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Is apparent optimum soil moisture equivalent to field capacity?

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Ying Zhao[1], Qiuli Hu[1], Lizhu Suo[1], Yi Wang[1] & Allen Hunt[2]

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Ecosystem gross primary productivity (GPP) is strongly influenced by soil moisture (SM), yet the exact SM–GPP relationship remains controversial. Peng et al.[1] reported that the apparent optimum soil moisture $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$—the moisture level where GPP peaks—varies widely among sites, with drier ecosystems showing lower $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$, which they interpret as photosynthetic acclimation. At first glance, $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ appears to align with the critical soil moisture threshold (θ_{crit}) that marks the onset of water limitation[2,3], as both indicate the moisture level at which GPP peaks and subsequent changes trigger stress—oxygen stress in overly wet conditions and water stress in excessively dry conditions. However, exceeding $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ likely indicates excessive moisture (and potential oxygen stress), whereas θ_{crit} signals the onset of water-deficit stress (Fig. 1a). Thus, if these two concepts are valid but distinct, using the concave quadratic model of Peng et al.[1] may oversimplify the GPP response by failing to capture a plateau of optimal moisture levels (Fig. 1a; the "constant rate" phase).

Peng et al.[1] derive $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ by fitting a concave quadratic curve to the GPP–SM relationship, thereby forcing a single, symmetric peak. In reality, plant productivity responses are rarely strictly unimodal—GPP and crop water uptake may rise under dry conditions, then plateau over a broad optimum, and only decline when soils become overly wet[4]. A more flexible model (e.g., piecewise or sigmoid) would better capture this complexity[5]. Our reanalysis reveals that $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ approximately equals to θ at field capacity (FC; θ_{FC}) (defined at water potential of ~ -330 hPa) at each site, and this relationship explains almost all the site-to-site variation ($r^2 \approx 0.98$, $p < 0.01$; Fig. 2). To obtain this result, we analyzed site-level data from flux networks: for each site, we took the reported $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ from Peng et al.[1] and estimated the site's θ_{FC} based on the local soil water retention curve (Table S1). We also find that θ_{crit} is about 67% of $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ (Fig. 1b), placing the typical growing-season soil moisture ($\mathrm{SM}_{\mathrm{growth}}$) between the wilting point and θ_{crit}. Thus, $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ (equivalent to θ_{FC}, field capacity) and θ_{crit} together define the end-points of readily available water (the classic range θ_{FC}–θ_{crit}), consistent with the constant-rate phase depicted in Fig. 1a. In this regard, $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ reflects well-established soil physical properties and highlights a significant interaction between soil moisture conditions and plant responses, potentially suggesting plant acclimation to soil water availability[6].

Peng et al.[1] reported a strong correlation between $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ and $\mathrm{SM}_{\mathrm{growth}}$, suggesting ecosystem acclimation to local moisture. However, because $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ is confined to a site's inherent moisture range, it may simply reflect environmental constraints rather than active acclimation, as ecosystems operate within local hydrological limits[7]. In arid regions, where high soil moisture is rarely observed, the apparent optimum is naturally lower than in humid areas[2]. In such cases, the concave quadratic model effectively reduces to a one-sided response (GPP rises with moisture and then flattens out), since there are no data demonstrating a decline at high SM. Thus, further evidence—such as long-term monitoring or experimental shifts in the optimum—is needed to substantiate true acclimation claims. Likewise, the claim of Peng et al.[1] that reduced $\mathrm{SM}_{\mathrm{growth}}$ lowers $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ by increasing belowground biomass allocation is intriguing but warrants further investigation—especially in a cold grassland context at 3500 m elevation (e.g., energy-limited ecosystem), where antecedent soil moisture changes or rising soil temperature (due to warming) may drive root plasticity rather than a genetically fixed adaptation[3].

