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A threshold precipitation function determines when ecosystem respiration depends on water

Terrestrial ecosystem respiration converts organic carbon into CO_2 and increases as temperature increases, which causes a positive feedback loop that could accelerate global warming. We identify a threshold precipitation function that determines when ecosystem respiration is temperature-limited or water-limited, which helps to reduce uncertainties in climate change projections.

This is a summary of:
Zhang, Q. et al. Water limitation regulates positive feedback of increased ecosystem respiration. *Nat. Ecol. Evol.* https://doi.org/10.1038/s41559-024-02501-w (2024).

Published online: 14 August 2024

The problem

Terrestrial ecosystem respiration (R_e), a crucial process in which organisms convert organic carbon into CO_2, represents a considerable source of carbon flux. As R_e is known to increase exponentially with temperature, this process poses a problem in the context of global warming. Vast amounts of organic carbon are stored in high-latitude regions, which act similarly to natural refrigerators owing to their cold climate. With rising global temperatures, this stored carbon is at risk of being released by R_e as CO_2, and creating a positive feedback loop that accelerates warming[1]. However, water availability can modulate the temperature sensitivity of R_e. For instance, a very dry piece of bread does not require refrigeration to remain preserved, which illustrates that dry conditions can render R_e less sensitive to temperature changes. Importantly, the effects of water availability on R_e are currently not well defined and this uncertainty could reduce the accuracy of climate change projections.

The solution

Precipitation can be used as a proxy for water availability in an ecosystem. We used statistical models to disentangle the effects of temperature and precipitation on R_e using the FLUXNET2015 database – a global ecosystem-scale resource of CO_2, water and energy exchange between the biosphere and the atmosphere, captured as eddy-covariance CO_2 flux observations. By applying a normal mixture regression model, we categorized 212 eddy-covariance sites into temperature-limited, precipitation-limited, or both temperature-limited and precipitation-limited, on the basis of residual indices from regression analyses. We then identified an empirical threshold precipitation function that separates temperature-limited from precipitation-limited R_e. This function was further supported by Budyko's dryness index (DI) (ref. 2), which states that DI < 1 indicates wet (energy-limited) conditions and DI > 1 indicates dry (water-limited) conditions (Fig. 1a). We hypothesized and confirmed that the transition between temperature and water limitation occurs at DI = 1, which provides a theoretical basis for the empirical threshold.

Thus, the effects of temperature and precipitation on R_e can be distinguished using a threshold precipitation function. This function (based on the DI) reveals that, above a certain threshold precipitation, R_e is sensitive to temperature; below this threshold, R_e becomes water-limited (Fig. 1b). Analysis of FLUXNET2015 data shows that in wet conditions (DI < 1), the temperature sensitivity (Q_{10}) of R_e decreases linearly with increasing dryness. In dry conditions (DI > 1), Q_{10} remains low and constant, which indicates that water limitation reduces the Q_{10} of R_e. This reduced sensitivity is due to lower substrate supply to soil microorganisms and decreased carbon flux exchange between soil or canopy and the atmosphere under dry conditions[3].

The implications

The implications of our findings extend to a broader understanding of global carbon cycling and climate change projections. Our research demonstrates that water availability, rather than temperature alone, notably regulates R_e (ref. 4). This insight implies that as arid regions expand owing to global warming, the positive feedback loop of R_e to climate change may be mitigated. Furthermore, our results highlight a critical gap in current Earth system models (a type of climate model), which often fail to account for the reduced temperature sensitivity of R_e under dry conditions. Incorporating the threshold precipitation function into these models could enhance their accuracy in predicting future climate scenarios.

Our results and conclusions are inherently limited to longer timescales, such as decades, and large spatial scales from regional to global, including biome-scale applications. They cannot be applied to seasonal or shorter timescales because the threshold precipitation function is based on Budyko's climatological framework, which assumes steady-state conditions. This framework does not account for transient states, dynamic changes or human activities, and simplifies the complex interactions within the water cycle, which potentially overlooks finer-scale processes and short-term fluctuations.

