Cold and humid climates enrich soil carbon stock in the Third Pole grasslands

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As a unique geographic unit, the Third Pole is globally recognized as the largest and highest mountainous region. Enormous amounts of soil organic carbon (SOC) are stored in this region, whose top layer is active in biochemical processes and highly sensitive to environmental changes. The warming intensity in the Third Pole has been predicted to be at least 0.3°C higher than the global average by the end of the 21st century.[1] Therefore, it is essential to understand the underlying mechanisms, especially the hydrothermal factors, controlling the top layer SOC in the Third Pole. This may help to predict the dynamics of soil carbon stock in future climate scenarios.

However, mechanisms underlying the formation and maintenance of SOC remain poorly understood. The SOC density is affected by some processes, including the C input obtained predominantly from plants and the C release

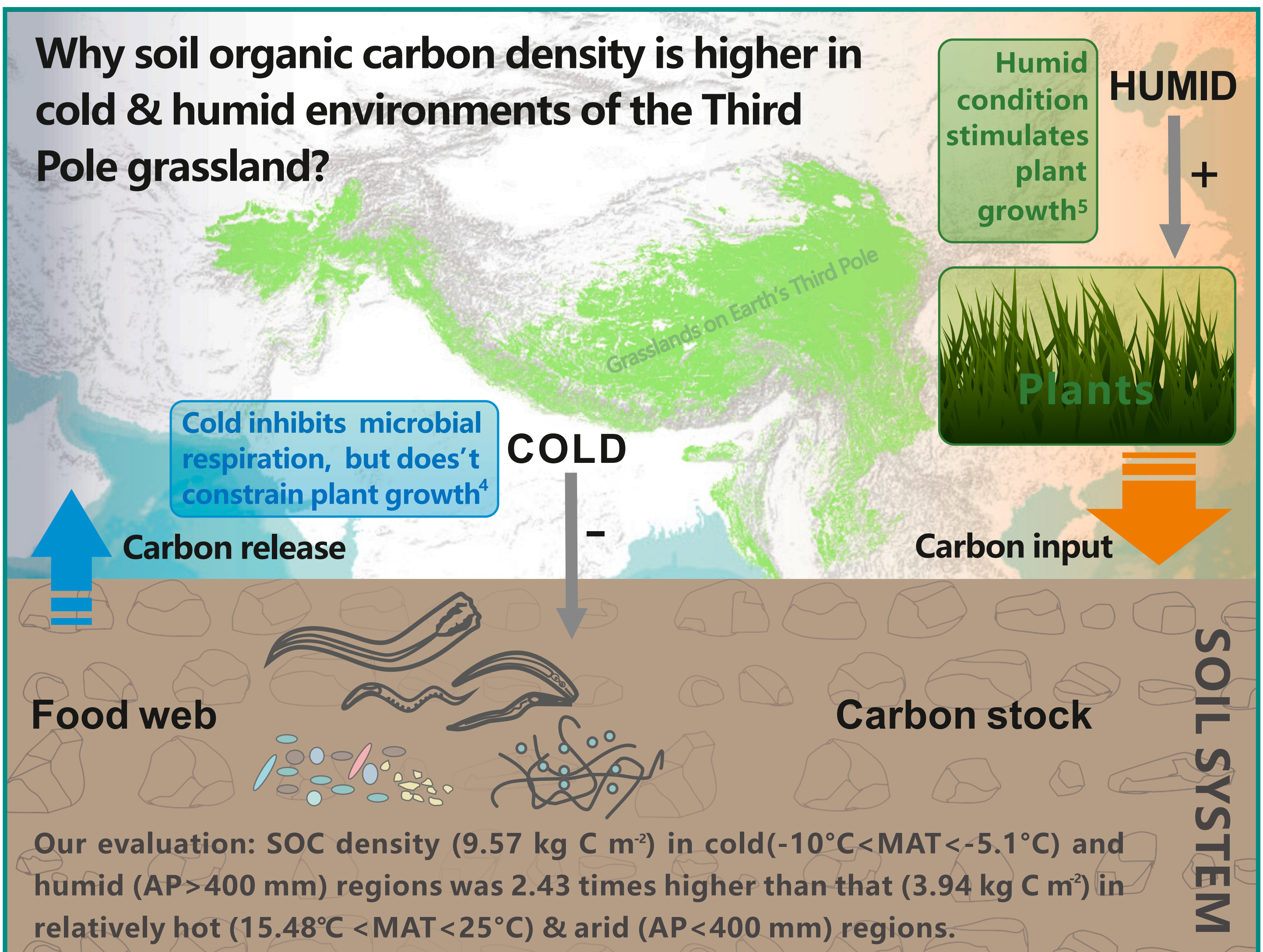

Figure 1. Conceptual figure of the effects of hydrothermal factors on soil organic carbon (SOC) stocks in the Third Pole grasslands "+" and "–" represent the stimulation and inhibition effects of the climate on ecological processes. MAT: mean annual temperature; AP: annual precipitation.

mainly from respiratory processes by microorganisms. These processes interact with each other and with environmental factors, such as the climate. The influence of environmental factors on the various processes that determine SOC density is generally complex and even contrary. For example, a temperature increase could facilitate microbial decomposition and generally increase C release, whereas positive effects of a temperature increase on plant C input can also be observed. Thus, their net effect on SOC density is unclear, and it includes positive (increasing), negative (decreasing), and unchanged[2,3] effects of warming and wetting.