Moreover, the study by Peng et al.[1] overlooks the role of vegetation composition and plant traits. Ecosystems are shaped not only by soil moisture availability but also by plant hydraulic traits; for example, drought-tolerant species sustain GPP at lower moisture levels, while moisture-loving species require higher water availability to maximize GPP[6]. Peng et al.[1] primarily attribute variability in $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ to local climate (water availability), yet species composition and long-term ecological filtering likely play a role—arid regions may achieve a lower $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ simply because only drought-tolerant species persist there[8]. Without distinguishing plant-specific physiological responses from environmental constraints, attributing shifts in $\mathrm{SM}_{\mathrm{opt}}^{\mathrm{GPP}}$ solely to acclimation is challenging[9]. Ultimately, as vegetation and soil co-evolve under specific climates, analyses should consider the variability in plant hydraulic strategies. It is also notable that plants often perform

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[1]College of Hydraulic and Civil Engineering, Ludong University, Yantai, Shandong, China. [2]Wright State University, Dayton, OH, USA.
e-mail: yzhaosoils@gmail.com

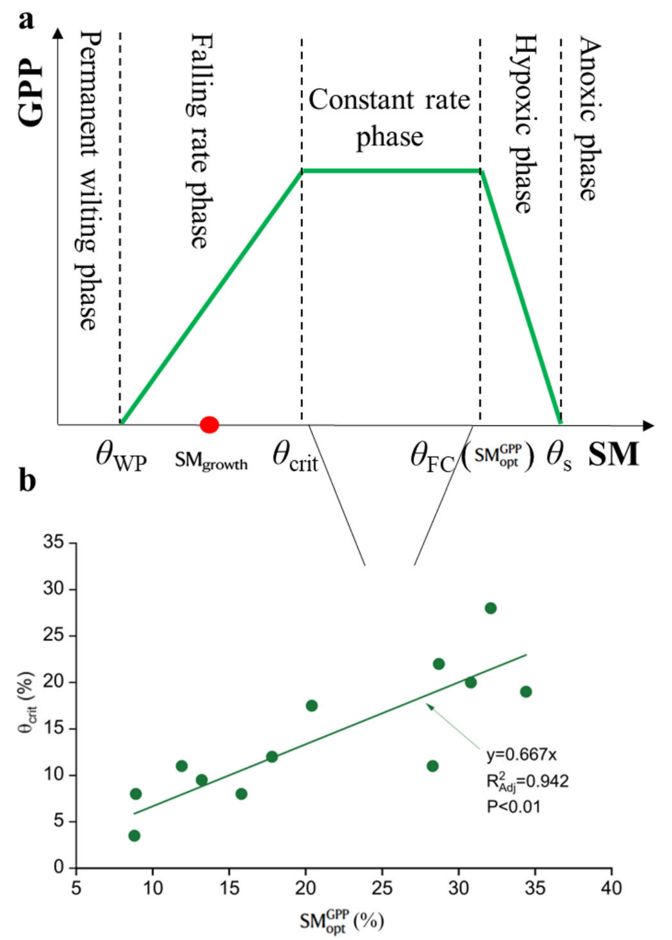

Fig. 1 | Soil moisture limits and optimum ranges for plant productivity. **a** Conceptual figure for gross primary productivity (GPP) as a function of soil moisture θ. This shows an increase, broad optimum (plateau at maximum GPP), and decline at very high moisture (adapted from de Melo et al.[4]). **b** Empirical relationship between SM_{opt}^{GPP} and θ_{crit}. On average, θ_{crit} is about 67% of SM_{opt}^{GPP} (horizontal dotted line). SM_{opt}^{GPP} is the apparent optimum soil moisture, θ_{wp} is plant wilting point, SM_{growth} is growing season soil moisture, θ_{crit} is critical soil moisture threshold, θ_{FC} is field capacity, and θ_S is saturated water content.

