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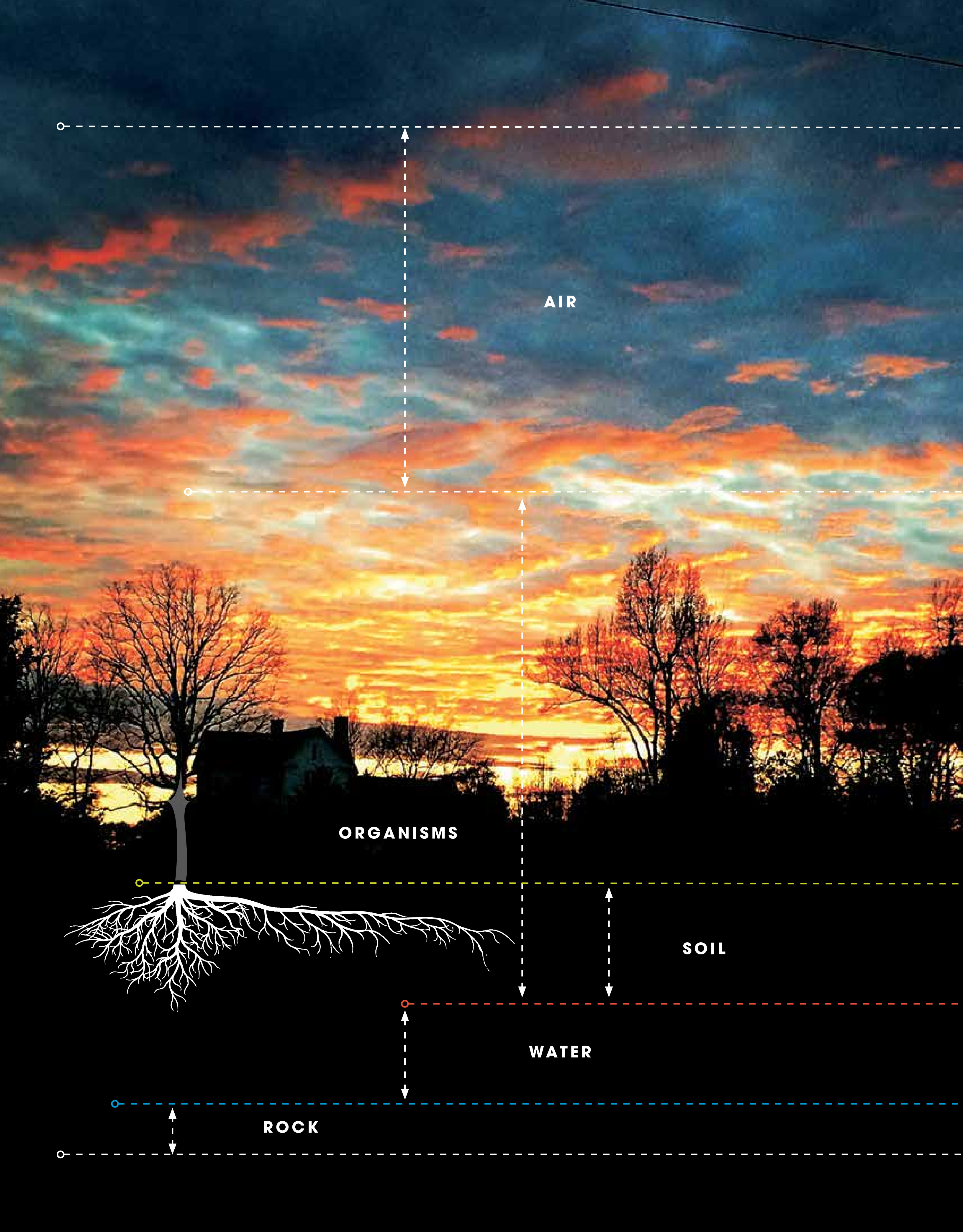
WHAT THE TREETOPS CAN TELL US

INSIDE CRITICAL ZONE SCIENCE, A NEW FIELD OF STUDY


AIR
ORGANISMS
SOIL
WATER
ROCK

TO THE DEEPEST ROOTS

Critical zone science, a new cross-disciplinary field of study, unearths secrets held in the organisms that sustain us.