The next steps include investigating why ecosystem respiration is less sensitive to temperature under dry conditions than wet conditions. We plan to explore this observation using enzyme kinetics to understand the underlying biochemical mechanisms. This future research will be challenging but crucial for refining climate models and predictions.

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EXPERT OPINION

"This manuscript provides a compelling analysis of the interacting influences of temperature and precipitation on ecosystem respiration at a global scale. The approach combines a solid theoretical framework that is well supported by empirical evidence, and mechanistic explanations that connect enzyme kinetics with potential feedbacks to climate change." **Elise Pendall, Western Sydney University, Sydney, New South Wales, Australia.**

FIGURE

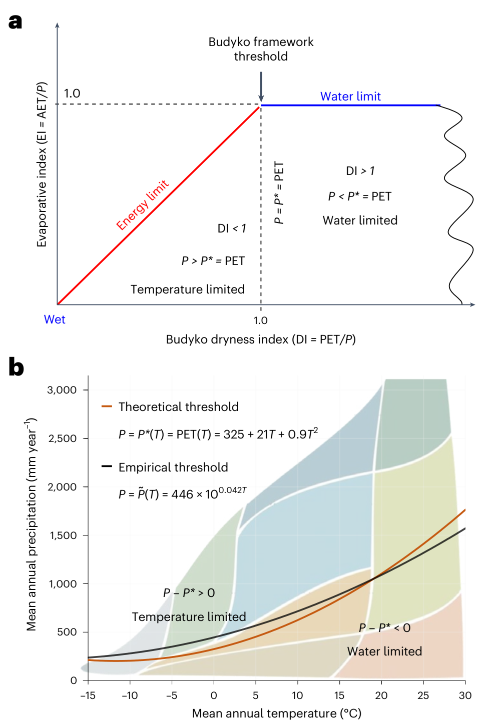

Fig. 1 | A threshold function for temperature-limited and precipitation-limited R_e. a, A hypothesized comparative threshold precipitation function $P \times (T) = \mathrm{PET}(T)$ determined from the Budyko dryness condition, DI = 1. **b**, The Budyko theoretical threshold and empirical threshold. The empirical results from FLUXNET data analysis were linked to the Budyko framework by assuming that Budyko dryness DI = 1 provides the condition to determine a threshold relationship between precipitation (*P*) and temperature (*T*). Thus, the space (*T*, *P*) is divided by the threshold curve into two regions – one in which R_e is dominated by temperature and one where it is dominated by precipitation. AET, actual evapotranspiration; PET, potential evapotranspiration. The different colours represent different ecosystem types. © 2024, Zhang, Q. et al.

BEHIND THE PAPER

Our research journey began on 5 March 2021, when Q.Z., a visiting PhD student, presented the research published in ref. 5. The key turning point came when I noticed a breaking point in the relationship between ecosystem respiration and temperature in the presented data, which suggest it was influenced by water conditions and encouraged Q.Z. to investigate this further using dryness data.

Our initial drafts faced an uphill struggle of multiple rejections from leading journals, owing to concerns about the theoretical framework and clarity. A breakthrough came in August 2022, when we incorporated calculations of Q_{10}, activation energy and leaf area index (a proxy for substrate availability) linked to the Michaelis–Menten equation. After further rejections, we submitted to *Nature Ecology & Evolution* and our paper was accepted after a few rounds of revisions.

Interdisciplinary collaborations among climatologists, ecologists and data scientists were crucial. This journey embodies 屡败屡战 (persevering despite repeated failures). **C.Y. & Q.Z.**

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FROM THE EDITOR

"It is likely that there would be a threshold between temperature and precipitation dependence of ecosystem respiration, but this study identifies and demonstrates this at a large scale and probes the mechanistic basis of the threshold." **Editorial Team, *Nature Ecology & Evolution*.**