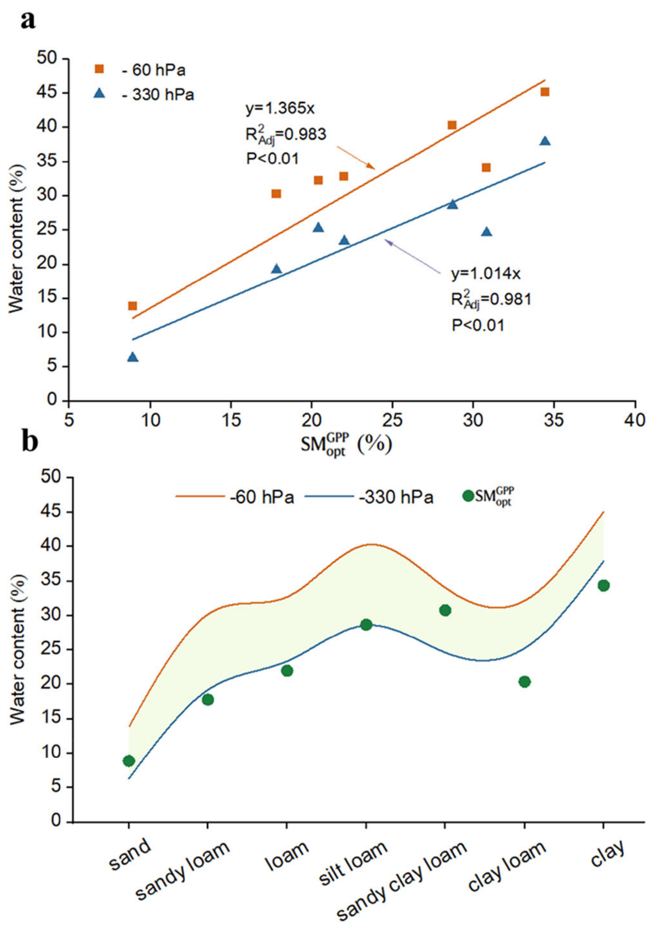

Fig. 2 | Apparent optimum soil moisture vs. field capacity (−60 and −330 ha, respectively) across global sites. **a** SM_{opt}^{GPP} plotted against the soil water content at field capacity (FC) for each site (with FC estimated at a matric potential between −60 and −330 hPa depending on soil texture). The regression value of about 1 between SM_{opt}^{GPP} and θ_{FC} at −330 hPa may indicate that θ_{FC} is better to be defined at −330 hPa in terms of plant–soil water relations. **b** Distribution of SM_{opt}^{GPP} for sites grouped by soil textural classes (sand, loam, clay, etc.). Mean SM_{opt}^{GPP} values align with typical water-retention characteristics of those soils, reinforcing that soil properties govern the optimal moisture for gross primary productivity (GPP).

optimally across a broad range of moisture levels; if they truly maximized function only at a very specific θ level, year-to-year fluctuations in climate would cause much larger variability in productivity. While Peng et al.[1] explore optimality principles on a global scale, further investigation into the mechanistic drivers of SM_{opt}^{GPP} is needed to enhance ecohydrological optimality theories[7].

These issues have significant implications for Earth system models. Many models use simplified soil moisture stress functions that fail to distinguish between the optimal moisture range (linked to θ_{FC}) and the thresholds that trigger stress. Treating SM_{opt}^{GPP} as a single sharp peak (as in a quadratic curve) oversimplifies complex soil–plant interactions. Process-based models should instead differentiate between optimal moisture conditions and stress thresholds to improve predictions of GPP and reduce uncertainties in carbon–climate feedbacks[10]. Our proposed empirical β-function, which more flexibly accounts for water-deficit stress vs. water-excess stress on GPP, can be easily integrated into current models (Eq. (1); see parameters in Fig. 1). This function allows for a plateau at high GPP and distinct slopes for dry and wet declines, potentially offering a better fit to observations than a symmetric quadratic. We present this as a concept to stimulate further research; future collaborative efforts could explore such functions in global datasets, combining the strengths of both approaches.

$$\beta = \begin{cases} 0, & \theta \le \theta_{WP} \\ \frac{\theta-\theta_{WP}}{\theta_{crit}-\theta_{WP}}, & \theta_{WP} \le \theta \le \theta_{crit} \\ 1, & \theta_{crit} \le \theta \le \theta_{FC} \\ \frac{\theta_S-\theta}{\theta_S-\theta_{FC}}, & \theta_{FC} \le \theta \le \theta_S \end{cases} \tag{1}$$

In summary, while Peng et al.[1] offer valuable global insights into the GPP–SM relationship, our reanalysis indicates that SM_{opt}^{GPP} essentially reflects θ_{FC}. The key concern is distinguishing SM_{opt}^{GPP} from θ_{crit}—their difference representing the range of readily available water—since a concave quadratic model may inaccurately collapse a broad optimum into a singular point. Rather than signaling a novel acclimation process, SM_{opt}^{GPP} appears to emerge largely from inherent soil water retention properties combined with long-term ecological sorting of plant traits. Future studies should adopt more flexible models and incorporate plant hydraulic diversity and, where possible, account for root plasticity. By refining model structures (e.g., using functions like β) and carefully decoupling environmental constraints from true physiological acclimation, we can better understand and predict how ecosystems will respond to changing soil moisture regimes under climate change.

Data availability

The data used to reproduce the figures are detailed in the Supplementary Information.

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Author contributions

Y.Z. and Q.L.H. analyzed the data. Y.Z. wrote an initial draft, which was improved through further discussion and editing by Q.L.H., L.Z.S., Y.W., and A.H.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Ying Zhao.

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