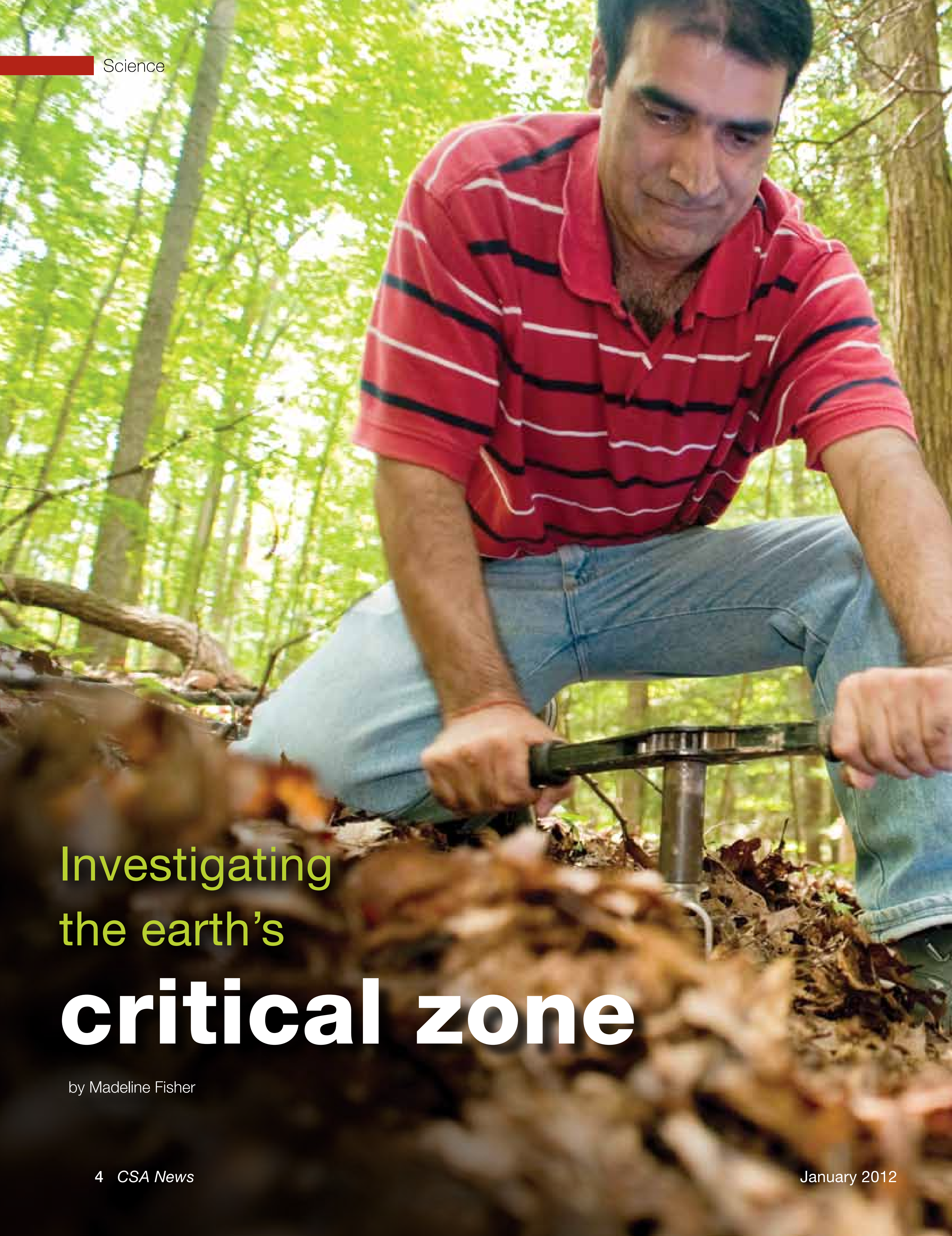

Investigating the earth's critical zone

by Madeline Fisher

To the ordinary eye, south-central Pennsylvania's Shale Hills catchment is a pleasant little tract of deciduous forest much like any other in the northeastern United States. Second-growth oaks and maples splash dappled shade across the 20-acre site, birds flit and call, and water babbles in a narrow, unnamed stream—the first leg on a long journey to the Susquehanna River.

But Pennsylvania State University geologist and SSSA member Susan Brantley is no ordinary observer; for her, the pretty scene evokes a host of questions about why the landscape looks the way it does. She's now delving into the answers more deeply than ever before. As a co-principal investigator of the Susquehanna Shale Hills Critical Zone Observatory (CZO), Brantley is among a growing cadre of scientists who investigate the earth's "critical zone": the living, evolving, outer skin of our planet where rock, soil, water, air, and organisms interact to regulate the environment that is critical to life.