TEXT & PHOTOGRAPHY BY **SCOTT HULER**

Dan Richter Ph.D. '80 and Will Cook '88 are poking around the basin of a tiny tributary of the Tyger River in South Carolina, looking for a buried tree stump. It is overcast, and a steady rain falls, and they are not having much luck. The scientist who discovered the buried stump on a previous expedition actually stumbled across it while she was lost; her directions have been good but somewhat open to interpretation. So Richter and Cook slog up one drainage after another in the chilly December rain, boots sinking into sandy riverbottom. Pines and bare, gray deciduous trees provide little shelter from the pelting rain; last fall's leaves stick to raingear that itself sticks to skin. It's not a particularly pleasant morning, but nobody is in a hurry.

This is science. Science involves a lot of trying to find stuff, and if standing in the rain in a silty riverbottom in December is what it takes, that's what you do.

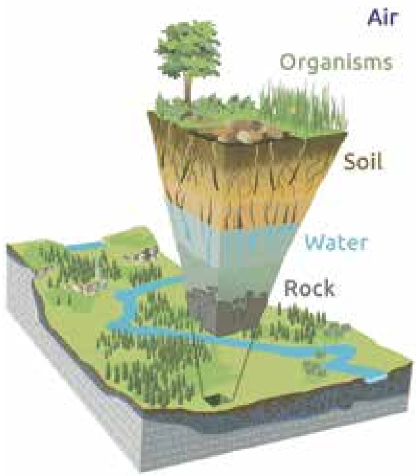
Plus, nobody wants to give up easily. A buried stump is something of a holy grail if you're trying to understand the history of a piece of land. You can core the stump, which, when you count the rings, tells you how old it was when it died; then you can carbon-date that core, telling you about when that death occurred. Suddenly you have a moment: a very particular time when that stump stood, and that was ground level, and its surrounding sediments tell you what the ground looked like. Then you can examine the sediments that have buried it, which tell you what kind of processes have gone on since then, in what order those progressed, and what's been going on since that tree stump first grew, far beneath the surface on which people now walk around. You have what the new discipline of critical zone science seeks above all things.

You have a story.

Story is central to critical zone science, a new cross-disciplinary field of scientific study born in the beginning of the twenty-first century yet containing a nineteenth-century soul. Engaging scientists who practice biology, pedology (the science of soil), ecology, hydrology, geology, geochemistry, geophysics, biogeochemistry, geomorphology, climatology, and even—in some ways, especially—anthropology, critical zone science describes its area of study as "treetops to bedrock."

That is, it concerns itself with the living skin of the Earth. Start tens of meters deep, where bedrock minerals begin to crumble into regolith (what scientists call the bottommost layer of soil, constituted mostly of broken pieces of bedrock), where only the deepest roots may penetrate. From there, reach to the tops of the tallest of the trees stretching down those roots, and you've found your critical zone—the zone critical to all the life on Earth.

Richter, professor of soils and forest ecology in the Nicholas School of the Environment, is right in the middle of this burgeoning new discipline, and Cook is his field lab manager. Richter talked about the critical zone a day and a half before the hunt for the stump, as Cook drove their car four hours through the dark early morning from Durham to the Calhoun Critical Zone Observatory, a 2,078-acre patch of piedmont upland that is one of only nine CZOs in the country. Richter is one of about a dozen principal investigators at the CZO, which he slyly calls the "Calzone," but he coordinates the research there and was largely responsible for its creation in 2013.



The National Science Foundation started its first critical zone observatories in 2007, though Richter notes that the science fully emerged in a paper published in 2001: "There is a founding document, if you will," Richter says, which calls the critical zone "the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources." A mouthful—you can see how "treetops to bedrock" has taken its place.

