

Article

Effects of Warming on Change Rate of Soil Organic Carbon Content in Forest Soils

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Abstract: Climate warming affects the carbon cycle in terrestrial environments. However, the effects of warming on the change rate of soil organic carbon (SOC) content in forest soils are unclear. Here, we extracted 276 data points from 98 published papers to examine the effects of warming on the change rate of SOC content in the soil mineral profile (0–20 or 0–30 cm), focusing on the regulatory effects of warming magnitude and duration and the humidity index. Warming promoted an increase in SOC content from 67.47 to 69.90 g kg^{−1} in forest soils, with a change rate of SOC content of 0.85 g kg^{−1} yr^{−1} on a global scale. The change rate of SOC content decreased from 1.22 to 0.11 g kg^{−1} yr^{−1} at a warming magnitude of 0–2 and >2 °C, respectively, and it changed from 0.96 to −0.81 to −0.51 g kg^{−1} yr^{−1} at warming durations of 0–5, 5–10, and >10 years, respectively. The change rate of SOC content was higher at a humidity index value of 30–50 than at 0–30 and >50. Although climate warming increases the SOC content, the change rate of SOC content decreases with increased magnitude and duration of warming but increases with an increased humidity index. These findings help elucidate SOC accumulation in the context of climate change.

Keywords: carbon cycle; climate change; forest soils; meta-analysis; warming magnitude; warming duration; humidity index



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1. Introduction

As a consequence of ongoing global climate change, greenhouse effect-associated increases in temperatures are having pronounced effects on carbon cycling in forest soils [1]. As the primary driving factor of climate change, rising temperatures alter the composition and content of soil organic carbon (SOC), which in turn affects the stability of the soil carbon pool [2], the maintenance of which is essential for ensuring global carbon cycle balance and mitigating the adverse effects of greenhouse warming [3]. Consequently, establishing the effects of global warming on SOC accumulation in forest soils on a global scale is essential.

To date, studies that have examined the impacts of warming on forest soils have tended to focus primarily on biotic and abiotic factors, such as plant biomass, soil microbial activity, and soil physicochemical characteristics [4–6]. For example, Xu et al. [7] noted that warming can promote increases in the aboveground biomass and litterfall in forest soils by 33% and 15%, respectively, whereas other studies have indicated that warming can have significant effects on the aggregate structure, pH, and water status of soils [8,9]. Although

Xu et al. [10] have reported that warming is associated with significant increases in the diversity of soil fungi and bacteria, Zhao et al. [11] detected a significant reduction in the alpha diversity of soil microorganisms in response to warming. These contrasting findings highlight the considerable lack of predictability regarding the effects of warming on SOC content. Previous research has also revealed that warming-associated changes in plant growth, soil structure, nutrient content, and microbial activity can have a pronounced effect on SOC content and the stability of the soil carbon pool [12]. To date, however, relatively few studies have assessed the effects of warming on the change rate of SOC content in forest soils on a global scale, which currently limits our understanding of soil carbon cycling in forest soils and the associated regulatory mechanisms.

Given the regional differences in the magnitude and duration of warming, the change rate of SOC content in forest soils has yet to be sufficiently established. In this regard, changes in soil microbial activity can lead to changes in the enzyme activities and physicochemical properties of the soil, thereby affecting the regulation of the decomposition and accumulation of SOC [12]. The magnitude and duration of warming are key factors determining the community structure and biological activity of the soil microbiota [13,14], and the findings of a recent meta-analysis have indicated that an increase in the magnitude of warming is associated with significant reductions in soil microbial diversity and biomass. Similarly, an increase in the duration of warming was found to result in a significant reduction in soil microbial biomass and the activity of soil enzymes associated with carbon cycling [10]. Increased warming can reduce soil moisture to the point of dryness, limiting the growth and reproduction of microorganisms [15]. With prolonged warming, the carbon pool available to soil microorganisms is depleted, microbial biomass and carbon-utilization efficiency decline, and the composition of the microbial community changes, resulting in a loss of soil carbon and, thus, a reduction in the accumulation of SOC [16,17]. Long-term warming also reduces the rate of plant growth, thereby causing negative feedback on the accumulation of SOC [18,19]. However, despite the extensive evidence of the potential effects of climate warming, the mechanisms by which the magnitude and duration of warming affect the change rate of SOC content in forest soils on a global scale have yet to be adequately established.

Global rainfall and temperature patterns affect plant growth, soil moisture, and microbial activity, which in turn have pronounced effects on soil carbon budget processes [20,21]. For example, in arid ecosystems, soil water is the main factor limiting plant and microbial growth, and under such circumstances, the processes associated with the accumulation of SOC are sensitive to changes in rainfall [22]. A combination of reduced rainfall and elevated warming can lead to soil water shortages in these areas, which is not conducive to the accumulation of SOC [23,24]. Conversely, in humid ecosystems, higher rainfall rapidly saturates the soil, and in such areas, warming evaporates excess soil water, thereby enhancing permeability and promoting microbial decomposition and the accumulation of SOC [25,26]. In this regard, values of the humidity index [humidity index = mean annual precipitation/(mean annual temperature + 10)] can be used to evaluate the overall effects of mean annual temperature and precipitation [27] and, thus, assess the effect of climatic factors on SOC accumulation under warming conditions. Accordingly, this provides theoretical support for the accurate estimation of terrestrial ecosystem carbon budgets in the context of climate change.

In this study, based on a meta-analysis, we analyzed the effects of warming magnitude and duration and the humidity index on the change rate of SOC content in forest soils on a global scale. Our hypotheses were as follows:

1. Warming promotes plant growth and changes in soil microbial activity [7,10], thereby increasing SOC content;

2. Warming leads to soil desiccation and reduced microbial activity [15–17]. Consequently, more pronounced increases in the magnitude and duration of warming will reduce the change rate of SOC content;
3. Increases in humidity and soil water content promote the growth and reproduction of soil microorganisms and accelerate soil nutrient cycling [28]. Consequently, higher humidity index values will coincide with increases in the change rate of SOC content under warming conditions.