Soils, plants, and other individual components of this zone—stretching from the tops of trees to the bottom of underground aquifers—have been characterized to some extent. But few studies have examined how all of the parts work together to shape the earth's surface or how natural processes integrate over time frames ranging from the super-fast scales of infiltrating rainwater to the geologic time scales of hillslope formation.

Using new sensor technologies, numerical modeling, and other advanced techniques, researchers are now trying to fill those data gaps to answer three basic questions: How does the critical zone form? How does it function today? And how will it evolve in the future, especially with humans playing an ever-increasing role in global change? Tackling it all is an audacious goal, admits Brantley, one that takes a coordinated effort by many scientists from diverse disciplines who can look across wide-ranging time scales.

"That's why I'm so excited that we're working on this tiny, 20-acre watershed," she says, "because we're all looking at the same thing in the same place."

Hope for a New Soil Science

There's another lofty aim here, as well. By their own admission, soil scientists have struggled to convey why soils matter to climate change, food security, and other pressing issues, and now critical zone research is offering a chance to do just that. But it means making a choice, says ASA and SSSA member Henry Lin, another co-principal investigator at Shale Hills. The discipline can choose to remain focused on understanding soil in terms of soil's own processes. Or it can decide to add a broader, more integrative dimension to its work.

"The second one is really the future because soil touches all the earth system's components," Lin says. "So, from my perspective, the critical zone idea provides a lot of hope for a new soil science."

With funding from the National Science Foundation (NSF), the Shale Hills CZO was established in 2007 along with two others: one in California's southern Sierra Mountains and another at Boulder Creek, CO. Three more were added to the NSF network in 2009: the Jemez-Catalina CZO in the Southwest, Delaware and Pennsylvania's Christina River Basin site, and a Puerto Rican observatory. CZOs now dot the European landscape, as well, including Germany's TERENO network and the European Union's SoilTrEC project, and China and Australia are also establishing observatories.

It's an impressive growth curve for a field that has only been officially around since 2001. That year, the National Research Council (NRC) released a highly anticipated report, "Basic Research Opportunities in Earth Science," outlining the top priorities in the discipline over the coming decade. Commissioned by NSF, it called for deeper investigation of some familiar topics, including the continents and the earth's interior. But the report's authors also recommended for study a newly minted concept, the critical zone, to emphasize that "we need to come together to understand the

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Illustration below courtesy of Jenny Parks. Top three images on this page courtesy of (l to r): Jennifer Z. Williams, SSHCZO coordinator; Henry Lin, co-principal investigator at Shale Hills; and Henry Gong, Nittany Memories Photography.

near-surface terrestrial environment in a meaningful, holistic way," Lin says. In a series of workshops that Brantley organized not long afterwards, soil scientists, geologists, and other earth scientists joined in refining the critical zone idea—and in encouraging NSF to launch a new observatory program based on it, says workshop participant Dan Richter, a Duke University soil scientist and ASA and SSSA member. Their recommendations and similar ones by the hydrological community of scientists were heard. In 2006, NSF announced its first request for CZO proposals.

Although NSF's CZO program and others around the world place special emphasis on soils, the field is fundamentally integrative and interdisciplinary. Just as geneticists will never grasp the functioning of whole organisms simply by studying individual genes or gene combinations, earth scientists can't hope to learn how the critical zone operates simply by investigating any one process or component, Lin says. This is why CZO research stresses the interfaces or links among chemical, biological, and physical processes more so than the processes themselves—pushing scientists to quantify the synergies and feedbacks between them. It's a promising approach and a challenging one because it requires integrating information across vastly different scales.

Ph.D. student Allan Bacon of Duke University cleans a soil pit at the Calhoun Experimental Forest in South Carolina, a Critical Zone Observatory seed site. *Photo by Jess Bacon.*

"How do we translate what we know about a soil aggregate, or a tiny pore space, or the microbial community into [knowledge of] the whole ecosystem, or how they lead to ecosystem services or landscape functions?" Lin asks. "That's a fundamental scientific issue. We don't yet have a clear solution to address the scaling."

Moreover, CZO scientists are examining the soil's historical record to understand how the critical zone evolved over hundreds to many thousands of years, adding a geologic time dimension not found in other observatory programs, Lin adds. At Shale Hills and other sites, for example, researchers are drilling dozens to hundreds of feet down to examine the chemistry and lithology of deeper—and, hence, older—below-ground layers. Other techniques involve measuring beryllium and uranium isotopes to produce long-term estimates of soil erosion and formation rates, respectively.

The ultimate goal is to integrate all biogeochemical, physical, geological, and other data into systems models that describe how the critical zone came to be and how it functions today.

Top three images on this page are courtesy of the Sierra Nevada Research Institute.

Researchers then hope to use the models to predict the future, as well, especially of the earth's water and soil.