Richter, meanwhile, has been doing work on soil for decades, probing its depth, its makeup, its processes, doing some of his work from his earliest days at Duke in the Calhoun. "Some of his dissertation work was on USFS experimental forests," says U.S. Forest Service scientist Mac Callaham, director of the Calhoun Experimental Forest, in which the Calzone is located. "And he has always known or somehow intuited the potential of a critical zone research station. We used to do a lot of camping down there whenever we were doing fieldwork. A lot of time around the campfire talking about the potential here." The Calhoun wasn't one of the initial six CZOs when the NSF started the program in 2007, but Richter kept up the pressure, and it was in the second wave, officially opening in 2014. "He wanted long-term, networked, highly collaborative NSF-funded research at the Calhoun. And he's worked toward that goal for twenty-five or thirty years.

"So he's it. He is the heart and soul of this."

After Chorover et al, 2007. Catalina-Jemez CZO. Based on an image by Ralph Kindlimann. Courtesy of Jon Chorover and colleagues, Catalina-Jemez Critical Zone Observatory

ON THE HUNT: Clockwise from left: Dan Richter (left) and Will Cook address a GPS unit as they duck out of the rain while seeking a buried tree stump; Richter and Cook in the Calhoun Critical Zone Observatory; critical zone scientists say their area of interest stretches from "treetops to bedrock."

"It's really a beautiful pattern. CO_2 builds up and O_2 is depleted because of respiration. The land is literally breathing."

The best way Richter can explain the critical zone approach is by bringing up the models of past centuries. The twentieth century was a time of enormous growth in scientific disciplines, but also a time in which those disciplines became siloed, he says. Geologists had their concerns, soil scientists had theirs, biologists had theirs. Even ecologists, working to connect things into a system, seemed to leave out much that happened when you got below the surface of the soil. Before that, though, scientists took wider views. "That's what Darwin did," Richter says. "Darwin got three geological awards even as he worked on biology." The twentieth-century embrace of specialization resulted in a great depth of knowledge and marvelous tools and techniques, but it separated scientists, limiting collaboration and understanding.

"Biologists and geologists haven't mixed for so long that there's a lot of work we can do together. Now it's time to share and react and interact. There's a lot pent-up and discoverable because we've been so stuck in our stove pipes and our silos."

So welcome to the critical zone. And though the critical zone spans, as they say, from treetops to bedrock, it has a special focus on the soil, the land—the critical zone of the critical zone, where everything jumbles up, the connective space. Raw materials and the life that needs them mixing together in the great blender of the soil.

Many experiments are going on at any time at the Calhoun CZO, but Richter and Cook make the car ride down every three weeks to gather three things: soil moisture readings, soil gas measurements, and baskets of leaf litter. They visit sites divided into three types—some agricultural, some covered by the pine succession forests that have taken over abandoned crop fields, and some still covered by legacy hardwoods, soil barely changed since before Europeans arrived. Together those sites tell the story of the Calhoun Experimental Forest and of the piedmont itself.

The forest was created in 1947, its land chosen specifically because it represented "poorest Piedmont conditions," in the words of Louis Metz M.F. '47, Ph.D. '50, the U.S. Forest Service scientist who wrote an early history of the forest and was part of the original group of scientists who created the Calhoun on land in the Sumter National Forest. Its charge from its creation was to try to understand the story of piedmont farmland, overfarmed by settlers using poor agricultural techniques and then abandoned.

"Some thought that the more farms a man could wear out the better farmer he was," Metz wrote. In many places in the piedmont—and throughout the Calhoun—scientists estimate more than a foot of topsoil has washed away, leaving what writer Robert Montgomery in 1929 called "a miserable panorama of unpainted shacks, rain-gullied fields, straggling fences, rattletrap Fords, dirt, poverty, disease, drudgery, and monotony that stretches for a thousand miles across the cotton belt." The Calhoun scientists have had the job from the very start of looking for ways to help the piedmont regenerate from that catastrophic human misuse. Many people look at the successional forests of loblolly pines that have grown up in those abandoned fields and declare the land to be healed of its centuries of abuse. Not Richter.

