UC SANTA BARBARA

THE Current

July 9, 2025
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A nuanced model of soil moisture illuminates plant behavior and climate patterns

Any home gardener knows they have to tailor their watering regime for different plants. Forgetting to water their flowerbed over the weekend could spell disaster, but the trees will likely be fine. Plants have evolved different strategies to manage their water use, but soil moisture models have mostly neglected this until now.

Researchers at UC Santa Barbara and San Diego State University sought a way to move beyond simple on/off models to capture the nuanced ways that plants manage water stress. To this end, they developed a nonlinear model that can observe these behaviors in satellite data. Their methodology, published in Geophysical Research Letters, will improve climate models and inform our own water management strategies.

“We found that plants don't respond to water stress in a simple, straight-line way,” said senior author Kelly Caylor, a professor at UCSB’s Bren School of Environmental Science & Management. “Instead, they have dynamic response patterns that reveal whether they're ‘water spenders’ or ‘water savers.’”

How soils dry out

Water can follow many paths after it rains. It can go down: running off the surface into streams and rivers or soaking into deep aquifers. Or it can go up: either evaporating directly from the soil or getting taken in by plant roots, which transpire the water through their leaves to the atmosphere. Scientists refer to these latter two processes as evapotranspiration.

The way in which soils dry out influences ecology, weather patterns and global resource cycles. Unfortunately, scientists didn't have much large-scale data on soil drydowns until recently, so they relied heavily on numerical simulations.

"Ironically, most models do not use soil moisture data, although the soil moisture is a central component to hydrological behavior," said lead author Ryoko Araki, a joint doctoral student at UCSB and SDSU. This data has been hard to collect and difficult to incorporate into models, so scientists tend to rely on precipitation or river flow rates instead.

The classic models assume that all plants reduce transpiration at the same rate, and at similar timings. "All plants — no matter young or old, summer or winter, tree or grass, small or large," Araki said.

This makes analysis and experimentation easier, but neglects plant behavior, a large part of what drives the process. Including the interplay between plants and the soil should improve the model's accuracy and predictive power, the authors concluded. They also reasoned that, if excluding plant behavior led to a linear model, then a non-linear model might help them investigate these water-use strategies.

Building a new model

Araki started with a linear model of evapotranspiration based on time and soil moisture. She then introduced a nonlinear variable to account for how plants change their water use in response to soil moisture itself.

Unlike scientists in decades past, Araki and her co-authors have access to a wealth of data, which they used to validate the new model with soil moisture measurements. They tapped NASA's SMAP satellite, which uses microwaves to measure average soil moisture across the Earth's surface.

The authors found that the nonlinear approach fit the satellite data far better than either of the two leading linear models. They also discovered that linear models tend to overestimate evapotranspiration rates, predicting that soils will dry out much faster than they actually do. A more accurate account of this process is a big deal in a state with perennial water worries.

According to Araki, some colleagues have criticized the nonlinear model as needlessly complex. While its predictions may be more accurate, they say, the additional parameter makes it more difficult to apply.

Araki acknowledges this, but counters that the results justify that tradeoff. “Even though the nonlinear model is more complicated, it fits the data better, and it captures more of the system’s behaviors,” she said. What’s more, it provides a way to investigate plant adaptations.

Peering at a plant’s playbook

It’s difficult to measure how plants manage their water uptake in response to environmental conditions. “Do they keep growing as much as they can while they still have some amount of water, or do they just completely stop transpiring to prevent tissue damage?” said co-author Bryn Morgan, a former UCSB doctoral student who is now a postdoctoral fellow at MIT.

A preliminary investigation revealed that different vegetation types adopt a range of strategies. Grasslands tended to show very little response to soil moisture, on average; they grew fast and crashed hard, maintaining high productivity until water was gone. In contrast, wooded areas took a more measured approach to water use.

Plants’ behaviors often reflect their life histories. Annual grasses set seed and then die after the ground dries up, while perennial grasses can go dormant once conditions aren’t optimal. Since grasses aren’t playing the long game, an aggressive strategy can pay off. In contrast, trees need to survive for decades to reproduce. “Trees monitor their water potential, which is analogous to their blood pressure,” Morgan said. “Some species are more aggressive like grasses, but many will reduce photosynthesis to prevent a ‘blood pressure drop.’”

“This research provides us with a much more nuanced ‘personality profile’ for how different ecosystems respond to water stress, transitioning from crude generalizations to sophisticated behavioral predictions,” Caylor said. The team will explore these dynamics further in an upcoming paper.

Soil moisture loss is a critical component of many models of larger Earth systems, such as precipitation feedback, carbon cycle, and solar energy partitioning. In fact, it’s one of the largest sources of uncertainty in our estimates of the carbon cycle, Morgan explained.

While it may be simpler, a linear model of soil drydown overlooks the dynamic relationship between plants and soil moisture. “It’s really important to have that interaction, because that’s going to propagate into other components in larger models,” Araki said.

This, in turn, will help us manage resources, forecast climate conditions and prepare for disasters. Farmers can better understand which crops will thrive under changing rainfall patterns. Water managers can incorporate more nuances on how different landscapes affect water availability. And conservationists can predict which ecosystems are most vulnerable to drought.

These findings will help us fine tune our conservation and adaptation strategies to specific challenges, much like trees and grasses adopt the water-use strategy that best fits their needs and limitations.

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