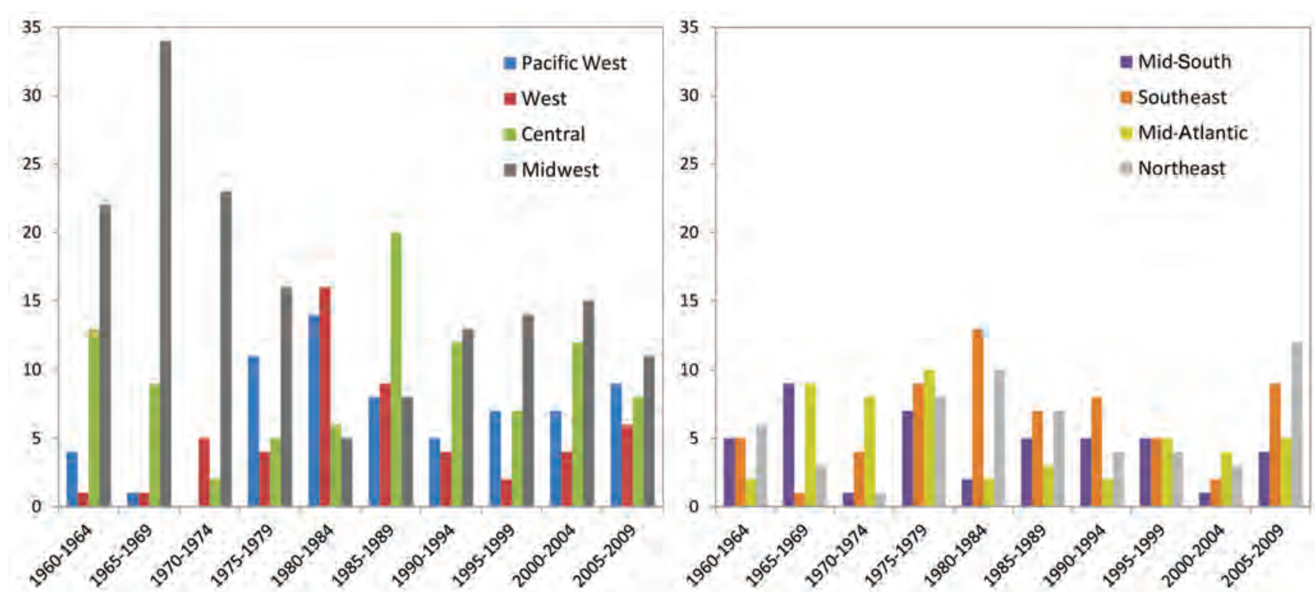


Fig. 10. Contribution per USA region in *Soil Survey Horizons* between 1960 and 2009. Bars are cumulative number of papers per region in 5 years.

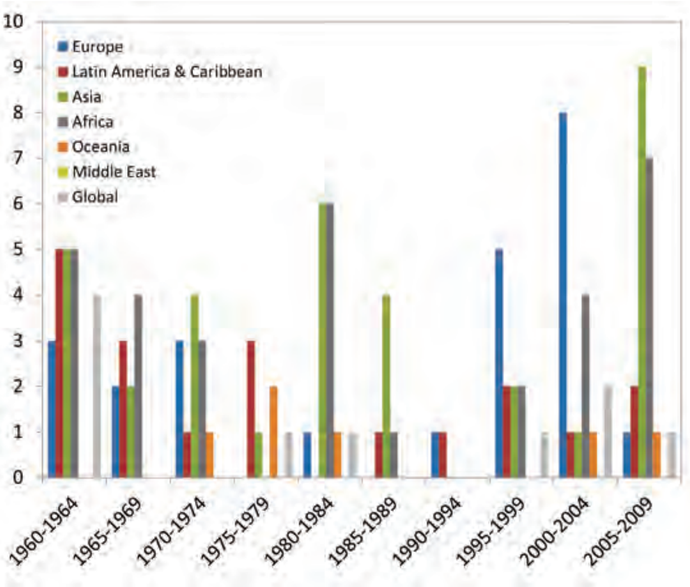


Fig. 11. Contributions per global region in *Soil Survey Horizons* between 1960 and 2009. Bars are cumulative number of papers per topic in 5 years.

The number of contributions from outside the United States has not changed much over time, although some increase can be observed in the past 5 years.