Recently, we observed that higher levels of annual accumulated precipitation (>400 mm) increased the normalized difference vegetation index (NDVI) in the Third Pole grasslands. In comparison, the lower temperature did not restrain the NDVI, which was distributed evenly across different temperature zones. Our findings demonstrated that the lower temperature did not inhibit plant growth, while the higher precipitation stimulated plant growth in the Third Pole grasslands (Figure 1). Some grassland studies within the climate ranges of our study area support the notion that the lower temperature inhibits microbial respiration but does not decrease vegetation productivity.[4] Additionally, the higher precipitation was reported to lead to the higher NDVI of these grasslands.[5]

These observations of the relationship between plant growth and hydrothermal factors provide an important clue for deciphering underlying mechanisms of top SOC density in the Third Pole grasslands. Clearly, the top SOC density was influenced by an equilibrium between the carbon input from vegetation and decomposition by microorganisms. On the Tibetan Plateau, the balance between plant C input and microbial C decomposition was reported to determine the direction of the overall accumulation of upper SOC stock under climate warming.[3] This carbon equilibrium is intricately regulated by the hydrothermal factors derived from the climate, which in turn influence vegetation growth and microbial decomposition.

In this way, we propose that the top SOC density tends to increase from hot and arid to cool and humid areas owing to increased plant carbon input in humid environments, as well as inhibited microbial decomposition at the low temperature that does not simultaneously restrain plant carbon input. Based on the key node identification in a random forest model, we divided the mean annual temperature (MAT) and annual precipitation (AP) into groups according to their effects on SOC density. Our evaluations revealed a notable trend in SOC density, which was higher under cold and humid conditions. In specific cold ($-10^\circ C < MAT < -5.1^\circ C$) and humid ($AP > 400$ mm) areas, the mean SOC density (9.57 kg C m^{-2}) was 2.43 times higher than that (3.94 kg C m^{-2}) in relatively hot ($15.48^\circ C < MAT < 25^\circ C$) and relatively arid ($AP < 400$ mm) areas. Meanwhile, plant C input represented by the NDVI did not change by a large extent in cold ($-10^\circ C < MAT < -5.1^\circ C$) areas and relatively hot ($15.48^\circ C < MAT < 25^\circ C$) areas. Notably, our finding that the low temperature did not inhibit plant growth may only apply to the region we studied. Whether this can be extrapolated to more regions depends on the range of climatic conditions in those specific regions, and further investigation is required to determine its effectiveness. In summary, a cold and humid climate benefits the soil carbon stock in the Third Pole grasslands. This finding may have critical implications in predicting future SOC changes in this region.

However, the effects of these hydrothermal factors may be counteracted by certain mechanisms. Thus, caution must be exercised when using these results for future climate scenarios because the nature of self-adaptation of the soil was not considered. We believe that soil is a complex system with a self-regulating function that can maintain the stability of soil carbon stock to a certain extent by buffering influences of environmental disturbances. Thus, the self-regulating capacity of soil relies on the adaptation or acclimation of biological communities (e.g., plants and microbes) in the soil system to environmental disturbances, including climate change, as well as strong interactions or feedback among these communities. Moreover, the response of herbivorous animals and soil fauna to climate change may also be critical in influencing the grazing pressure on grasslands and soil food web. Thus, the judgment that cooling and wetting may benefit the soil carbon stock in the Third Pole grasslands may be arbitrary for future climate scenarios, as plants and soil food web members of microbes and herbivorous animals may respond and develop adaptations and interact differently under future cooling and wetting scenarios.

To address this issue, in addition to the investigation of the self-adaptation of the soil system in stabilizing SOC, a more accurate regional SOC assessment with lower uncertainties is required to reveal the spatial patterns of SOC in the Third Pole. Although previous studies have investigated SOC density in this region, reliable assessments at the regional scale are limited by high uncertainties. The extracted evaluations of this region from widely adopted global estimations by SoilGrids, SoilGrids 2.0, and the Harmonized World Soil Database (HWSD) suffer from low sample sizes or representatives, especially in high-altitude areas. Inevitably, extrapolating data from low- to high-altitude areas using these products leads to high inaccuracies and uncertainties. Although challenging, a comprehensive and accurate evaluation of the spatial pattern of SOC in the Third Pole is the best way to determine the underlying mechanisms of SOC density and to provide a solid basis for predicting carbon dynamics in future climate scenarios.

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DECLARATION OF INTERESTS

The authors declare no competing interests.