2. Materials and Methods

2.1. Data Collection

Data were mainly collected from the Web of Science (<http://apps.webofknowledge.com/>, accessed on 10 August 2024), Google Scholar (<http://scholar.google.com/>, accessed on 10 August 2024), and CNKI (<http://www.cnki.net/>, accessed on 10 August 2024) databases. The search was conducted on 10 August 2024, using the search terms listed in Table 1. The criteria for the inclusion of studies were as follows: (1) the study was based on an experimental study design (not a review); (2) the study included a control group (no warming) and treatment group (warming); (3) the research object was a forest soil; (4) the study involved no analysis of interactions between other environmental factors (e.g., nitrogen addition and carbon dioxide concentration); (5) data on the magnitude and duration of warming are available, whether they are directly reported or obtainable by calculation; and (6) if data for only a single soil layer were reported in the original study, we obtained this directly, whereas if data for multiple soil layers were provided, we mainly obtained those pertaining to the surface layer. Most of the data obtained from studies were related to the mineral soil layer (0–20 and 0–30 cm).

Table 1. Search terms used in this study.

Search Terms 1	Search Terms 2
warming or increased temperature or heat or elevated temperature or climate	and soil carbon or soil nutrients or soil properties or soil microbial or soil enzyme or plant production or plant biomass

As a consequence of screening, we obtained 276 data points from 98 papers. SOC data that were reported in tabulated form were retrieved directly, whereas data presented graphically were retrieved using GetData Graph Digitizer 2.24. Data regarding longitude, latitude, mean annual temperature (MAT), and mean annual precipitation (MAP) were also obtained.

2.2. Data Analysis

The percentage change in SOC content and change rate of SOC content were calculated using a previously described approach [29], as shown in the following equations:

$$\text{Percentage of SOC content change (\%)} = \frac{\text{SOC}_t - \text{SOC}_c}{\text{SOC}_c} \times 100, \text{ and} \quad (1)$$

$$\text{Change rate of SOC content} = \frac{\text{SOC}_t - \text{SOC}_c}{\Delta T}, \quad (2)$$

where SOC_t and SOC_c are the SOC content under warming and control conditions, respectively.

Values of the humidity index comprehensively reflect the effects of environmental factors (MAP and MAT) and were calculated using the following equation, as described previously [27]:

$$\text{Humidity index} = \frac{\text{MAP}}{\text{MAT} + 10} \quad (3)$$

To analyze the effects of warming magnitude, warming duration, and humidity index on SOC, we divided these factors into different groups, as shown in Table 2. Differences in the percentage change in SOC content and rate of SOC content change among the different groups of warming magnitude, warming duration, and humidity index were evaluated using a one-way analysis of variance ($p < 0.05$). The correlations of percentage change in SOC content and rate of SOC content change with warming magnitude and duration and humidity index were evaluated based on regression analysis.

Table 2. Groupings defined for warming magnitude, warming duration, and humidity index.

Variable	Grouping
Warming magnitude	0–2 °C, >2 °C
Warming duration	0–5 yr, 5–10 yr, >10 yr
Humidity index	0–30, 30–50, >50

3. Results

3.1. Main Effects of Warming on SOC Content

The distribution of the study sites for which data were obtained is shown in Figure 1, and the distribution and frequency of the percentage change in SOC content and change rate of SOC content are shown in Figure S1. Overall, warming promoted an increase in SOC content from 67.47 to 69.90 g kg^{−1}, with percentage change in SOC content and rate of SOC content change values of 1.08% and 0.85 g kg^{−1} yr^{−1}, respectively (Figure 2a–c).

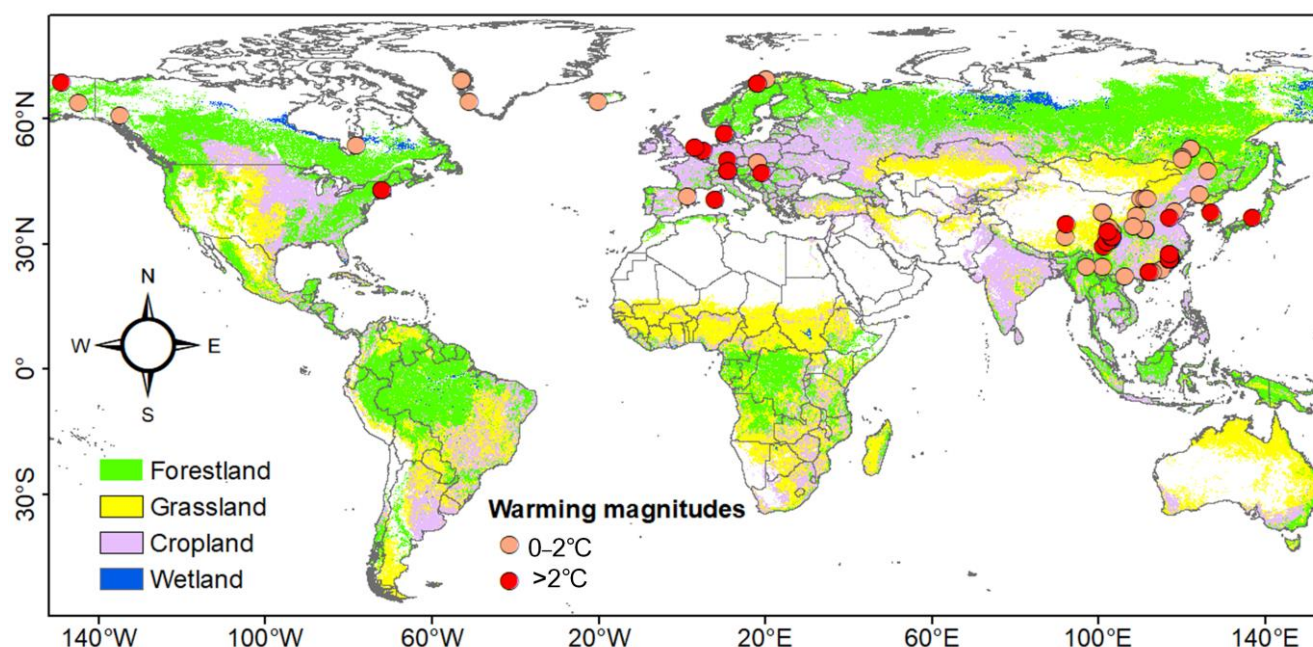


Figure 1. Global distribution of the sites from which the data used in this study were obtained.