Discussion and Conclusions

Soil Survey Horizons began in 1960 as a more or less regional newsletter for soil surveyors and pedologists. Between 1960 and 2009, the content of *Soil Survey Horizons* changed considerably in terms of its subjects, its appearance, and the depth and type of contributions. The overall philosophy of *Soil Survey Horizons* has not changed much over the years and was summarized in 1990 as follows: suggestions for contributors to *Soil Survey Horizons* were articles on ideas, problems, and philosophies, concerning the study of soils in the field. Articles, announcements, letters, and news items are welcome. In 1996 came the announcement that *Soil Survey Horizons now accepts diskettes!* Both 5.25 and 3.5 inch were accepted, and files were preferably prepared in WordPerfect and sent in "revisable form text" format.

In the first decade, most of the contributions came from the Central and Midwest part of the United States, and a considerable percentage of those focused on Mollisols. Contributions from outside the USA have constituted less than 10% of the items published but that is changing, and *Soil Survey Horizons* has transformed from a regional publication to a national and more international publication that also includes works that would not strictly be viewed as field based. In that sense, it reflects what has happened in the soil science discipline, where field work has become less prominent in the past decade. However, we think that with increased digitalization and computerization of our knowledge base the demand for field-based studies will automatically increase because the pedologic knowledge remains behind the modeling work and for validation and increased understanding. The future for *Soil Horizons* is therefore exceptionally bright if it continues to encourage and harvest field-based and pedology observations and reports.

It seems that *Soil Survey Horizons* has changed from a newsletter with many different types of contributions (ideas, cartoons, songs, field experiences, anecdotes, poems) to a type of publication with scientific papers. It has lost some of its brilliance and distinctiveness and has become a rather serious publication. This pattern is probably not unique to *Soil Survey Horizons*, and there are very few people today who write soil poetry, songs, or verses and publish those in this journal.

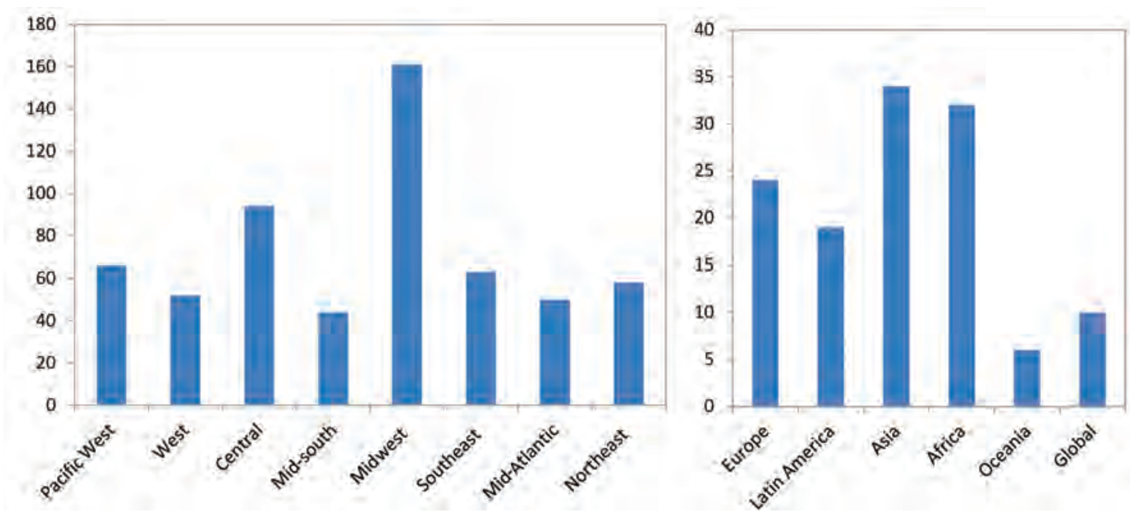


Fig. 12. Total number of contributions per U.S. region and across the world in *Soil Survey Horizons* between 1960 and 2009.

Many contributions in the 1960s and 1980s focused on soil mapping, and there was a declining number of soil mapping contributions in the 1990s. However, since 2005 the number has increased again which may reflect the increased global interest in digital soil mapping (Grunwald et al., 2011; McBratney et al., 2003). *Soil Survey Horizons* is moving from field mapping to more quantitative methods and digital soil mapping (Hash and Noller, 2009). Technologies like EMI (e.g., Kern et al., 2008) and GPR (e.g., Doolittle et al., 2007, 2005) have been widely used and tested throughout the United States, and this is reflected in the number of contributions in *Soil Survey Horizons*. It also shows that the journal remains an outlet for field-based soil research activities, and the auger and spade are now accompanied by magnetic inducers and radars. Also the number of pedometrics papers has increased in the past few years, which may reveal that more quantitative approaches have entered the domain of field observations and field soil scientists.