"This is a green blanket," he says of the pine forest. "Lift up a corner of the blanket..." and profound questions arise. How well are those loblollies taking carbon from the air and storing it in the soil?—a question now of profound importance. Critical zone scientists are on that. When you clear-cut land, the traditional story says the land dries out; but some studies seem to show that in clear-cut land, rivers not only flood faster during major rains but maintain higher base flows as well. As the Carolinas work to dry out from only the most recent catastrophic flood, how hydrology mixes with not just geology and climate but also land-use history could not be more important. Critical zone scientists explore not just carbon and water cycles but also energy budgets through systems—vital in a warming world.

And critical zone scientists are looking ever more closely at the soil itself. The soil has centuries of land-use habits in its very composition. Critical zone scientists help it tell its story, when that story may help save our planet.

Richter comes to that storytelling, collaborative, boundary-crossing nature of critical zone science rightfully. He majored as an undergrad in philosophy, only ending up as a scientist after a few unscripted post-college years made him decide to go back to school. A little time in New York trying to become a photographer, a hike of about half of the Appalachian Trail, and when Richter was trying to figure out what was next, his girlfriend—now his wife, Susan—suggested forestry.

"I had never heard of forestry," he laughs. "I had never heard of natural resources, I had practically never heard of ecology. I was so deeply involved in the liberal arts; that made me sit up." Forestry schools had loads of prerequisites, but when he reached out to Mississippi State, where Susan was returning home for an M.B.A., they asked him to prepare only by taking a summer-school course. So he went along and took a class taught by G.L. Switzer and L.E. Nelson. The class changed his life.

"It was two months of hot, hot, hot midsummer in the swamps of Mississippi, in the uplands," he says. "And I remember exactly the day where Switzer got us on this bus, no air-conditioning," and took them to a stand of pines to discuss soil. "The guy's on his knees," Richter recalls. "He's in this reverent position. He's scraping off the pine needles, and he's digging his hand into the earth, and all of sudden he's recounting basically the environmental history of the land, with the slaves and the Faulkners and the people." It wasn't just minerals and earthworms and beetles and decaying plants; it was history, the history of everything.

"And I'm saying, 'Nobody in this damn world is doing this!' It's like philosophy—or good writing. There's something underneath that's so powerful. I saw that in soil." Richter knew what he was doing for the rest of his life.

A couple of semesters at Mississippi State led him to Duke, where he got his Ph.D. in soil science, and in his work now he brings that same enthusiasm and reverence to the soil and to the story it carries. "The other day I was driving down the road, and I broke out in utter laughter. I just realized how lucky I am. I found what I wanted to find, what I needed to find. And it's the lowly soil. It's the earth." He also brings that liberal-arts background. He has started a textbook chapter he wrote by quoting Faulkner on the past not being past, and in conversation he recommends reading not just Lyell and Darwin but also T.H. Huxley's lecture on chalk, in which Huxley notes "a great chapter of the history of the world is written in the chalk."

Richter sees the history of the piedmont in the Calhoun CZO soil.

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Richter and Cook park by the side of an asphalt two-lane. They have spent all morning making such stops. From their car they take a suitcase filled with instruments they call the black box, and they carry it to a spot in a pine or hardwood grove. They uncap plastic pipes that stick out of the ground, dangle sensors to varying depths to measure oxygen, carbon dioxide, and other gases flowing through the soil.

Beyond merely measuring gases, they take samples, filling tiny balloonlike bags to take back to labs for further analysis. When they're on sites that include trees, they also put in paper bags the leaf litter that's fallen since their last visit, emptying laundry baskets lined with screens that let rain out but capture every pine needle, leaf, and nut that's dropped from above to interact with the soil. They'll grind up the litter and test it for nutrients; they'll test the soil for how well those nutrients seem to be integrating.

