The science of the in-between: Why the vadose zone matters

By Megan Sever

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Ryan Stewart using thermal imaging to understand how critical vadose zone properties affect plant heat stress. Photo courtesy of Georg Leitinger.

What happens just underneath the Earth's surface is responsible for our agricultural systems, regulates our climate, and supports our infrastructure. A multistate group of soil scientists recently published a *Vadose Zone Journal* review that outlines key areas of research happening in this unsaturated zone. Knowledge gaps turn into research opportunities as the scientists review what we know—and don't know—about how soil moisture, the hydrologic cycle, emerging soil contaminants, and more.

Check out the short video below summarizing the main points of this article and next month's companion article.

It's February 16, 2026, just over a year after the Eaton Fire destroyed half of the buildings in historic Altadena, California, and the Palisades Fire devastated Pacific Palisades, Topanga, and Malibu. An atmospheric river has aimed its firehose squarely at the Los Angeles area and has started unleashing torrential rains. Runoff pours off highways onto city streets below where sewer drains are overwhelmed and shin-deep floods stall cars, including a Waymo outside the Natural History Museum. The aqueducts of LA have turned into roaring muddy rivers. Warnings have been issued for burned areas to beware of mudslides and debris flows. Evacuations are ordered for parts of the LA Basin's burned hills.

A similar scene plays out anytime heavy rains hit burned areas. Denuded of anchoring vegetation and now water repellent, soils and rainwater careen down hillsides, carrying remnants of whatever burned—including ash, charred vegetation or buildings, and contaminants like heavy metals—downslope and into local waterways. Removal of vegetation that previously prevented erosion is one reason for post-fire debris flows. But it's the water repellency that has scientists intrigued. Was the soil hydrophobic prior to the fire? What part of the soil—like, how deep—is water repellent? Just the thin surface, or layers deep? How does the structure of the soil itself change in a fire? What happens to ash and contaminants? Do they still get filtered through the soil or do they run off into surface waters now? These are questions that scientists studying the vadose zone hope to answer as they examine burned areas.

The vadose zone is the portion of the Earth's surface that extends from the land surface to the water table. It's predominantly unsaturated, so water typically percolates through into the saturated zone below, filtering contaminants and nutrients. It contains soil, minerals, nutrients, rocks, air, water, roots, organic matter like decomposing vegetation, microorganisms like fungi and bacteria, and animal life like worms, insects, moles, ground squirrels and all of their burrows. All of these pieces interact to create a dynamic environment fundamental to life on Earth.

Ryan Stewart's research team collects soil samples after a wildfire in Mt. Chimney State Park, North Carolina. Photo courtesy of Jingjing Chen.