Many fascinating articles have been published in *Soil Survey Horizons*. To name a few: "Antipededogenis Factors and Human Survival" by Francis Hole (1971), "The Making of a Soil Scientist" (Stolpe, 1983), "The Time Factor of Soil Formation" (Harpstead, 1989); "Soil Sampling by the Lewis and Clark Expedition" (Anderson, 2003), "Science on the Normandy Beaches: J.D. Bernal and the Prediction of Soil Trafficability For Operation Overlord" (Lark, 2008), "USDA-NRCS Soil Scientists in Afghanistan" (Dubee et al., 2009), as well as Peter Birkeland's (2010) article on how he wrote his seminal book *Soils and Geomorphology*, and Stan Buol (2010) on *Soil Genesis and Classification*, the family saga of the Weindorfs in New Mexico (Weindorf, 2011), the stunningly beautiful soil portraits of Jay Noller (2010), and many more. None of these articles would have probably made it into the straight-jacket culture of most peer-reviewed journals and prove to us that a great discipline has a great publishing culture.

Soil Survey Horizons has also published some opening contributions on topics that are common now but not during the time they were published, and these include urban soils and soil survey (Olson, 1963), forensic soil science (Werchan, 1965), and multispectral sensors in soil survey (Parker and Milfred, 1970)—the ideas and concepts in these articles were all ahead of their time.

May *Soil Horizons* continue in these footsteps—publishing articles that are fascinating, eye openers, entertaining, novel, and worth reading, and if possible: ahead of their time!

Acknowledgments

We thank Lisa Al-Amoodi at the SSSA Headquarters for providing us with access to the 50 volumes of *Soil Survey Horizons*. This work is dedicated to Prof. F.D. Hole for he was not only an outstanding soil scientist full of ideas and creativity, but if he had not hatched the idea for this publication, we would not have been able to write this paper.

References

Anderson, S.P. 2003. Soil sampling by the Lewis and Clark expedition. Soil Surv. Horiz. 44:1–5.

Arnold, R.W. 2003. Percepts of American pedology: Sharing our intellectual legacies. Soil Surv. Horiz. 44:107–111.

Birkeland, P.W. 2010. Why and how I wrote *Soils and Geomorphology*. Soil Surv. Horiz. 51:114–115.

Bouma, J. 1975. The trees and the forest. Soil Surv. Horiz. 16:12–16.

Brevik, E.C. 2012. *Soil Survey Horizons*—50 years of communication. Soil Horiz. doi:10.2136/ssh2012-53-1-1brevik.

Buol, S.W. 1997. Beginnings of *Soil Survey Horizons*. Soil Surv. Horiz. 38:39–40.

Buol, S.W. 2006. The beginnings of *Soil Survey Horizons*. Soil Surv. Horiz. 47:38.

Buol, S.W. 2010. Evolution of the text *Soil Genesis and Classification*. Soil Surv. Horiz. 51:116–117.

Buseck, C. 1962. Professor....I don't think you're built for this type of work [cartoon]. Soil Surv. Horiz. 3(3):10.

Dolezel, C. 1964. Just another day [cartoon]. Soil Surv. Horiz. 5(1):15.

Doolittle, J.A., J.J. Daigle, J.A. Kelley, and J.W. Tuttle. 2005. Using GPR to characterize plinthite and ironstone layers in Ultisols. Soil Surv. Horiz. 46(4):179–184.

Doolittle, J.A., F.E. Minzenmayer, S.W. Waltman, E.C. Benham, J.W. Tuttle, and S.D. Peaslee. 2007. Ground-penetrating radar soil suitability map of the conterminous United States. Geoderma 141:416–421. doi:10.1016/j.geoderma.2007.05.015

Dubee, B., J. Nemecek, and E. Tallyn. 2009. USDA-NRCS soil scientists in Afghanistan. Soil Surv. Horiz. 50:116–119.

Fanning, D.S. 1961. Soil science and the modern world. Soil Surv. Horiz. 2:4–5.

Franzmeier, D.P. 1991. Proposed new suborders. Soil Surv. Horiz. 32:55–56.

Grunwald, S., J.A. Thompson, and J.L. Boettinger. 2011. Digital soil mapping and modeling at continental scales: Finding solutions for global issues. Soil Sci. Soc. Am. J. 75:1201–1213. doi:10.2136/sssaj2011.0025.

Harpstead, M. 1989. The time factor of soil formation. Soil Surv. Horiz. 30:39–40.