At other times they'll core the trees to see how well they grow in soil with those nutrients. They'll measure the trees, count them, do some multiplication, and figure out how much tree biomass different types of soil like to support. Cook uses a credit card to scrape out the tiny pieces of grit that gloved hands miss when gathering leaves from the screened laundry baskets. A few measurements, a few samples, and they close the black box and head to another site. They have a lot of ground to cover and only so much time. They want to finish in a single day so they can sleep overnight in the tiny spartan house they use as a headquarters and spend the next day looking for that stump.

This time they walk up a double-track to a spot along a wire fence between two green-gold harvested cornfields. This is an agricultural plot, but they take the same measurements. "Oxygen is stable at 20.1," Cook says, and Richter makes a notation as crows call, the wind whispers through nearby pines, and the sun angles its way through the sky; a gentle breeze lifts spider silk from goldenrod, and it floats away. They start their work around 9 a.m. and continue until it gets dark, taking readings from more than a dozen different spots. They don't break for lunch.

It's a long day. For a while they're joined by colleagues from

Georgia, who are using larger and more cumbersome machinery to take soil moisture readings. The various readings the group is taking are the basic science, the creation of data that yield an understanding of how the critical zone goes about its business.

"The amazing thing," Richter says, "is the beauty of the data set that has emerged" from the various projects that have been going on in the Calhoun CZO. "It just emphasizes how dynamic the ecosystem is." At one point the group takes readings alongside a metal structure called a land atmosphere flux tower, which looks a little like a utility pylon. "Its instruments are above the canopy," Richter says, and it measures fluctuations of carbon dioxide and water, the exchange between the land and the atmosphere: "It's the integrated signal of the whole critical zone."

That signal, in a way, is the story.

Sharon Billings Ph.D. '98, professor of ecology and evolutionary biology at Kansas University and one of Richter's Calhoun collaborators (and his one-time grad student), explains. Richter and Cook send their little balloons of gas to Billings' lab, where apart from just amounts of, say, carbon dioxide, she determines the original source of that carbon. Soil microbes, like all living things, breathe; the soil gas the team samples contains the carbon they exhale. Different sources of carbon have different isotopic signatures, and so by checking isotopes, "we can make inferences about the kind of carbon [soil microbes] are using to make that CO_2," Billings says. "You don't have to go too deep before you hit a region in the soil where the microbes are still telling the story of their past that the layperson walking through the forest might not know."

INSTRUMENTAL: The briefcases full of equipment Richter and Cook use to gather soil gas samples in the field were designed by Zach Brecheisen Ph.D. '18.

For example, one isotopic signature comes from what soil scientists call bomb carbon. Nuclear-bomb tests taking place from 1945 through the early 1960s released radioactive isotopes of carbon. All over the world, plants photosynthesized that carbon, moving it deep into the soil through roots, building it up in leaf litter. Within the soil, microbes release that bomb carbon in their respiration.

That specifically dated carbon enables Billings to figure out which carbon is going where in the Calhoun. In the samples from reference hardwood plots, she says, roots of trees hundreds of years old go very deep, pumping fresh carbon meters deep in the soil. In the agricultural plots, deep soil gas is "much more reflective of bomb carbon," which hasn't moved for decades. The successional pine forests are moving more fresh carbon more

Megan Mendenhall

deeply, but nothing like the hardwood forests. That tells a story not just about soil but also about carbon sequestration, of vital importance on a warming planet.

These studies have been going on since 1947, when Metz and his cohort started the experimental forest. Metz's colleague Carol Wells in 1962 started gathering soil samples about every five years, allowing scientists to see what was going on at particular depths as time went on. When Richter returned to Duke and joined the faculty in 1987, Wells was nearing retirement, "and he was literally giving away his old experiments." Richter took on the soil samples, and he now manages that long-term soil experiment, not only gathering new samples every few years but also working on new ways to better examine what remains of the original samples. With every new experiment or measurement, the remaining sample grows smaller, so Richter's team finds ways to gather more information using less material. "He took me to the Calhoun, and I could see the potential," Richter says of Wells. "Then it basically took over my life."