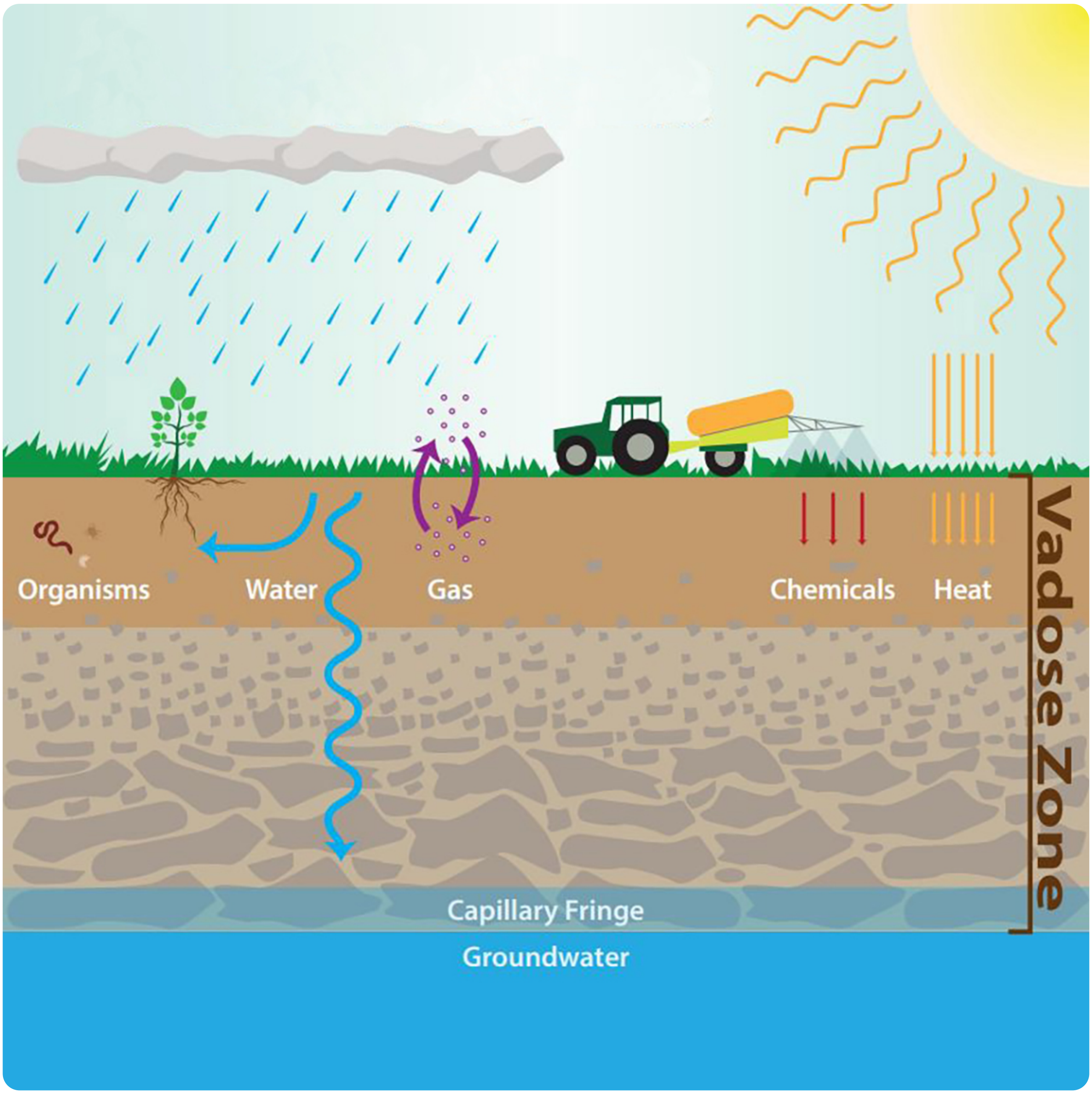
The vadose zone is "critically important for everything we rely on—our clean air, clean water, food, and even infrastructure," says Ryan Stewart, a soil hydrologist at Virginia Tech University. "All of these functions depend on the vadose zone, even though it's kind of hidden below the surface. Even though it's out of sight, it shouldn't be out of mind," Stewart says.

Fire alters the vadose zone. It changes infiltration, storage, and flow pathways. Sealing at the surface reduces water absorption, increasing runoff. But how these processes occur and to what extent are open questions, important for predicting debris flows and managing drinking water risks.

In fact, there are many open questions about what happens in this critical zone. A review published last year in *Vadose Zone Journal* catalogued six of the current biggest questions and emerging research opportunities in vadose zone science. In this story, the first of two, we will look at how scientists from many different backgrounds are coming together to study the vadose zone and hopefully answer some of these big questions. We will also look at how scientists are researching brand new issues, such as how so-called forever chemicals work their way through the vadose zone, and how access to ever-developing technologies can help. In the second feature, to be published next month, we will dive deeper into fire and vadose zone interactions.

Studying a critically important zone

The vadose zone is the critical interface between the land surface and groundwater, regulating water infiltration, evaporation, transpiration, carbon cycling, plant growth, contaminant attenuation, and aquifer recharge. It is also the foundation of human infrastructure. Water content in this layer constantly shifts in response to precipitation, irrigation, root uptake, temperature, and soil structure. Acting as the primary filter and regulator of water quantity and quality for underlying aquifers, the vadose zone controls not only how quickly water replenishes groundwater but also how rapidly pollutants migrate from the surface to groundwater.