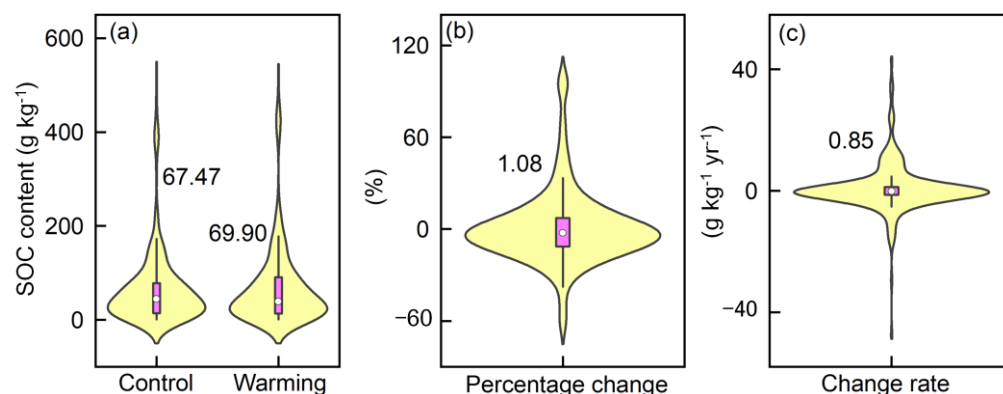


Figure 2. Effects of warming on (a) soil organic carbon (SOC) content and (b) the percentage and (c) rate of SOC content change.

3.2. Effects of Warming Magnitude on SOC Content

The magnitude of warming had a regulatory effect on SOC (Figure 3). With respect to the percentage change in SOC content, we detected a reduction from 1.93% at a warming magnitude of 0–2 °C to 0.29% at >2 °C; the corresponding rates of SOC content change declined from 1.22 g kg⁻¹ yr⁻¹ at 0–2 °C to 0.11 g kg⁻¹ yr⁻¹ at >2 °C (Figure 3a,b). Moreover, the percentage ($p = 0.030$) and rate ($p > 0.05$) of SOC content change were negatively correlated with the magnitude of warming (Figure 3c,d).

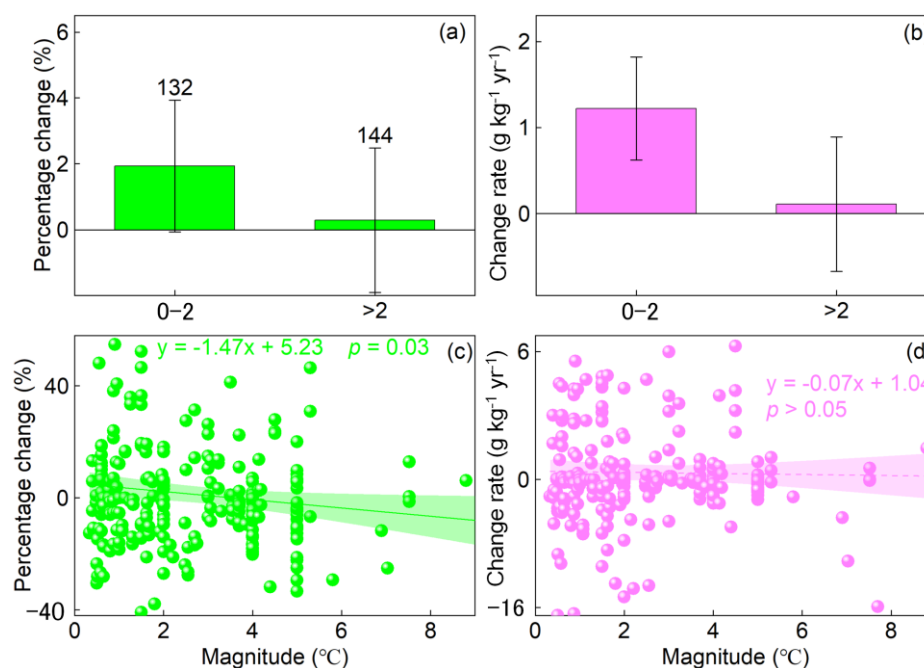


Figure 3. Effects of magnitude of warming on (a) the percentage change in soil organic carbon (SOC), (b) rate of SOC content change, and relationship between (c) percentage and (d) rate of SOC content change and magnitude of warming.

3.3. Effects of Warming Duration on SOC Content

The percentage change in SOC content declined from 2.41% at a warming duration of 0–5 years, to −0.95% at 5–10 years, and then to −11.52% at >10 years, whereas the rate of SOC content change declined from 0.96 g kg⁻¹ yr⁻¹ at 0–5 years, to −0.81 g kg⁻¹ yr⁻¹ at 5–10 years, and then increased to −0.51 g kg⁻¹ yr⁻¹ at >10 years (Figure 4a,b). The percentage ($p = 0.021$) and rate ($p > 0.05$) of SOC content change were negatively correlated with the duration of warming (Figure 4c,d).