COLLECTIONS: Only the tiniest fragment of the soil samples gathered in the Calhoun Long-Term Soil Experiment over more than fifty years

"There's a lot pent-up and discoverable because we've been so stuck in our stove pipes and our silos."

"The whole weathering process is mediated by respiration," Richter says—by plants taking in water and carbon dioxide and sunshine, breathing out oxygen into the air and, underground, breathing out carbon dioxide into the soil. "Roots, fungi, earthworms, bacteria. Carbon dioxide dissolves in water, creating carbonic acid, and that attacks minerals, interacts with fracture systems and groundwater." A liberal-arts major to the core, Richter turns quickly to metaphor: "It's really a beautiful pattern. CO_2 builds up, and O_2 is depleted because of respiration. The land is literally breathing."

A professor in his master's program likened soil to skin, the largest organ in the human body, but Richter likens soil to a treadmill—as the top layer erodes, the bottom layer is always building, and so minerals freed by weathering move their way up through the soil toward the surface. It can take a million years for it to move a meter or ten, but that's the process. "It's the bio-geo connection I'm interested in documenting," Richter says. "It's a very simple point, but I don't think it's very well appreciated at all."

And the interdisciplinary nature of critical zone science helps make those connections. "I wouldn't feel confident in a biology department," he says, "but when you get a small group of people, and they're motivated, they do stuff." Soil people, biologists, geologists, chemists, physicists, modelers—whatever they take a notion to study, someone in the group will have a needed skill.

And anthropologists. Don't forget anthropologists. Apart from all the bugs and the animals and the plants and the water, the energy budget and the carbon cycle, the critical zone includes the study of people. Nowhere are the people who play a role in the living history of the land itself more central than in the Calhoun Critical Zone Observatory, where the Tyger River flows and Richter looks for its stories.

"You have the people right in the middle of it," says Richter. He tells a story of connecting with people at one of the tiny Baptist churches in the Calhoun. Walking near one of those churches, he met two men collecting trash, got to talking, and began getting information about the people in the area, the people in the cemetery, and even slaves buried in unmarked graves nearby. "You ask about the history of the church, and you've got a friend on your hands—and a repository of information." He's walked the terrain with people using dowsing rods to show him where they believed people were buried.

That kind of connection is fundamental to critical zone science. "We're trying to capture that lived experience," says Calhoun anthropologist Don Nelson, assistant professor of anthropology at the University of Georgia. "The way people think about their environment now. Get them to walk the landscape with us and talk about what they see."

That personal information helps tie things together. Cook has mosaicked a series of aerial photographs from 1933, from when the U.S. government was buying the land to create the Sumter National Forest, from which the Calhoun was created. Grad student Zach Brecheisen Ph.D. '18 georectified those joined photographs, and the resulting image can now be connected with data gathered in the field as well as LIDAR images of the soil. (LIDAR works like radar but uses light from a laser instead of radio waves.) Deed chains and census data can provide a lot of information about land-use history, but often that person walking along the road has information worth a month of calculation and research.

"It's a time machine," Richter says of the Calhoun and its riches. "We love that aspect." And again, the people are at the center of that study. "They can help us interpret the landscape in ways the census alone won't do," Nelson says.

"Dan talks about the underlying hypothesis that drives the science," Nelson goes on. "While everything looks pristine and lovely at the surface, the past land-use history has fundamentally changed the way the biogeochemistry and hydrology actually function." With investigator Michael Coughlan, now a research associate at the University of Oregon, Nelson has published papers beyond biogeochemistry and how the Calhoun came to represent the "poorest piedmont conditions." Their most recent paper addresses land-use history going back not just to those ruinous post-Civil War farmers but all the way back to Native Americans. "We have this general narrative that people ruined the environment: namely, sharecroppers," Coughlan says. "But maybe European colonists did their slash and burn farming, and they started ruining the environment."