The vadose zone is the critical interface between the land surface and groundwater, regulating water infiltration, evaporation, transpiration, carbon cycling, plant growth, contaminant attenuation, and aquifer recharge. Illustration courtesy of Markus Flury/SSSA *staff.*

Despite its central role in sustaining agriculture, ecosystems, and drinking water supplies, much about the vadose zone’s chemical, biological, and physical processes remains poorly understood. Closing these knowledge gaps is essential to protecting this vulnerable layer as environmental pressures grow amid a changing climate. Intensifying hydrological extremes—heavier rainfall, longer and stronger droughts—and more human-caused stress on land are all endangering the resources in this dynamic zone.

These stresses are real and immediate, hitting farmers and growers hardest when floods inundate fields or drought dries them out. “It is very difficult to farm because farmers and growers have to cope with changing environment and changing market conditions,” says Wei Zhang, a soil physicist at Michigan State University. “I think growers and producers still look to land grant universities and scientists to develop solutions. It’s important that we are committed to developing solutions to support them because they are really the foundation of our society—that’s where our food is from,” Zhang says.

With this charge in mind, Stewart, Zhang, and a whole host of other scientists came together in the U.S. Multistate Research Project W5188 (and W4188 before this), sponsored by the USDA. “In many ways, the activities of this group have never been more relevant, as societies seek solutions to pressing problems related to food security, land and water resources, and climate change,” the group wrote in *Vadose Zone Journal*.

Vadose zone science is, at the core, transdisciplinary. While the basis of vadose zone science may be in soil physics, Stewart says, other members of the group include everything from biogeochemists, climate scientists, ecologists, hydrologists, microbiologists, and plant physiologists to engineers, food scientists, and epidemiologists. This loose-knit group came together to look at some of the issues that have broad applicability across their sciences.

The six crosscutting issues the team took on include:

- Scaling and modeling of vadose zone properties and processes.
- Soil moisture monitoring.
- Surface energy balance.
- Interplay between preferential water flow paths and biogeochemical processes.
- Interactions between fires and vadose zone dynamics.
- Emerging contaminants and their fate in the vadose zone.

USDA-ARS hydrologists Tom Jackson and Parmecia Jones test soil moisture using different methods to see which more accurately validates data obtained via satellites. Photo by Stephen Ausmus, USDA-ARS.

Many of these issues—such as understanding and modeling spatial and temporal variability in soil properties and preferential flow—have persisted for decades, says Markus Berli, a soil physiologist at the Desert Research Institute in Nevada, and a member of the team. "A lot of the basic questions are still the same as in the 1960s. There haven't been any big paradigm shifts. But we have much better tools now.” Those tools include remote sensing, powerful computers and programs to run process-based and physics-based models, new in-the-ground sensors, and even artificial intelligence. Applying these tools to solve vadose zone mysteries has grown more urgent in recent years.

The paper was not only meant to be a “state-of-the-science” comprehensive review of vadose zone science, but it can also be used as a roadmap for anyone looking to advance vadose zone research.

Scales, models, and fieldwork

One of the central challenges in vadose zone research is scale. Scientists can measure soil moisture, porosity, or hydraulic properties in a single location or field with impressive precision, but translating those localized snapshots into watershed-scale model predictions remains difficult, Stewart says. The challenge goes both ways: Broad satellite observations must also be calibrated and interpreted in ways that make sense at the field level. Soils are extremely heterogeneous, including sand, silt, and clay as well as rocks, roots, wood, and other debris, and they vary enormously across different topographies. They also shift over time with storms, drought, and land use. Preferential flow—water moving through preferred pathways like animal burrows, root paths, or soil cracks rather than seeping uniformly—varies widely and remains difficult to model. Coupled physical, chemical, and biological processes further limit the accuracy of traditional models. Even with significant advances in modeling, including physics-based AI models, bridging small-scale processes with ecosystem-scale forecasts remains a work in progress.