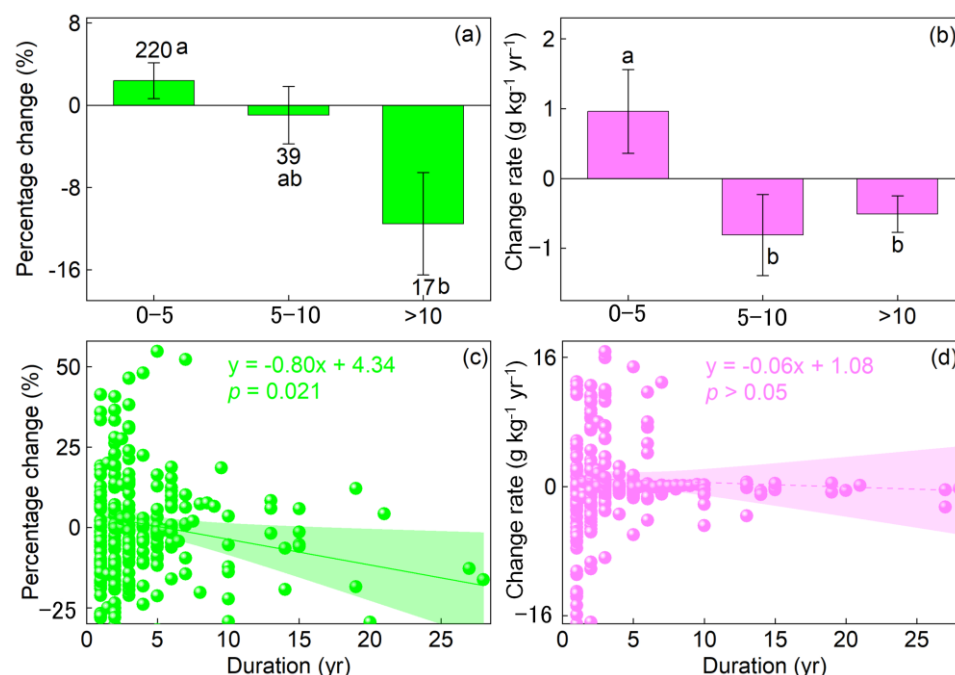


Figure 4. Effects of the duration of warming on (a) percentage change in soil organic carbon (SOC), (b) rate of SOC content change, and the relationship between (c) the percentage and (d) rate of SOC content change and the duration of warming. Note: Different letters indicate significant differences ($p < 0.05$).

3.4. Effects of Humidity on SOC Content

Values obtained for the percentage change in SOC content and rate of SOC content change were higher at humidity values of 30–50 (percentage change = 3.76%; rate of change = 1.54 g kg⁻¹ yr⁻¹) than at values of 0–30 (−1.73%; −0.2 g kg⁻¹ yr⁻¹) and >50 (0.34%; 0.69 g kg⁻¹ yr⁻¹) (Figure 5a,b). Moreover, the percentage ($p > 0.05$) and rate ($p = 0.028$) of SOC content change were positively correlated with humidity index values (Figure 5c,d).

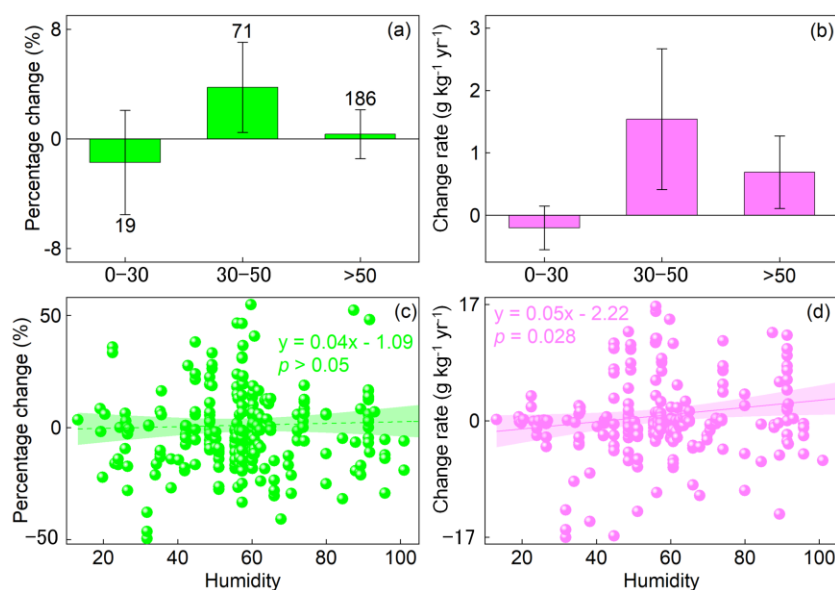


Figure 5. Effects of humidity index on (a) the percentage change in soil organic carbon (SOC), (b) the rate of SOC content change, and the relationship between (c) the percentage and (d) rate of SOC content and humidity index values.

4. Discussion

4.1. Dynamics of SOC Content

Consistent with the findings of a previous study [10], our study revealed that warming increases the SOC content in forest soils (0–20 cm or 0–30 cm) on a global scale. Climate change and warming regulate SOC accumulation mainly by affecting plant growth, microbial activity, and soil respiration [4,30,31].

Warming promotes photosynthesis and plant growth and is accordingly associated with increases in litter content and the rates of root turnover [7,32]. For example, the findings of a recent meta-analysis have indicated that global warming leads to increases of 15.7%, 4.4%, 6.8%, and 7.0% in plant photosynthesis, net primary production, and above- and below-ground plant C pools, respectively [33]. Accordingly, an increase in fresh organic carbon input caused by warming increases the SOC content [34]. By modulating the activity of decomposers, warming also contributes to the regulation of litter decomposition [14,34]. Temperature is an important factor that affects the activities of soil microorganisms and enzymes, which play important roles in the turnover of soil organic matter [35,36]. As warming increases microbial activity [10,37], it will also accelerate litter decomposition and increase SOC content [38]. Additionally, warming may contribute to changes in the plant community structure and, more importantly, increases in vegetation productivity and leaf quality [39], similarly resulting in an increase in SOC content.

4.2. Dynamics of SOC Content as Affected by Warming Magnitude

In contrast to the dynamics we described in Section 4.1, Yan et al. [38] demonstrated that warming decreases SOC content using integrated global-scale data. This discrepancy may be related to differences in the magnitude of warming [10], which may lead to differences in plant communities and microbial activity [40].

Our findings indicated that an increase in the magnitude of warming was associated with a significant reduction in the percentage change in SOC content in the forest soils (0–20 cm or 0–30 cm) on a global scale, with the rate of SOC content changes showing a similar trend of decline, albeit non-significantly (Figures 3 and 6). These findings indicate that although a certain extent of warming can contribute to promoting the rates of SOC content change, excessive warming will attenuate this effect and may even have inhibiting effects. This can be attributed to the fact that over a certain range of temperatures, warming promotes plant growth. The resulting increase in plant biomass contributes to increases in soil surface organic matter, thereby increasing the growth and activity of soil microorganisms [41], which in turn accelerates litter decomposition and conversion and increases SOC content [5].

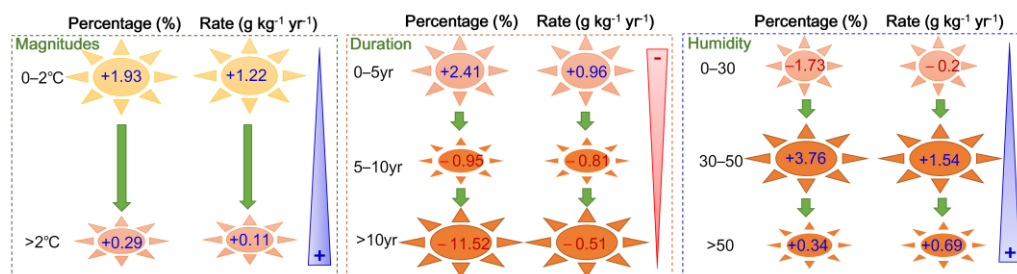


Figure 6. Conceptual framework of the effects of warming on the percentage and change rate of soil organic carbon (SOC) content.

