International Journal of Academic Research and Development
www.allreviewjournal.com
ISSN: 2455-4197
Received: 24-01-2026, Accepted: 23-02-2026, Published: 10-03-2026
Volume 11, Issue 1, 2026, Page No. 66-73

Effects of climate warming on the rate of change of soil organic carbon in Indian forest soil

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Abstract
Rising global temperatures influence the carbon cycle within terrestrial ecosystems. Nevertheless, the specific response of soil organic carbon (SOC) in forest soils to warming remains insufficiently understood. To investigate this relationship, 276 observations obtained from 98 published studies were analyzed. The study focused on SOC variations in mineral soil layers at depths of 0–20 cm or 0–30 cm, while also considering the influence of temperature increase, length of warming exposure, and the humidity index. The results showed that warming slightly increased SOC levels in forest soils, with values rising from 67.47 g kg^{-1} to 69.90 g kg^{-1}. Globally, the mean rate of SOC change was estimated at 0.85 g kg^{-1} per year. However, the rate declined as warming intensity increased. When temperature rise ranged between 0–2°C, SOC change reached 1.22 g kg^{-1} yr^{-1}, but dropped to 0.11 g kg^{-1} yr^{-1} when warming exceeded 2°C. Over longer warming periods, SOC change shifted from 0.96 g kg^{-1} yr^{-1} (0–5 years) to −0.81 and −0.51 g kg^{-1} yr^{-1} for 5–10 and over 10 years, respectively.

Keywords: Carbon cycle, climate change, forest soils, meta-analysis, warming magnitude, warming duration, humidity index

Introduction

Ongoing global climate change has intensified the greenhouse effect, leading to increasing temperatures that significantly influence carbon cycling in forest soils [1]. Temperature rise, considered one of the principal drivers of climate change, can modify both the composition and concentration of soil organic carbon (SOC). Such changes influence the stability of soil carbon reserves [2], which play a crucial role in maintaining equilibrium within the global carbon cycle and reducing the harmful consequences associated with greenhouse warming [3]. Therefore, understanding how global warming influences SOC accumulation in forest ecosystems at the global level is an important scientific objective.

Previous investigations examining the impacts of warming on forest soils have mainly focused on a range of biological and physical factors, including plant biomass production, soil microbial dynamics, and the physicochemical properties of soil [4, 5, 6]. For instance, Xu *et al.* [7] reported that increased temperatures can enhance aboveground plant biomass and litter deposition in forest ecosystems by approximately 33% and 15%, respectively. Other studies have demonstrated that warming can substantially influence soil characteristics such as aggregate formation, soil pH, and moisture conditions [8, 9]. Although Xu *et al.* [10] observed that warming may significantly enhance the diversity of soil fungi and bacteria, Zhao *et al.* [11] reported a notable decline in the alpha diversity of soil microorganisms under warming conditions. These differing observations indicate that the response of SOC to warming remains uncertain and difficult to predict. Earlier studies have also shown that warming-induced alterations in vegetation growth, soil structure, nutrient availability, and microbial processes can strongly influence SOC levels and the stability of soil carbon pools [12]. Despite these findings, only a limited number of studies have evaluated how warming affects the rate of change of SOC content in forest soils at a global scale. This lack of comprehensive research currently restricts our understanding of soil carbon dynamics and the regulatory mechanisms governing SOC in forest ecosystems.

Regional variations in both the intensity and duration of warming mean that the rate at which SOC changes in forest soils has not yet been clearly determined. Changes in soil microbial activity can alter enzyme activity as well as the physicochemical properties of soil, which in turn regulate the processes responsible for SOC decomposition and accumulation [12]. The magnitude and persistence of warming are major factors that shape microbial community structure and biological activity in soils [13, 14]. A recent meta-analysis suggested that stronger warming intensity is linked with significant decreases in microbial diversity and microbial biomass in soils. Likewise, prolonged exposure to warming has been shown to reduce both microbial biomass and the activity of enzymes involved in soil carbon cycling [10]. Higher temperatures can also decrease soil moisture levels, sometimes resulting in excessively dry soil conditions that inhibit microbial growth and reproduction [15]. When warming persists for long periods, the carbon resources available to microorganisms become depleted. As a consequence, microbial biomass declines, carbon-use efficiency decreases, and shifts occur in microbial community composition, ultimately leading to the loss of soil carbon and reduced SOC accumulation [16, 17]. In addition, extended warming periods can slow plant growth rates, which further produces negative feedback effects on SOC formation and storage [18, 19]. Although numerous studies have documented the potential consequences of climate warming, the specific mechanisms through which warming intensity and duration regulate SOC change rates in forest soils worldwide remain insufficiently clarified.