Much of what researchers know still begins with fieldwork. “If we want to really understand what’s happening, we need boots on the ground—to collect samples from the field," Zhang says. Berli agrees. "We've gotten very good at measuring this stuff in the ground. Grab a shovel, dig, take a sample to the lab, analyze it," Berli says. "But the limitation has always been that it's very local—a snapshot of that soil at that location and moment—and soils are very, very variable, not just in space but also in time."

Manual field work is important for calibrating imagery data. Soil scientist Dong Wang uses a probe to collect soil moisture data as technician Matt Gonzales and agricultural engineer Jim Gartung record grape canopy cover with a spectral camera. Photo by Stephen Ausmus, USDA-ARS.

Remote sensing offers a way to expand those snapshots into panoramas across larger landscapes, but satellites have limits. Most satellites see only surface conditions and often at resolutions too coarse to capture what's happening belowground. Newer technologies are beginning to narrow that gap, Berli says. NASA's NISAR Mission, for example, can estimate soil moisture at roughly 100-by-100-yard resolution—far sharper than previous systems—while drone-based platforms may achieve square-meter detail, he says. However, new experimental approaches that better quantify heterogeneity are also needed, the team wrote. Connecting the expanding big-picture datasets with on-the-ground measurements is essential for turning observations into predictions about everything from potential floods, droughts, and fires to contaminant transport and greenhouse gas fluxes.

Improved field data, for example on how cracks in shrink-swell soils open and close and affect water movement, or how roots and the surrounding soil create pathways for preferential flow, are helping strengthen models, but more data are needed. Additional field data are also needed on soil physical and biogeochemical processes to better understand when and where short-lived bursts of carbon release occur, how often they happen, and how long they last. Incorporating such observations into models is essential for improving predictions of water and carbon cycling.

Soil moisture and evapotranspiration

Soil moisture content sits at the center of vadose zone dynamics, linking subsurface processes to weather, climate, agriculture, carbon cycling, and water resources. Moisture content is important for predicting drought and floods, crop yield and potential famine, wildfires, and groundwater dynamics like aquifer recharge. Yet measuring and predicting ever-changing soil moisture levels across space and time remains challenging.

Because of the importance of soil moisture, a number of ground-based monitoring networks that include local surface and rootzone soil moisture measurements have come online in recent years, along with new satellites that infer surface soil conditions. “The million dollar question is how do we have to measure moisture content on the ground so we have the best possible measurements that we can then compare to what we see from space?" Berli asks. Soil moisture content is a perfect example of the scale problem: Ground-based sensors capture accurate local data, but are limited in coverage, and satellites capture surface conditions—usually not more than a couple inches deep—at coarse resolutions. Bridging those scales and understanding how moisture moves vertically and laterally through the heterogeneous subsurface is essential for improving drought forecasts, irrigation management, and groundwater recharge estimates.

At the Henry A. Wallace Beltsville Research Center, scientists use sensors to monitor carbon dioxide, water vapor, and energy exchanges between the Earth's surface and the atmosphere at a Long-Term Agroecosystem Research (LTAR) field. Photo by Stephen Ausmus, USDA-ARS.

Soil moisture also plays a key role in the surface energy balance, determining how incoming solar energy is divided between heating the air and evaporating water. The warming of the land surface and atmosphere causes fundamental changes to weather patterns and to every component of the water cycle. Evapotranspiration—the combined loss of water through soil evaporation, surface water evaporation, and plant transpiration—represents the primary pathway by which moisture returns to the atmosphere. Accurately measuring evapotranspiration requires higher-quality atmospheric and land-surface observations and is essential for assessing climate change, managing irrigation and water infrastructure, and improving agroecosystem and hydrologic models. Under a changing climate marked by more frequent extremes, improving soil moisture and evapotranspiration monitoring and integrating them into land-surface and ecosystem models is critical for predicting both water availability and temperature dynamics.