Soil moisture plays a key role in soil carbon sequestration and loss during warming [42]. Warming increases soil surface temperature and reduces soil moisture [43], and soil water status is a key factor determining the growth of plants and microorganisms [22]. The desiccation of soil limits plant and microbial growth, inhibits the activity of microorganisms

with strong carbon sequestration capacities, and enhances microbial communities and enzyme activities with strong carbon decomposition capacities, which collectively result in a reduction in SOC content [10,44]. At conducive temperatures, an increase in the magnitude of warming stimulates microbial activity and accelerates the decomposition of readily decomposed substances in plant residues, thereby leading to an accumulation of the more recalcitrant substances derived from plants and organic matter of microbial origin [44,45]. However, excessive warming limits this process, which causes the SOC content to change from positive to negative [12,46].

4.3. Dynamics of SOC Content as Affected by Warming Duration

The findings of a previous study have provided evidence to indicate that extended periods of warming do not contribute to a consistent accumulation of SOC; instead, there tends to be an initial increase and subsequent decline in accumulation [10]. In the present study, we observed a significant increase in the percentage change in SOC content in forest soils (0–20 or 0–30 cm) in response to an increase in the duration of warming, whereas the rate of change in SOC content was found to be characterized by a non-significant trend of decline (Figures 3 and 6). In this respect, we observed a negative rate of change at warming durations in excess of 5 years.

Although short-term warming (<5 years) has been established to be conducive to SOC accumulation, SOC emission is more likely to occur in response to medium- and long-term warming (>5 years). Plants grow rapidly during the initial stages of warming. However, although this response is associated with high nutrient consumption, the amount of nutrients generated by the return of plant litter tends to be higher than that consumed, thereby contributing to a net accumulation of nutrients [15,41]. The findings of a recent meta-analysis have indicated that short-term warming promotes increases in soil microbial biomass and enzyme activities, with the most pronounced effects being observed with respect to the activities of enzymes associated with carbon cycling [10]. Consequently, although short-term warming will contribute to an acceleration in litter decomposition, long-term warming is likely to be associated with drought conditions, thereby reducing plant photosynthesis and growth and, hence, the production of plant biomass [18,19]. This could be attributable to the fact that under such conditions, plants allocate a larger proportion of available carbon resources to structures and compounds that contribute to resisting drought stress [46]. Long-term warming also leads to a loss of soil nutrients and reduces microbial activity and biomass [10,18,19], thereby promoting a significant negative feedback on SOC content.

4.4. Dynamics of SOC Content as Affected by Humidity Under Warming Conditions

The response of SOC content to changes in humidity is closely related to corresponding changes in soil moisture determined by variations in precipitation and temperature [47,48]. Our findings indicated that on a global scale, changes in the rate of SOC content in forest soils (0–20 or 0–30 cm) were positively correlated with the humidity index. The findings of numerous previous studies have provided evidence that an increase in the humidity index corresponds to an increase in soil water content, with a higher soil water content being more beneficial to the growth and propagation of soil microorganisms [28,49]. As these microbes contribute to enhancing the utilization of soil water and nutrients by plants [50], an increase in soil microbial diversity and biological activity accelerates the rate at which nutrients are cycled in the soil, thereby enhancing the accumulation efficiency of SOC [51,52].

This study showed that rather than undergoing a continual increase in response to higher humidity index values, the rate of change in SOC content reaches a peak value at a humidity of 30–50. Under optimal soil water and aeration conditions, soil microorganisms

can not only utilize sufficient water resources [53] but also obtain adequate oxygen for metabolic activities. As the rate of change in SOC content is largely determined by the decomposing activities of soil microorganisms, optimal soil water conditions can contribute to maintaining the rate at which the accumulation of SOC changes within a relatively high range [54]. However, excessively low or high levels of soil water, and the associated arid or anaerobic conditions, will inhibit plant root growth and soil microbial activity [55,56]. In particular, higher humidity index values are associated with higher levels of soil moisture, which reduces soil aeration and microbial activity [57,58]. Moreover, increases in humidity are conducive to an excessive loss of soil carbon [25], which in turn leads to a reduction in the efficiency with which SOC accumulates.

4.5. Study Limitations

Despite our important findings, this study does have certain limitations. First, we only considered the effects of warming on the rate of SOC content change in forest soils. To enhance our understanding of carbon cycling in terrestrial ecosystems, further studies are needed to elucidate the mechanisms underlying SOC content in different types of land-based environments, including grassland, shrubland, and wetland ecosystems. Second, we only considered changes in SOC content in the soil surface (mineral soil layer), and it is conceivable that warming would have differing effects on the accumulation of SOC in different soil layers (surface and depth layers). Accordingly, future studies should examine the effects of warming on the SOC dynamics of deeper soil layers. Third, the dynamics of soil carbon in the litter layer significantly affected the carbon cycle process of forest ecosystems. This study merely considered the influence of warming on SOC content in the soil layer, without considering the changes of SOC in the litter layer. Therefore, research on the effects of warming on the accumulation of SOC in the litter layer should be conducted in the future.

5. Conclusions

The change rate of SOC content in the soil mineral profile (0–20 cm or 0–30 cm) was positive ($0.85 \text{ g kg}^{-1} \text{ yr}^{-1}$) under warming conditions, indicating that warming increases SOC content (from 67.47 to 69.90 g kg^{-1}) in forest soils on a global scale. However, we identified reductions in the rate of change in SOC content with increases in the magnitude (a reduction from 1.22 to 0.11 $\text{g kg}^{-1} \text{ yr}^{-1}$) and duration (a reduction from 0.96 to $-0.51 \text{ g kg}^{-1} \text{ yr}^{-1}$) of warming. The rate of change in SOC content started to become negative at warming durations in excess of 5 years, indicating that long-term warming limits SOC accumulation. Moreover, our findings indicate that higher humidity is conducive to the accumulation of SOC content and accelerates the change rate of SOC content under warming conditions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/f16010059/s1>: Figure S1: Distribution (a) and frequency (b) of the percentage and rate of soil organic carbon (SOC) under warming.