Hartemink, A.E. 2012. Soil science reference books. Catena 95:142–144. doi:10.1016/j.catena.2012.02.010

Hartemink, A.E., A.B. McBratney, and J.A. Cattle. 2001. Developments and trends in soil science: 100 volumes of Geoderma (1967–2001). Geoderma 100:217–268. doi:10.1016/S0016-7061(01)00024-6

Hartemink, A.E., A. McBratney, and B. Minasny. 2008. Trends in soil science education: Looking beyond the number of students. J. Soil Water Conserv. 63:76a–83a. doi:10.2489/jswc.63.3.76A

Hash, S.J., and J. Noller. 2009. Incorporating predictive mapping to advance initial soil survey: An example from Malheur county, Oregon. Soil Surv. Horiz. 50:111–115.

Hawley, J.W. 1961.7th Approximation song. Soil Surv. Horiz. 2(2):16

Hole, F.D. 1971. Antipededogenis factors and human survival. Soil Surv. Horiz. 12:11–15.

Hole, F.D. 1976. A state soil. Soil Surv. Horiz. 17:3–4.

Hole, F.D., and O.W. Bidwell. 1989. Proposal for a national soil of the United States. Soil Surv. Horiz. 30:77–79.

Hunt, C.B. 1976. Soil—A dirty four letter word. Soil Surv. Horiz. 7:7–10.

Ivanov, I.V., and T.S. Lukovskaya. 2003. Scientometric (bibliometric) analysis of publications in Pochvovedenie for 100 years (1899–1998). Euras. Soil Sci. 36:107–120.

Jenny, H. 1965. Tessera and pedon. Soil Surv. Horiz. 6:8–9.

Kern, A., E.C. Brevik, T.E. Fenton, and P.C. Vincent. 2008. Comparisons of soil ECa maps to an order 1 soil survey for a Central Iowa field. Soil Surv. Horiz. 49:36–39.

Krusekopf, H.H. 1963. Soil surveyor, soil scientist or pedologist. Soil Surv. Horiz. 4:20–22.

Lark, M. 2008. Science on the Normandy beaches: J.D. Bernal and the prediction of soil trafficability for operation Overlord. Soil Surv. Horiz. 49:12–15.

McBratney, A.B., M.L.M. Santos, and B. Minasny. 2003. On digital soil mapping. Geoderma 117:3–52. doi:10.1016/S0016-7061(03)00223-4

McCracken, R.J. 1993. Evangelists, scholars, historians, lab types, computer buffs, map makers and auger pullers in the soil survey. Soil Surv. Horiz. 34:61–71.

Moore, A.H. 1966. [Soil scientist cartoon]. Soil Surv. Horiz. 7(2):12.

Nachtergaele, F.O. 1990. Soil surveyors: An endangered species. Soil Surv. Horiz. 31:83–84.

Noller, J. 2010. Soil portraits. Soil Surv. Horiz. 51:35–36.

Olson, G.W. 1963. Urban soil survey. Soil Surv. Horiz. 4:5–8.

Parker, D.E., and C.J. Milfred. 1970. A look at the soil scientist of the future. Soil Surv. Horiz. 11:4–12.

Peterson, F.F. 1981. Homonyms, synonyms, cant, and confusion. Soil Surv. Horiz. 22:22–24.

Quandt, L., and F.C. Watts. 1995. State soils of the United States. J. Soil Water Conserv. 50:340–342.

Soil Survey Horizons. 1962. A *Soil Survey Horizons* cartoon. Soil Surv. Horiz. 3(2):24.

Soil Survey Staff. 1960. Soil classification, a comprehensive system, 7th Approximation, USDA, SCS, U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1975. Soil taxonomy. Agriculture Handbook No. 436. USDA, SCS, Washington, DC.

Soil Survey Staff. 2010. Keys to soil taxonomy. 11th ed. USDA-NRCS, Washington, DC.

Stella, J. 1998. The greywacke cover-up. Soil Surv. Horiz. 39:127–130.

Stolpe, N. 1983. The making of a soil scientist. Soil Surv. Horiz. 24:20–24.

Summers, F. The big push [cartoon]. Soil Surv. Horiz. 7(3):3.

Villars, T.R. 1990. Advances in chaos research: The secret formula to the soil science institute. Soil Surv. Horiz. 31:61–63.

Watts, F.C., L.A. Quandt, and F.D. Hole. 1992. State soils of the United States. Soil Surv. Horiz. 33:87–91.

Werchan, L.E. 1965. Soilsmen double as detectives. Soil Surv. Horiz. 6:14–15.

Weindorf, D.C. 2011. Men of the soil—A family legacy. Soil Surv. Horiz. 52:23–25.

Wilde, S.A. 1968. A simple soil classification. Soil Surv. Horiz. 9:13.

Wilson, M.A. 2006. The 1970s: New beginnings for *Soil Survey Horizons*. Soil Surv. Horiz. 47:81.

Young, F.J. 1988. Towards the science of soil survey. Soil Surv. Horiz. 29:40–42.