When is a soil too dry for plants to take up water?

As soil dries, plants limit water loss by closing tiny apertures called stomata in their leaves. A global analysis reveals that the soil water-content values at which this stomatal control starts depend on the hydraulic properties of the soil, and that plants' ability to adapt to drought are specific to soil texture.

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The question

Water evaporates from plant leaves through minuscule holes called stomata. At a global scale, this process — called transpiration — is a key component of the terrestrial water cycle. When soil is moist enough, transpiration is controlled by net radiation. By contrast, below a critical threshold in soil moisture, soil water content limits the transpiration rate. Stomata close at this threshold, thereby also reducing plant growth and photosynthesis. Understanding the conditions under which soil water limits plant transpiration is key to predicting the impacts of climate change on terrestrial ecosystems.

The main factors responsible for water limitation are debated, with some studies pointing to atmospheric dryness[1], and others emphasizing soil dryness[2]. Soil–plant–atmosphere models can help to resolve this question, but only if their hydraulic parameters are identified. Yet, the precise origin of water limitation in the soil–plant–atmosphere continuum is still unclear. This is particularly the case at the ecosystem scale, at which hydraulic properties are not well understood. The 'bottleneck' could occur in the plant's leaves, in xylem vessels or roots or in the soil. Moreover, it is not clear whether models of single plants, which are typically tested in laboratory conditions, are representative at the ecosystem scale.

The observation

We combined ecosystem gas-exchange data[3] and sap-flow measurements in trees[4] with principles of soil–plant hydraulics[5], to explain global means and variation in observed soil-water thresholds in terms of hydraulic properties specific to soils with different textures (Fig. 1). We show that soil-texture classes defined by particle-size distribution (distinguishing coarse-textured, sandy soils from fine-textured, clay-like soils) consistently determine the relative importance of atmospheric drying versus soil drying in reducing transpiration. These soil-texture categories also determine the location of the hydraulic bottleneck on the soil–plant continuum.

Our analysis reveals that soil texture plays a crucial, yet overlooked, part in regulating the flow of water to a plant's root, and in the transition of an ecosystem's transpiration to being limited by water rather than by net radiation. Our results indicate that ecosystems on sandy soils are more sensitive to soil drying, whereas those on fine-textured soils (such as clay) are more sensitive to atmospheric drying. Similarly, soil texture controls the hydraulic bottleneck, such that ecosystems on sandy soils are more constrained by soil hydraulics than are those on fine-textured soils. Consequently, plants in sandy soils have fewer opportunities to adapt to water limitations. We posit that the ability of soils to supply water to roots underlies the sensitivity of ecosystems to soil texture, because loss of hydraulic conductance of water through the soil triggers stomatal closure. The spatial scale of water flow to roots is in centimetres, regardless of the scale of observation. Therefore, a model based on a single plant, and on soil properties obtained in small, centimetre-scale samples, yielded accurate results at the ecosystem scale.

Future directions

By demonstrating the role of soil hydraulic properties in ecosystem transpiration fluxes, our study reconciles long-standing principles of plant–water relations with debates about the drivers of water limitation in terrestrial ecosystems. Our work also helps to predict the effects of climate change on evapotranspiration. Soil hydraulic properties mostly determine whether an ecosystem is more sensitive to soil drying or to atmospheric drying, and whether water limitations arise in the soil or in the plant. This could help, for example, to find better-targeted solutions for breeding drought-tolerant crops or to predict tree-mortality risks more accurately.

An obvious limitation is that information on soil hydraulic properties is scarce, and we had to use what are known as pedotransfer functions to estimate these properties from more easily available but indirect information, such as soil texture. However, plants and soil microorganisms modify soil properties in complex, dynamic ways. We therefore advocate more measurements of soil hydraulic properties and more awareness of site-specific soil properties. A follow-up question concerns how plants modify and interact with the soil hydraulic properties — for example, by adapting their root distribution.

