

COMMENTARY

Multifactorial effects matter: Moving thermal adaptation into a real-world setting

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Climate change has begun to modify our planet in ways that are not fully understood. Limiting warming to 1.5°C requires global greenhouse gas emissions to peak before 2025 and be reduced by 43% by 2030, as invoked in the 6th Report by the Intergovernmental Panel on Climate Change (IPCC, 2022). To mitigate changing climate and, specifically, to reduce atmospheric carbon dioxide (CO₂), soils are considered to play an influential role. As a consequence, quantifying soil respiration over time and understanding the process that regulates CO₂ emissions are fundamental to improving climate models and helping develop management practices and policies.

Our knowledge of how mineralization of soil organic carbon is affected by elevated temperatures and how it shapes ecosystems is still evolving. Positive feedback of climate warming on heterotrophic respiration of organic carbon has been incorporated into soil organic carbon and Earth system models based on the assumption that the observed sensitivity of soil respiration to temperature under today's climate conditions will hold in a warmer world. This suggests that warming-induced increases in CO₂ emission from soils will cause more warming. However, the temperature sensitivity of soil respiration was found to decrease under warming in some field experiments (Conant et al., 2011), a phenomenon sometimes referred to as “thermal acclimation,” and more often as “thermal adaptation” to denote the adjustments of respiration rates of soil microbes decomposing soil organic carbon at elevated temperatures (Bradford et al., 2008). A better understanding of this thermal adaptation of microbial respiration is needed.

In recent years, thermal adaptation has been investigated to a greater extent by considering microbial metabolism and community structure (Chen et al., 2022). Along with the fact that different species of fungi (Crowther & Bradford, 2013) and bacteria (Tian et al., 2022) have their own thermal adaptation capacity and

timescale, we by now understand that microbial thermal adaptability is affected both by community structure and individual physiological adjustments. Notably, recent studies that used a wide range of soils revealed that the potential thermal adaptation of soil microbial respiration may be widespread (Bradford et al., 2019). These insights lay the foundation for incorporating thermal adaptation into regional predictions of feedback from warming on the terrestrial carbon cycle. Although a thermal compensatory response of microbial respiration may diminish the increasing positive feedback of climate warming on soil respiration, limited efforts have been made to understand the magnitude, direction, and constraints of this thermal compensatory response over time, considering that multiple factors affect organic carbon mineralization in soils.

Up to now, thermal compensatory responses of microbial respiration were mostly investigated under optimal moisture environments that may sustain high levels of microbial activity while allowing physiological effects to be detected independent of the influence of other abiotic controls. For the vast majority of published research, a single soil moisture level of 50%–70% of water-holding capacity, rather than a moisture gradient, was used across different studies to study microbial respiration to elevated temperatures (Li et al., 2022). However, climate warming is predicted to reduce soil moisture by decreasing precipitation and enhancing evaporation. Therefore, soil moisture should allow to account for its regulating impact on microbial respiration under a warming world, which is essential for our understanding of feedback between the carbon cycle and climate change. Unfortunately, at the current stage, little information exists about the degree of the adaptation of microbial respiration to warming that goes beyond the temperature itself.

The paper presented in this issue by Li et al. (2022) starts to fill a gap in our understanding about this carbon-cycle–climate feedback by investigating whether and how the thermal compensatory response of microbial respiration is affected by changes in soil

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moisture based on two manipulative experiments. They found suppressed thermal compensatory responses under dry soil conditions. They linked this moisture regulation to shifts in enzymatic activity and carbon use efficiency (CUE), which highlighted the importance of microbial physiology in regulating and predicting the soil carbon response to climate change and its feedback. In addition to microbial physiology, these findings also put a renewed spotlight on how microorganisms access organic matter (Davidson & Janssens, 2006). Moisture not only influences community composition and thereby microbial physiology, but also whether organic matter is accessible, including movement of substrate to the microbe (Barnard et al., 2020). Energy needed to access organic matter changes with, for example, interactions with minerals and CUE of glucose was found to increase with finer soil texture (Islam et al., 2023).