Native Americans of the late-Mississippian era practiced bottomland agriculture that didn't degrade the environment, says Coughlan. The first Europeans settled where the Native Americans had lived, but even then, things didn't immediately go downhill. "It didn't happen until plantation economy. Slavery allowed the key European-American players to amass a great amount of wealth and clear a lot of land. That's when the degradation starts occurring." Their results begin to give a sense of the human story of the Calhoun lands from their earliest days. "This is not land use in the abstract," he says. "But we're actually able to say this particular area was part of a plantation, one of the first to expand and become the idea of the pre-Civil War slave cotton plantation, so we can look at those things and how they have differentially affected the landscape. The goal will be to start connecting these findings directly with the stuff that Dan Richter is finding with the soils, because we can actually account for the histories and why different things occurred in different places."

Add in the mosaicked maps and deed trails, and you end up with that critical zone ideal: information about the soil, the trees, the hydrology, the geology, the history, the people. Oh, and speaking of history, what about that stump? "We went back down there," Richter says, "and found three of them!" Right where he and Cook had been looking. "With those three stumps, there's six feet of legacy sediment."

The stories don't live only in the Calhoun CZO, of course. For one thing, in Richter's lab the entire history of the long-term soil experiment started by Wells lives in a beautiful wooden cabinet, with brass drawer pulls, filled with jars of soil. A sign on the cabinet calls it "the gold mine," which Richter regularly says it is. Walk through the lab, and you'll find rows of carefully labeled tree cores, like boxes of pencils, and even 3D-printed representations of some of the topography. For another thing, another researcher doing work near the Calhoun is currently suggesting that the piedmont soil, long perceived as almost purely created by that treadmill up from bedrock, in some places includes colluvium—stuff from landslides, which aren't usually included in piedmont models.

"The best thing of all," he says, "at the base, there's peat!" That indicates a buried wetland, and significant Earth movements a hundred thousand years ago, but what thrills him is the unexpectedness: "We need to overhaul how we look at Piedmont bedrock contributing to the soil. It's right at the heart of why I find humanities so important to the sciences."

That is, scientists had similar theories in the 1930s, but their research was sidelined by World War II and mostly forgotten. Knowing not just the science but the history of the science? That's critical zone thinking.

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Once you're thinking in a critical zone way, you never stop crossing boundaries, and no experimental forest can contain you; the ideas just roll forward. Richter recently got to thinking about "the irony about changing soil so much yet knowing so little about it." Humankind has had enormous effects on soil, yet soil remains understudied. Which to Richter has brought up cities.

"The whole United States, its soils have been mapped. Each county has a fairly detailed soil map. But the funny thing is, the cities are unmapped. Where we live is the frontier. The places we've modified the most are the places we don't have a map of. That leaves us with, for example, urban soil lead problems that are incredible."

Scientists have gotten to work on that, and "now there's enough blood data on kids, especially young kids, so you can map where kids or families live." Lead turns out to travel in the top one inch of soil. "It's not a water problem," Richter says. "It's a soil problem." Lead from the auto fuels in use in the 1950s through the 1970s, from lead paint that has flaked off houses and been ground into the soil. Older and poorer neighborhoods—of houses with lead paint and yards nearer big roads, where gasoline products settled for decades—are most affected. And again: The lead isn't in the pipes, it's not in the air. It's in the soil.

"For me, this was a discovery, like last year," Richter says. "I was appalled at myself" for not seeing the issue sooner. "But it goes to the heart of what a soil is. It's a memory. It's a legacy of everything that has gone on there in the past. It so well represents everything that has gone on in our cities. Lead has been removed from the gas and the paint thirty years ago, but it's still in the soil." Kids track it in and out of the house, then the house gets contaminated. "You can predict lead concentration in the blood by merely soil variables." Richter has already written an op-ed with a graduate student urging cities to test and map city soils like counties and states have done for their more natural soils.

"It just reminds me how little we know even about the soil that's most directly connected with us," he says. "Maybe that's my niche. I mean, it goes right to the heart of what the soil is." It goes right to the heart of the critical zone.

It goes to the heart of the story. ■