Beyond its scientific value, Lin believes this attempt at forecasting holds an important lesson for the public. "Sustainability has to revolve around soil and water as the foundation," he says. "Without this foundation, the sustainability of the entire environment is at risk."

The Anthropogenic Impact

Richter agrees, adding that CZO research won't just help us know our changing world better, but also our own role in that evolution. Scientists have traditionally viewed humans as somewhat apart from soil formation and other natural processes—a disturbance at times, yes, but not really integral to ecosystem functioning or development. And yet, "here we are in a world in which humanity is increasingly a force to be reckoned with," he says, meaning we can no longer expect to comprehend these processes while leaving people out of the picture. Some earth scientists have even begun calling our time the "Anthropocene"—an age where humans are forcing change on a global scale. "Incredible as it may seem, earth scientists estimate that humanity is today earth's primary geomorphologic agent," Richter says.

Even more unsettling is the exceedingly rapid pace of that change, Richter adds, especially when it comes to the intensity of agriculture and its profound influence on our soils, water, and atmosphere. "These are things we all know," he says, "but there is still a lot of potential to understand the connections better" between people and the landscape.

A prime illustration of his point has arisen out of early work at Shale Hills. When the CZO launched, one of Brantley's first projects was a detailed examination of the site's soil chemistry with her graduate student, Elizabeth Herndon. The pair sampled 21 sites along a ridge, coring from the surface down to the bedrock of shale, and then analyzed the concentrations of different soil elements in the samples. What they soon discovered were levels of manganese that

Critical Zone Observatories around the World

Following are some of the Critical Zone Observatories (CZOs) around the world:

National Science Foundation (NSF) CZO Network, U.S.

- Boulder Creek (CO)
- Christina River Basin (DE and PA)
- Jemez River Basin and Santa Catalina Mountains (AZ and NM)
- Luquillo (Puerto Rico)
- Southern Sierra (CA)
- Susquehanna Shale Hills (PA)

Soil Transformations in European Catchments (SoilTrEC), European Union

- Fuchsenbigl, Austria
- Koiliaris River Basin, Crete, Greece
- Damma Glacier, Canton Uri, Switzerland
- Kladska Lake, Chatteau, Mt. Lysina, Czech Republic

Other European CZOs

- Kindla, Sweden
- Plynlimon, United Kingdom
- Strengbach, France
- Terrestrial Environmental Observatories (TERENO), Germany

Red Soil Site, China

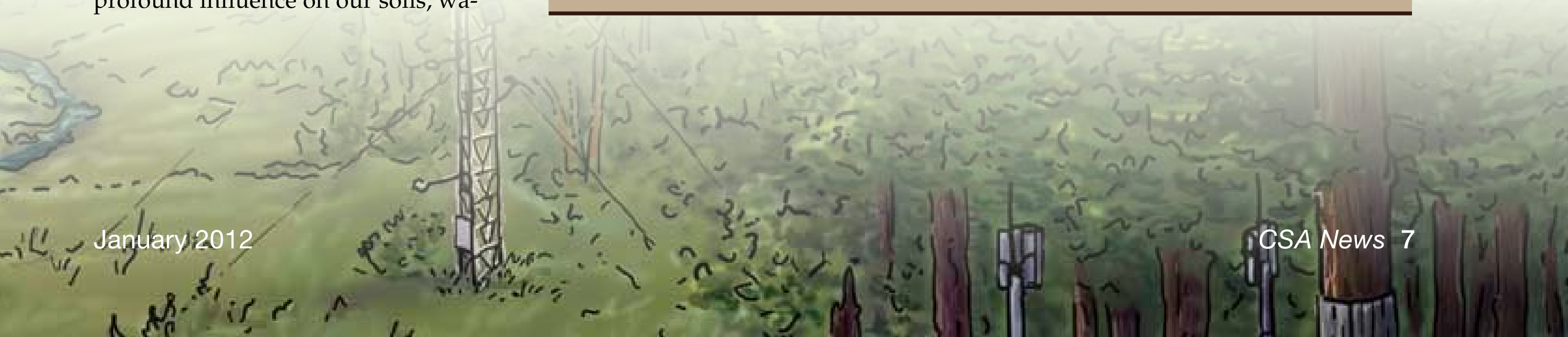

Illustration below courtesy of Jenny Parks. First two images above on this page are courtesy of the Christina River Basin Critical Zone Observatory. The right-most photo above is by Aaron Thompson, University of Georgia.

just didn't add up. Soil manganese typically comes from disintegrating bedrock during the soil formation process, meaning the element's concentration in soil should roughly match the bedrock concentration minus any losses. The Shale Hills soils, however, contained up to 17 times more manganese than the parent shale below.

"There was just too much," Brantley says, "and that led to the discovery that the excess manganese in the soil had to do with atmospheric deposition."