The paper by Li et al. (2022) motivates us to think more broadly about the effects of one environmental condition on the response to another—as shown here for moisture effects on temperature sensitivity of organic carbon mineralization in soils. The persistence of soil organic carbon is not only affected by moisture and temperature, but also by pH, the availability of nutrients, osmotic potential, spatial heterogeneity, and molecular diversity among others (Cotrufo & Lavelle, 2022). The interaction of multiple factors on thermal adaptation of microbial respiration has received surprisingly little attention. If only one factor, moisture, has such profound effects on temperature sensitivity, how much larger may interactions of several more factors be? We already know from recent studies that the effects of multiple factors on microbial community composition and mineralization in soil are profound (Rillig et al., 2019). With an increasing number of

co-occurring factors including moisture, temperature, but also salinity and adding various compounds, soil respiration decreased especially when more than five factors occurred together (Rillig et al., 2019). However, individual interactions remain obscure due to the number of factors, and this provides an enduring research task. If we develop these thoughts further, we can also expect the rate of change, not just the magnitude and duration of change, to be relevant for these interactions. Moisture and temperature can change rapidly or slowly, and so can all the other factors mentioned above.

In sum, experiments of temperature effects that focus on only one factor will not offer sufficient mechanistic understanding because they do not reflect realistic climate change. We have most often studied climate change impacts by isolating various drivers and manipulating them in an ideal state, despite the fact that in reality those drivers can change at the same time and may produce unexpected results due to complex interacting effects. Even though global change experiments that examine multiple interacting global change factors exist, few have been applied to studies on thermal compensatory responses of microbial respiration. A new generation of experiments may be needed that fully explores the interactions between factors that affect temperature sensitivity and other responses of organic carbon mineralization in soils. The current paper is an apt incentive to think more deeply about that. Future research that includes multiple factors is needed for a better representation of the nature of climate change interactions, for a more synthetic understanding of thermal response of microbial respiration, and for more realistic conceptual models that add interpretive strength regarding ecosystem response to global change (Figure 1).

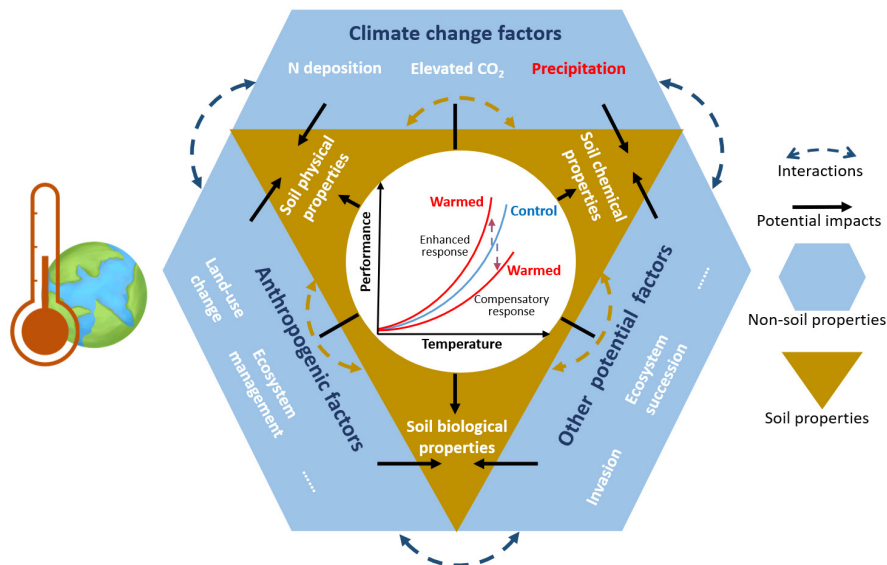


FIGURE 1 Schematic diagram of multiple factors, singly or in combination, affecting the sensitivity of soil organic carbon mineralization in a warmer world. Within the center white circle, different scenarios of how increasing temperature affects microbial performance illustrates compensating or enhancing thermal response. The outermost blue hexagon denotes three main categories of non-soil properties, which include climate change, anthropogenic, and other factors. The middle brown triangle denotes three main categories of soil properties, which include physical, chemical, and biological properties. Dotted lines with two-way arrows depict interactions. Solid arrows depict potential impacts. Specific to Li et al.'s study (2022), thermal adaptation of microbial respiration was found to shift to an enhanced response (as depicted by upward arrow) with decreased moisture content.

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CONFLICT OF INTEREST

The authors declare no conflict of interests in preparation of this manuscript.

DATA AVAILABILITY STATEMENT

No data were used for this commentary.

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