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EXPERT OPINION

"This study explores a factor that is seldom considered in analyses of spatial differences in the sensitivity of different sites to water stress — the role of soil texture. The findings add an interesting dimension to discussions on the impacts of drought stress on vegetation productivity, growth and vulnerability." (CC BY 4.0)

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FIGURE

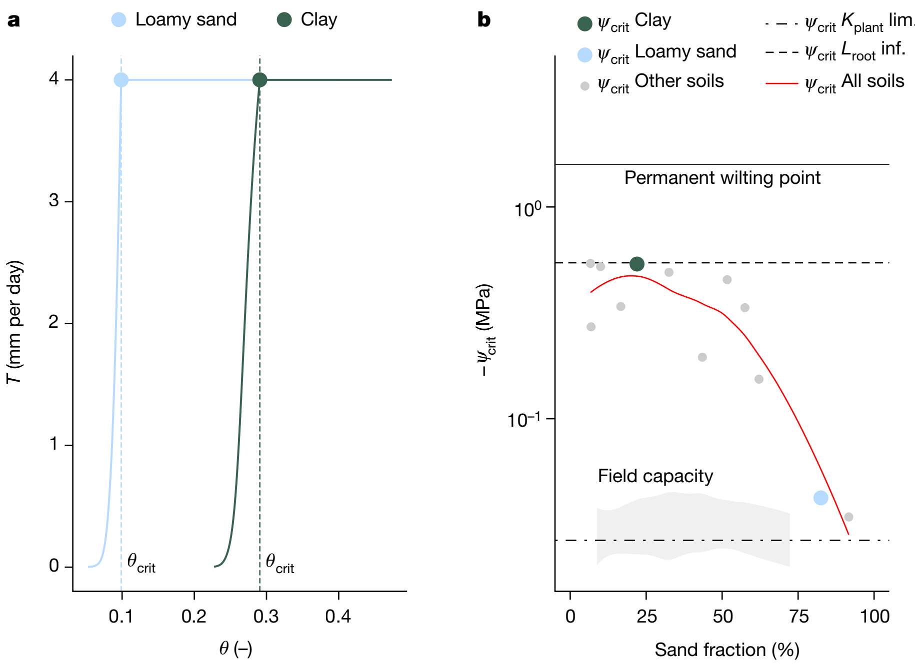

Figure 1 | Soil-water thresholds of transpiration limitation depend on soil texture. a, At a critical threshold of soil moisture (θ_{crit}), plants reduce transpiration (T). These thresholds depend on soil texture. **b**, The more negative the soil water potential (Ψ), the more difficult it is for plants to absorb water. A data-based simulation shows that, in soils with high sand content, plants stop transpiring at relatively high soil-water content (Ψ_{crit}), owing to the limited ability of these soils to conduct water. In soils with low sand content (for example, clay) plants can fully transpire to soil moistures close to the wilting point. The dependency of Ψ_{crit} on soil texture would not be visible if plants had a limiting hydraulic conductance (K_{plant}), in which case stomata would close when the soils were at their maximal water-holding field capacity, or if plants had infinitely long roots (L_{root} inf). Mpa, megapascals. Wankmüller, F. J. P. *et al./Nature* (CC BY 4.0).

REFERENCES

1. Novick, K. A. *et al. Nature Clim. Change* **6**, 1023–1027 (2016).
2. Liu, L. *et al. Nature Commun.* **11**, 4892 (2020).
3. Fu, Z. *et al. Glob. Change Biol.* **28**, 2111–2123 (2022).
4. Poyatos, R. *et al. Earth Syst. Sci. Data* **13**, 2607–2649 (2021).
5. Carminati, A. & Javaux, M. *Trends Plant Sci.* **25**, 868–880 (2020).

BEHIND THE PAPER

This work all started almost by chance, when we derived the hypothetical relationships between transpiration, leaf status and soil-water status. In some ways, the picture that has emerged reconciles perspectives that hold that water limitation is soil-based or plant-based. It also enabled us to predict a number of plants' responses to water limitations; in the meantime, those data became available globally. When our colleague Fabian Wankmüller, with the help of co-authors Louis Delval and Martin Baur, found that the observations matched the expected behaviour well, we really understood the impact of our concept. We acknowledge the monitoring networks FLUXNET and SAPFLUXNET for collecting many high-quality data and making them available to the community.

A.C. and **M.J.**

FROM THE EDITOR

This analysis stands out, not only because it tackles the fundamental and pressing issue of resolving the controls of water limitation for terrestrial plants under global change, but also because it rigorously combines model simulations, field data and global projections to reveal the key role of soil properties in mediating these processes.

Editorial team, *Nature*