She and Herndon now estimate that nearly 55% of the soil manganese in some Shale Hills sites has come from the atmosphere. They also think much of it was deposited from the late 1700s to mid-1800s, when stone furnaces across central Pennsylvania were busily smelting iron for the burgeoning railroad industry. Now more than 150 years after those activities ceased, their legacy is still detectable not only in soil but in trees, which become "charged up" with large amounts of manganese over time and then slowly release it, Brantley says. And Shale Hills is not alone. As she and Herndon have dug into the scientific literature, they've uncovered reports of elevated manganese concentrations throughout the northeast, the United States, and the world, especially in industrialized areas.

Anthony Aufdenkampe, associate research scientist at the Stroud Water Research Center, conducts a tour of the Christina River Basin Critical Zone Observatory site. *Photo courtesy of the Christina River Basin Critical Zone Observatory.*

"So, it's a signal of anthropogenic impact that's very widespread and that nobody was really looking at," Brantley says. "And it really was something that we discovered through the CZO."

Long-term Soils Experiments

This is exactly the kind of exciting, unexpected discovery that working intensively in one site can net, Richter says, and he should know. When he first arrived at Duke, he inherited a research project in South Carolina, the Calhoun Long-Term Soil-Ecosystem Study, which is now nearly 60 years old. Established on eroded, former cotton land, the experiment has monitored changes in the soil and the entire ecosystem as trees planted by researchers have grown over time. "I've had 25 years of surprises and a wonderful time shepherding that project," Richter says.

He's in fact so enthusiastic about long-term soils research that, about a decade ago, he began asking other sites worldwide for information about their research and has been pulling them together in an online community ever since. Based at Duke and numbering more than 250 long-term soil experiments (LTSEs) at present, the inventory project has published

Top three images on this page are courtesy of Henry Gong, Nittany Memories Photography.

papers and held a series of workshops at different experimental locations. Richter now wants to see it reach the next level. While most of the LTSEs have so far been pursuing their own hypotheses to their own purposes, he hopes to capitalize on the range of climates and management systems they span by proposing cross-site research on important scientific issues.

One issue, for example, is how long-term fertilization with inorganic nitrogen affects key soil components such as organic matter, clay minerals, and soil organisms. These questions have implications for the sustainability of farmlands worldwide, and scientists have recently been arguing about them in the pages of the *Journal of Environmental Quality* (JEQ) and other publications. But so far, only one meta-analysis of data from the world's LTSEs (published last year in JEQ) has examined such a question, Richter says—in this case, whether fertilizing with inorganic nitrogen stimulates the decomposition of organic matter. "So it's exciting for us to try to move this website community, which is a collection of metadata and experiments, to the next stage where we actually conduct research across the sites," he says.

For more on this subject, see the special section on Critical Zone Observatories in the August 2011 issue of *Vadose Zone Journal* at http://vzj.geoscienceworld.org/content/10/3.toc.

Forging Strong Ties

The NSF CZOs are heading in the same direction. Although each was conceived with its own set of hypotheses and research aims, the sites are now forging strong ties to one another and their counterparts worldwide, says Enriqueta Barrera, NSF's CZO program director. Scientists at American CZOs serve on the advisory boards of Europe's SoilTrEC sites, for example, and University of Delaware hosted an international meeting last November designed to strengthen those relationships even further. CZOs need to establish standard protocols for collecting data, for instance, to enable cross-site comparisons in the future, Lin says. And like Richter, CZO scientists want to hone in on research questions to pursue together.

More U.S. CZOs could also be added in the future. Richter's South Carolina experiment is now a CZO "seed" site. And a recent review of CZO science by NSF's geosciences advisory committee recommended establishing new sites in places that are so far poorly represented, including agricultural regions; climate-sensitive areas, like the Arctic; and those where sedimentation, rather than erosion, predominates. The program's growth is a little uncertain given today's budget climate, Barrera says. But regardless of what happens, scientists can apply for money from other NSF programs to work at CZOs—they are open to anyone. "That's a plus," she says. "It's a way we can entrain others to participate in the critical zone observatories."

Richter is also doing what he can to attract more people to the burgeoning field. As described in the November–December 2011 issue of the *Soil Science Society of America Journal*, he helped launch and leads a new SSSA working group whose goal is to foster interdisciplinary research on the rapid changes today's soils are undergoing, mainly due to human activities. Although not a critical zone group per se, it shares many of the same objectives, he says, including developing a "larger vision" for soil science, reinforcing the links between soils and other scientific fields, and reaching out better to the public.

It remains to be seen, of course, where these hopes for the discipline actually go. But, in the meantime, Richter is happy to see one dream realized: the launching of NSF's CZO program. "It has been very satisfying," he says, "to watch it start to grow and take off."

M. Fisher, lead writer for CSA News *magazine*