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Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

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Conflicts of Interest: The authors declare no conflict of interest.

References

- Wang, J.; Taylor, A.; D'Orangeville, L. Warming-induced tree growth may help offset increasing disturbance across the Canadian boreal forest. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2212780120. [[CrossRef](#)] [[PubMed](#)]
- Reich, P.B.; Sendall, K.M.; Stefanski, A.; Rich, R.L.; Hobbie, S.E.; Montgomery, R.A. Effects of climate warming on photosynthesis in boreal tree species depend on soil moisture. *Nature* **2018**, *562*, 263–267. [[CrossRef](#)] [[PubMed](#)]
- Melillo, J.M.; Frey, S.D.; DeAngelis, K.M.; Werner, W.J.; Bernard, M.J.; Bowles, F.P.; Pold, G.; Knorr, M.A.; Grandy, A.S. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. *Science* **2017**, *358*, 101–104. [[CrossRef](#)] [[PubMed](#)]
- Zhang, Q.; Feng, J.; Li, X.; Chen, Y.; Schimel, J.P.; Zhu, B. Effect of field warming on soil microbial carbon use efficiency—A meta-analysis. *Soil Biol. Biochem.* **2024**, *197*, 109531. [[CrossRef](#)]
- Dong, H.; Lin, J.; Lu, J.; Li, L.; Yu, Z.; Kumar, A.; Zhang, Q.; Liu, D.; Chen, B. Priming effects of surface soil organic carbon decreased with warming: A global meta-analysis. *Plant Soil* **2024**, *500*, 233–242. [[CrossRef](#)]
- Jiang, Y.; Wu, S.; Yang, L.; Liu, Y.; Gao, M.; Ni, H. Short-Term Simulated Warming Changes the Beta Diversity of Bacteria in Taiga Forests' Permafrost by Altering the Composition of Dominant Bacterial Phyla. *Forests* **2024**, *15*, 693. [[CrossRef](#)]
- Xu, S.; Ou, J.; Qiao, X.; Zeng, Z.; Wang, J. Experimental warming affects soil carbon dynamics in boreal and temperate forests: A meta-analysis. *Environ. Res. Lett.* **2024**, *19*, 103002.
- Ma, R.; Kou, T.; Cheng, X.; Yu, N. Long-term warming altered soil physical structure and soil organic carbon pools in wheatland field. *Exp. Agric.* **2024**, *60*, e1. [[CrossRef](#)]
- Qiao, L.; Zhou, H.; Wang, Z.; Li, Y.; Chen, W.; Wu, Y.; Liu, G.; Xue, S. Variations in soil aggregate stability and organic carbon stability of alpine meadow and shrubland under long-term warming. *Catena* **2023**, *222*, 106848. [[CrossRef](#)]
- Xu, H.; Huang, L.; Chen, J.; Zhou, H.; Wan, Y.; Qu, Q.; Wang, M.; Xue, S. Changes in soil microbial activity and their linkages with soil carbon under global warming. *Catena* **2023**, *232*, 107419. [[CrossRef](#)]
- Zhao, J.; Xie, X.; Jiang, Y.; Li, J.; Fu, Q.; Qiu, Y.; Fu, X.; Yao, Z.; Dai, Z.; Qiu, Y.; et al. Effects of simulated warming on soil microbial community diversity and composition across diverse ecosystems. *Sci. Total Environ.* **2024**, *911*, 168793. [[CrossRef](#)] [[PubMed](#)]
- Liu, X.; Tian, Y.; Heinzle, J.; Salas, E.; Kwatcho-Kengdo, S.; Borken, W.; Schindlbacher, A.; Wanek, W. Long-term soil warming decreases soil microbial necromass carbon by adversely affecting its production and decomposition. *Glob. Change Biol.* **2024**, *30*, e17379. [[CrossRef](#)] [[PubMed](#)]
- Yang, L.; Pan, J.; Wang, J.; Tian, D.; Zhang, C.; Zhao, X.; Hu, J.; Yang, W.; Yan, Y.; Ma, F.; et al. Soil microbial respiration adapts to higher and longer warming experiments at the global scale. *Environ. Res. Lett.* **2023**, *18*, 034044. [[CrossRef](#)]
- Meng, C.; Tian, D.; Zeng, H.; Li, Z.; Chen, H.; Niu, S. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. *Sci. Total Environ.* **2020**, *705*, 135992. [[CrossRef](#)] [[PubMed](#)]
- Yu, Z.; Zhang, C.; Liu, X.; Lei, J.; Zhang, Q.; Yuan, Z.; Peng, C.; Koerner, S.E.; Xu, J.; Guo, L. Responses of C:N:P stoichiometric correlations among plants, soils and microorganisms to warming: A meta-analysis. *Sci. Total Environ.* **2024**, *912*, 168827. [[CrossRef](#)]
- Han, H.; Li, C.; Liu, R.; Jian, J.; Abulimiti, M.; Yuan, P. Warming promotes accumulation of microbial- and plant-derived carbon in terrestrial ecosystems. *Sci. Total Environ.* **2023**, *905*, 166977. [[CrossRef](#)]
- Shi, L.; Lin, Z.; Tang, S.; Peng, C.; Yao, Z.; Xiao, Q.; Zhou, H.; Liu, K.; Shao, X. Interactive effects of warming and managements on carbon fluxes in grasslands: A global meta-analysis. *Agric. Ecosyst. Environ.* **2022**, *340*, 108178. [[CrossRef](#)]
- Xu, W.; Yuan, W. Responses of microbial biomass carbon and nitrogen to experimental warming: A meta-analysis. *Soil Biol. Biochem.* **2017**, *115*, 265–274. [[CrossRef](#)]
- Sun, Y.; Wang, C.; Chen, H.; Liu, Q.; Ge, B.; Tang, B. A global meta-analysis on the responses of C and N concentrations to warming in terrestrial ecosystems. *Catena* **2022**, *208*, 105762. [[CrossRef](#)]
- Zhou, G.; Zhou, X.; Eldridge, D.J.; Han, X.; Song, Y.; Liu, R.; Zhou, L.; He, Y.; Du, Z.; Delgado-Baquerizo, M. Temperature and Rainfall Patterns Constrain the Multidimensional Rewilding of Global Forests. *Adv. Sci.* **2022**, *9*, 2201144. [[CrossRef](#)]
- Xue, S.; Yi, X.; Cui, H.; Li, M.; Peng, J.; Zhu, Y.; Duan, G. Global biogeographic distribution of Bathyarchaeota in paddy soils. *Msystems* **2023**, *8*, e00143–23. [[CrossRef](#)] [[PubMed](#)]
- Qu, Q.; Wang, Z.; Gan, Q.; Liu, R.; Xu, H. Impact of drought on soil microbial biomass and extracellular enzyme activity. *Front. Plant Sci.* **2023**, *14*, 1221288. [[CrossRef](#)] [[PubMed](#)]
- Xu, H.; Qu, Q.; Yang, J.; Wang, Z.; Wang, M.; Liu, R.; Xue, S. Impact of drought on terrestrial ecosystem C-N-P stoichiometry and microbial nutrient limitation. *Soil Tillage Res.* **2024**, *236*, 105951. [[CrossRef](#)]