Emerging challenges

Two of the most urgent and rapidly evolving frontiers in vadose zone research are the effects of wildfire on the vadose zone and the fate of emerging contaminants—challenges that are converging as the climate is changing. More frequent and severe fires are altering soil structure, water repellency, infiltration, and erosion patterns, changing how water and "stuff" move through the unsaturated zone. At the same time, growing awareness of contaminants such as PFAS, pharmaceuticals and personal care products, and microplastics has revealed how little is known about their transport, persistence, and transformation before they reach groundwater. Burned landscapes can further complicate this picture, mobilizing pollutants bound up in ash and accelerating their transport downslope or downward through the vadose zone. These pressures underscore a new reality: The vadose zone is not just a passive filter beneath our feet but a dynamic and vulnerable system responding to intensifying environmental stress. Understanding how fire-altered soils and emerging contaminants interact within this layer has become critical for protecting water resources, ecosystems, and communities.

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There is so much scientists don't know about both issues, Berli says. For example, he says, because soils aren't usually studied before a fire, scientists don't know if or how water repellent the soil was before fire struck. "If you have water repellency after the fire, it might not just be caused by the fire itself. It might have gotten way worse, but there might already be some water repellency there before the fire." Likewise, scientists don't know how much preferential flow was already occurring in the vadose zone. "We do know that water repellency causes preferential flow," Berli says. "So, if you have highly water repellent conditions, you will end up with preferential flow paths." But the only way to know how much repellency and flow patterns change with a fire is to study the areas before a fire, work Berli and his team are doing with soil plots and controlled burns in Nevada.

Water droplets on subsurface soil horizon after wildfire in Mt. Chimney State Park, North Carolina. Photo courtesy of Jingjing Chen.

Another before-and-after question that will likely only be answered through experimentation and observation is how new chemicals and plastics degrade or transform in the vadose zone. Take PFAS: There are thousands of PFAS compounds, Zhang says, but only a fraction has been well studied. Of those understudied PFAS, scientists don't even know for sure which ones are dangerous to humans or ecosystems, he says. Of the thousands, scientists know the toxic effects of some, like PFOA and PFOS, but toxicity in the rest will vary with chemical structure and interactions in the vadose zone.

To begin assessing toxicity, scientists can look at analogs, Berli says. "Ask the chemists, 'How did the analog behave?' Then ask them, 'Is this new molecule polar, or nonpolar? How do you think it will react?'" From those comparisons, he says, chemists can typically offer a sense of how a new contaminant might behave in the environment.

Contaminant transport through the vadose zone has been studied for decades, Zhang says, particularly fertilizers, pesticides, and heavy metals. The environmental fate of any chemical depends strongly on its sorption to soils, with factors like organic matter and clay content, iron and aluminum oxide concentrations, and chemistry of the surrounding solution influencing the sorption rate. Soil type and soil structure also shape subsurface oxidation–reduction conditions, Zhang says, which further affect how contaminants persist, transform, or move through the vadose zone.

*Wei Zhang's Ph.D. students Chenxi Li **(left, pictured)** and Qinyuan Cao study metal uptake by carrots under different influences, such soil water regimes or soil amendments. Both students, who aim to enhance food safety and nutrition of food crops through soil management, are funded by USDA-NIFA. Photos courtesy of Wei Zhang **(left)** and Qinyuan Cao **(right).***

"Soil type and soil structure are fundamental soil physical properties that influence how energy and matter flow—water, nutrients, and pollutants, including PFAS," Zhang says. Physical properties are "fundamental to how we understand pollutant movement through soil," he says. But a lot of transformation also happens because of biological organisms—bacteria, fungi, and other organisms—living in the soil, so they need to be accounted for as well, he adds.

It's important to get a handle on how these emerging contaminants transform or move, because what contaminants do in the vadose zone directly controls their concentrations in groundwater, surface water, crops and our food, and the atmosphere.

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Studies have shown that crops take up PFAS, Zhang says. But how much varies with the type of chemical, the soil properties, and the crop. “Different crops take up PFAS differently and distribute them to different parts of the plant.” But then what? How much of those chemicals then make it into human food, or animal food (and then meat), is an area of active research at Michigan State and elsewhere, he adds.