Patterns of global rainfall and temperature strongly influence plant productivity, soil moisture availability, and microbial functioning, all of which play important roles in soil carbon budget processes [20, 21]. In dry ecosystems, soil water availability is often the primary constraint on plant development and microbial activity. Under such circumstances, SOC accumulation processes become particularly sensitive to fluctuations in rainfall [22]. When reduced precipitation occurs together with higher temperatures, soil water scarcity can develop in these regions, creating unfavorable conditions for SOC accumulation [23, 24]. In contrast, humid ecosystems frequently experience greater precipitation that can quickly saturate the soil. In such environments, warming may increase evaporation of excess soil moisture, thereby improving soil aeration and permeability while enhancing microbial decomposition and SOC accumulation processes [25, 26]. The humidity index, calculated as mean annual precipitation divided by the sum of mean annual temperature plus ten [humidity index = mean annual precipitation/(mean annual temperature + 10)], can be used to evaluate the combined influence of precipitation and temperature on ecosystems [27]. This indicator provides an effective approach for assessing the influence of climatic factors on SOC accumulation under warming conditions and offers theoretical support for accurately estimating carbon budgets in terrestrial ecosystems under climate change.

In the present study, we conducted a meta-analysis to examine how warming magnitude, warming duration, and the humidity index influence the rate of SOC change in forest soils worldwide. The following hypotheses were proposed:

Warming stimulates plant growth and modifies microbial activity in soils [7, 10], which may contribute to increases in SOC content.

Higher warming intensity and prolonged warming duration can lead to soil drying and reduced microbial activity [15, 16, 17], thereby lowering the rate of SOC change.

Greater humidity levels and improved soil moisture conditions enhance microbial growth and accelerate nutrient cycling processes [28]. Consequently, higher humidity index values are expected to correspond with increased rates of SOC change under warming conditions.

Materials and Methods

1. Data Collection

The dataset used in this study was compiled primarily from three scientific databases: Web of Science (http://apps.webofknowledge.com/, accessed on 10 September 2025), Google Scholar (http://scholar.google.com/, accessed on 10 September 2025), and CNKI (http://www.cnki.net/, accessed on 10 September 2025). All searches were conducted on 10 September 2025 using the keywords presented in Table 1. Several selection criteria were applied to ensure the reliability of the dataset. First, only studies based on experimental research designs were considered, while review articles were excluded. Second, each study needed to include both a control treatment without warming and an experimental treatment involving warming. Third, the research had to focus specifically on forest soil systems. Fourth, studies examining combined effects with other environmental factors, such as nitrogen addition or elevated carbon dioxide concentration, were excluded. Fifth, information regarding the magnitude and duration of warming had to be available either directly reported in the study or calculable from the provided data. Finally, if SOC values were reported for only one soil layer, those data were used directly, whereas when multiple layers were presented, data from the surface layer were prioritized. Most collected data corresponded to mineral soil depths of 0–20 cm or 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

After screening, a total of 276 observations from 98 published studies were included in the dataset. Soil organic carbon values reported in tables were extracted directly, while values presented in figures were digitized using GetData Graph Digitizer 2.24. Additional environmental variables, including longitude, latitude, mean annual temperature (MAT), and mean annual precipitation (MAP), were also compiled.

2. Data Analysis

The percentage variation in SOC content and the rate of SOC change were determined following a previously established method [29]. The calculations were performed using the following equations:

Percentage of SOC content change (%) =

$$\frac{(SOCt - SOCc)}{SOCc} \times 100 \quad (1)$$

$$\text{Change rate of SOC content} = \frac{(SOCt - SOCc)}{\Delta T} \quad (2)$$

where SOCt represents the SOC content measured under warming conditions, whereas SOCc denotes the SOC content recorded under control conditions.

The humidity index, which reflects the combined influence of environmental variables such as mean annual precipitation (MAP) and mean annual temperature (MAT), was calculated using the equation described previously [27]:

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

To investigate how warming magnitude, warming duration, and the humidity index influence SOC responses, these variables were categorized into several groups as summarized in Table 2. Variations in both the percentage change of SOC content and the rate of SOC change among different categories were assessed using one-way analysis of variance ($p < 0.05$). Additionally, regression analysis was conducted to examine relationships between SOC responses and warming magnitude, warming duration, and humidity index.

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

Results

1. Main Effects of Warming on SOC Content

The spatial distribution of the study locations from which the dataset was obtained is illustrated in Figure 1, whereas the frequency distribution of both the percentage change in SOC content and the rate of SOC change is presented in Figure S1. In general, warming resulted in a slight increase in SOC levels, rising from 67.47 to 69.90 g kg⁻¹. Correspondingly, the average percentage change in SOC content and the rate of SOC change were 1.08% and 0.85 g kg⁻¹ yr⁻¹, respectively (Figure 2a–c).