24. Chen, Z.; Wei, X.; Ni, X.; Wu, F.; Liao, S. Changing precipitation effect on forest soil carbon dynamics is driven by different attributes between dry and wet areas. *Geoderma* **2023**, *429*, 116279. [[CrossRef](#)]
25. Xu, S.; Wang, J.; Sayer, E.J.; Lam, S.K.; Lai, D.Y.F. Precipitation change affects forest soil carbon inputs and pools: A global meta-analysis. *Sci. Total Environ.* **2024**, *908*, 168171. [[CrossRef](#)]
26. Wu, F.; Wang, Y.; Wang, J. Asymmetric responses of soil bacterial community and soil respiration to precipitation changes: A global meta-analysis. *Land Degrad. Dev.* **2023**, *34*, 1887–1896. [[CrossRef](#)]
27. Yang, Y.; Mohammad, A.; Feng, J.; Zhou, R.; Fang, J. Storage, patterns and environmental controls of soil organic carbon in China. *Biogeochemistry* **2007**, *84*, 131–141. [[CrossRef](#)]
28. Chang, W.; Song, Q.; Zheng, X.; Li, C.; Wang, L.; Li, H.; Zhang, L.; You, C.; Xu, H.; Xu, L.; et al. Leaf trait variations and correlations across four forests with similar mean annual precipitation in northern China. *Ecol. Indic.* **2024**, *165*, 112199. [[CrossRef](#)]
29. Yang, Y.; Yang, J.; Dong, Q.; Li, D.; Tan, B.; Wu, Q.; Xu, Z.; Xu, H. Heavy Nitrogen Application Rate and Long-Term Duration Decrease the Soil Organic Carbon and Nitrogen Sequestration Rates in Forest Ecosystems. *Forests* **2024**, *15*, 1585. [[CrossRef](#)]
30. Bradford, M.A.; Wieder, W.R.; Bonan, G.B.; Fierer, N.; Raymond, P.A.; Crowther, T.W. Managing uncertainty in soil carbon feedbacks to climate change. *Nat. Clim. Chang.* **2016**, *6*, 751–758. [[CrossRef](#)]
31. Knorr, W.; Prentice, I.C.; House, J.I.; Holland, E.A. Long-term sensitivity of soil carbon turnover to warming. *Nature* **2005**, *433*, 298–301. [[CrossRef](#)] [[PubMed](#)]
32. Phillips, C.A.; Elberling, B.; Michelsen, A. Soil Carbon and Nitrogen Stocks and Turnover Following 16 Years of Warming and Litter Addition. *Ecosystems* **2019**, *22*, 110–124. [[CrossRef](#)]
33. Lu, M.; Zhou, X.; Yang, Q.; Li, H.; Luo, Y.; Fang, C.; Chen, J.; Yang, X.; Li, B. Responses of ecosystem carbon cycle to experimental warming: A meta-analysis. *Ecology* **2013**, *94*, 726–738. [[CrossRef](#)] [[PubMed](#)]
34. Morrison, E.W.; Pringle, A.; van Diepen, L.T.A.; Grandy, A.S.; Melillo, J.M.; Frey, S.D. Warming alters fungal communities and litter chemistry with implications for soil carbon stocks. *Soil Biol. Biochem.* **2019**, *132*, 120–130. [[CrossRef](#)]
35. Li, S.; Barreiro, A.; Almeida, J.P.; Prade, T.; Martensson, L.M.D. Perennial crops shape the soil microbial community and increase the soil carbon in the upper soil layer. *Soil Biol. Biochem.* **2025**, *200*, 109621. [[CrossRef](#)]
36. Tian, Y.; Schindlbacher, A.; Malo, C.U.; Shi, C.; Heinze, J.; Kengdo, S.K.; Inselsbacher, E.; Borken, W.; Wanek, W. Long-term warming of a forest soil reduces microbial biomass and its carbon and nitrogen use efficiencies. *Soil Biol. Biochem.* **2023**, *184*, 109109. [[CrossRef](#)]
37. Wu, X.; Li, J.; Zhu, J.; Jiang, Y.; Huang, Z.; Wu, P.; Ma, X. Effects of Simulated Warming on Bacterial Community Structure in Litters of Chinese Fir Based on Displacement Test. *Forests* **2024**, *15*, 908. [[CrossRef](#)]
38. Yan, C.; Yuan, Z.; Shi, X.; Lock, T.R.; Kallenbach, R.L. A global synthesis reveals more response sensitivity of soil carbon flux than pool to warming. *J. Soils Sediments* **2020**, *20*, 1208–1221. [[CrossRef](#)]
39. Spohn, M.; Bagchi, S.; Biederman, L.A.; Borer, E.T.; Brathen, K.A.; Bugalho, M.N.; Caldeira, M.C.; Catford, J.A.; Collins, S.L.; Eisenhauer, N.; et al. The positive effect of plant diversity on soil carbon depends on climate. *Nat. Commun.* **2023**, *14*, 6624. [[CrossRef](#)]
40. Xu, H.; Wang, M.; You, C.; Tan, B.; Xu, L.; Li, H.; Zhang, L.; Wang, L.; Liu, S.; Hou, G.; et al. Warming effects on C:N:P stoichiometry and nutrient limitation in terrestrial ecosystems. *Soil Tillage Res.* **2024**, *235*, 105896. [[CrossRef](#)]
41. Sollinger, A.; Ahlers, L.S.; Dahl, M.B.; Sigurdsson, P.; de Carlan, C.L.N.; Bhattarai, B.; Gall, C.; Martin, V.S.; Rottensteiner, C.; Motleleng, L.L.; et al. Microorganisms in subarctic soils are depleted of ribosomes under short-, medium-, and long-term warming. *ISME J.* **2024**, *18*, wrac081. [[CrossRef](#)] [[PubMed](#)]
42. Zhao, F.; Wu, Y.; Hui, J.; Sivakumar, B.; Meng, X.; Liu, S. Projected soil organic carbon loss in response to climate warming and soil water content in a loess watershed. *Carbon Balance Manag.* **2021**, *16*, 24. [[CrossRef](#)] [[PubMed](#)]
43. Su, R.; Wu, X.; Hu, J.; Li, H.; Xiao, H.; Zhao, J.; Hu, R. Warming promotes the decomposition of oligotrophic bacterial-driven organic matter in paddy soil. *Soil Biol. Biochem.* **2023**, *186*, 109156. [[CrossRef](#)]
44. Cai, M.; Zhao, G.; Zhao, B.; Cong, N.; Zheng, Z.; Zhu, J.; Duan, X.; Zhang, Y. Climate warming alters the relative importance of plant root and microbial community in regulating the accumulation of soil microbial necromass carbon in a Tibetan alpine meadow. *Glob. Change Biol.* **2023**, *29*, 3193–3204. [[CrossRef](#)]
45. Zhou, J.; Liu, Y.; Liu, C.; Zamanian, K.; Feng, W.; Steiner, S.K.; Shi, L.; Guillaume, T.; Kumar, A. Necromass responses to warming: A faster microbial turnover in favor of soil carbon stabilisation. *Sci. Total Environ.* **2024**, *954*, 176651. [[CrossRef](#)]
46. Chen, Y.; Han, M.; Yuan, X.; Zhou, H.; Zhao, X.; Schimel, J.P.; Zhu, B. Long-term warming reduces surface soil organic carbon by reducing mineral-associated carbon rather than “free” particulate carbon. *Soil Biol. Biochem.* **2023**, *177*, 108905. [[CrossRef](#)]
47. Wang, B.; Chen, Y.; Li, Y.; Zhang, H.; Yue, K.; Wang, X.; Ma, Y.; Chen, J.; Sun, M.; Chen, Z.; et al. Differential effects of altered precipitation regimes on soil carbon cycles in arid versus humid terrestrial ecosystems. *Glob. Change Biol.* **2021**, *27*, 6348–6362. [[CrossRef](#)]
48. Ren, C.; Zhao, F.; Shi, Z.; Chen, J.; Han, X.; Yang, G.; Feng, Y.; Ren, G. Differential responses of soil microbial biomass and carbon-degrading enzyme activities to altered precipitation. *Soil Biol. Biochem.* **2017**, *115*, 1–10. [[CrossRef](#)]