Calling these new compounds “‘emerging contaminants’ just means our knowledge about them is not adequate,” Zhang says. “They are not regularly monitored, managed, or regulated” because they’re new. “But every contaminant goes through that cycle because our scientific understanding, the public awareness, the regulation and policy, and the engineering technology to treat contamination all evolve over time.” Think about lead, he says. It’s been used since antiquity, but humans didn’t know it was toxic until the middle of the last century. Even leaded gasoline wasn’t fully phased out globally until 2021. Things get regulated once we understand their harmful effects to humans and ecosystems, he says.

“Given the substantial quantities of emerging contaminants being released into the environment, further innovations in data collection, interpretation, and modeling tools will be needed for years to come,” the team wrote in the review article.

The importance of working together

The Multistate Research Project has gained attention and has even won an award from the USDA Multistate Review Committee. The project’s success highlights the interdisciplinary nature of vadose zone science and the importance of collaboration, Stewart says. “The easy solutions in soil physics have been done, so now we need to apply our skills to more interdisciplinary and transdisciplinary problems,” he says. “The nature of the science is much more complex.”

Berli has another example of why it’s important to work together. At a recent conference, he was listening to a colleague from another scientific discipline presenting about a breakthrough. “A bunch of soil physicists were sitting in the audience and looked at each other and said, ‘We’ve known that for 40 years.’ But that knowledge hasn’t made it into other disciplines,” he says. “Soil physics research is decades ahead of many of its applications in various related fields,” he says. And he bets that goes both ways. Collaborating is the only way to ensure everyone is working with a full deck.

Collaborations can be multistate or even within one university. “At Michigan State, we try to lower or even remove the boundaries for people to work together,” Zhang says. “We train students as T-shaped scholars: They need disciplinary depth, and they need broader exposure to other disciplines—to understand other people’s language, communicate well, and work well in a large team.”

Ryan Stewart’s Virginia Tech research team surveying a post-mining landscape as part of a study to understand how land use change alters hydrological processes and critical zone weathering. Photo courtesy of John Hoben.

Another reason it’s good to bring everyone together: talking about and coming to some agreement about what’s important to study. In soil physics, the “holy grail is: how does soil structure affect vadose zone hydrology? That’s one of the big open questions, starting from how we quantify structure, to how we get it into our larger vadose zone concepts,” Berli says. But the funny thing is, he says, “One person will tell you, ‘Structure is everything.’ And if you talk to another person, the person will tell you, ‘Why do you care? It doesn't matter.'"

"If I had all the resources, I would love to put a team together under a One Health umbrella that brings everybody together to look at how human activities are shaping our world and environment and impacting our health and the health of other organisms on this planet," Zhang says. In the next few years and decades, he says, "the field will become very exciting because you will see the infusion of ideas from other disciplines into soil physics and also diffusion of exciting ideas from soil physics to others."

What comes next?

New tools—drones, satellites, robots, evermore sensitive sensors, advanced imaging techniques like x-ray computed tomography, machine learning algorithms—are all promising, Stewart says. Sensors have gotten much better and much less expensive, and scientists can measure things at scales that were previously unimaginable, he says. But ultimately, he and the team wrote, "success in these efforts will depend on modelers and experimentalists engaging in discussions and learning from one another." It's unlikely that fieldwork will be completely replaced either. There's just no substitute, Stewart says, for digging profiles and seeing what's happened (and happening) below the surface.

Dig deeper

Stewart, R. D., Flury, M., Ajami, H., Anderson, R. G., Green, T. R., Jin, Y., Patrignani, A., Shillito, R., Zhang, W., Najm, M. R. A., Babaeian, E., Berli, M., Brookshire, E. N. J., Daigh, A. L. M., Franklin, S., Giovando, J., Heinse, R., Heitman, J., Huang, J., … & Zhang, F. (2025). Emerging issues and research opportunities in vadose zone processes. *Vadose Zone Journal*, *24*, e70030. https://doi.org/10.1002/vzj2.70030