49. Zhang, C.; Xi, N. Precipitation Changes Regulate Plant Soil Microbial Biomass Via Plasticity in Plant Biomass Allocation in Grasslands: A Meta-Analysis. *Front. Plant Sci.* **2021**, *12*, 614968. [[CrossRef](#)]
50. Xu, H.; Qu, Q.; Xue, S.; Wang, M. A global analysis of the effects of forest thinning on soil N stocks and dynamics. *Catena* **2024**, *246*, 108411. [[CrossRef](#)]
51. Gaudel, G.; Xing, L.; Shrestha, S.; Poudel, M.; Sherpa, P.; Raseduzzaman, M.; Zhang, X. Microbial mechanisms regulate soil organic carbon mineralization under carbon with varying levels of nitrogen addition in the above-treeline ecosystem. *Sci. Total Environ.* **2024**, *917*, 170497. [[CrossRef](#)] [[PubMed](#)]
52. Camenzind, T.; Mason-Jones, K.; Mansour, I.; Rillig, M.C.; Lehmann, J. Formation of necromass-derived soil organic carbon determined by microbial death pathways. *Nat. Geosci.* **2023**, *16*, 115–122. [[CrossRef](#)]
53. Zhang, L.; Xiong, S.; Shen, Y.; You, C.; Li, H.; Wang, L.; Liu, S.; Tan, B.; Xu, H.; Xu, L.; et al. Changes in soil microbial community and function across stand age of *Cryptomeria japonica* var. *sinensis* plantations in subtropical China. *Appl. Soil Ecol.* **2024**, *203*, 105645.
54. Zhou, Z.; Wang, C.; Luo, Y. Response of soil microbial communities to altered precipitation: A global synthesis. *Global. Ecol. Biogeogr.* **2018**, *27*, 1121–1136. [[CrossRef](#)]
55. Wang, Y.; Song, C.; Liu, H.; Wang, S.; Zeng, H.; Luo, C.; He, J. Precipitation determines the magnitude and direction of interannual responses of soil respiration to experimental warming. *Plant Soil* **2021**, *458*, 75–91. [[CrossRef](#)]
56. Wang, X.; Chen, F.; Zeng, J.; Wang, Z.; Feng, Y.; Wang, X.; Ren, C.; Yang, G.; Zhong, Z.; Han, X. Divergent responses of soil glomalin and microbial necromass to precipitation reduction: New perspectives from soil aggregates and multi-trophic networks. *Soil Biol. Biochem.* **2025**, *200*, 109638. [[CrossRef](#)]
57. Du, Y.; Wang, Y.; Hui, D.; Su, F.; Yan, J. Significant effects of precipitation frequency on soil respiration and its components-A global synthesis. *Glob. Change Biol.* **2022**, *29*, 1188–1205. [[CrossRef](#)]
58. Yang, J.; Jia, X.; Ma, H.; Chen, X.; Liu, J.; Shangguan, Z.; Yan, W. Effects of warming and precipitation changes on soil GHG fluxes: A meta-analysis. *Sci. Total Environ.* **2022**, *827*, 154351. [[CrossRef](#)]

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