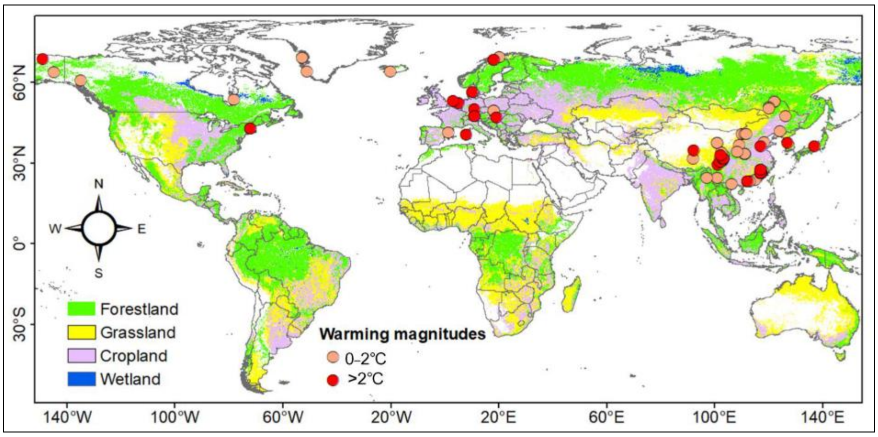

Fig 1: Global distribution of the sites from which the data used in this study were obtained

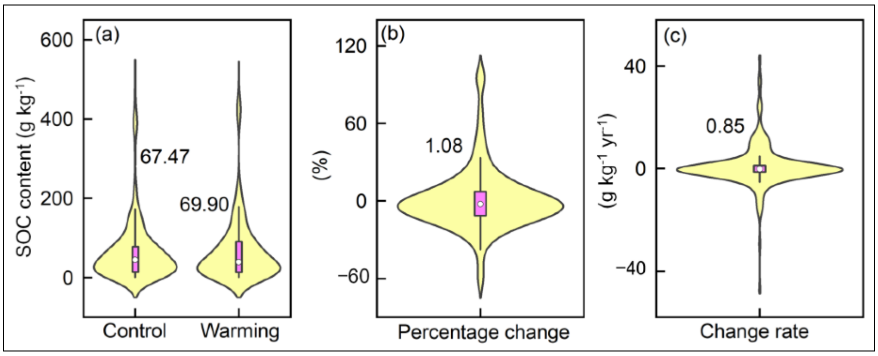

Fig 2: Effects of warming on (a) soil organic carbon (SOC) content and (b) the percentage and (c) rate of SOC content change

2. Effects of Warming Magnitude on SOC Content

The intensity of warming exerted a noticeable influence on SOC dynamics (Figure 3). In terms of percentage variation in SOC content, values decreased from 1.93% under a warming magnitude of 0–2 °C to 0.29% when warming exceeded 2 °C. Likewise, the rate of SOC change declined from 1.22 g kg⁻¹ yr⁻¹ at 0–2 °C to 0.11 g kg⁻¹ yr⁻¹ under warming levels above 2 °C (Figure 3a,b). Furthermore, both the percentage change ($p = 0.030$) and the rate of SOC change ($p > 0.05$) exhibited negative relationships with increasing warming magnitude (Figure 3c,d).

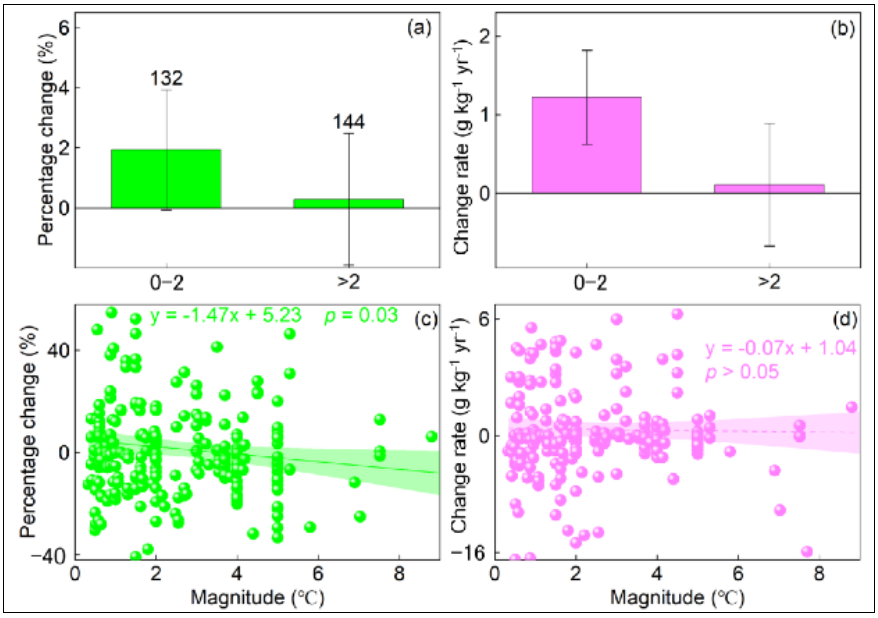

Fig 3: Effects of magnitude of warming on (a) the percentage change in soil organic carbon (SOC), (b) rate of SOC content change, and relationship between (c) percentage and (d) rate of SOC content change and magnitude of warming

3. Effects of Humidity on SOC Content

The percentage variation in SOC content and the rate of SOC change were greatest when the humidity index ranged between 30 and 50, with values of 3.76% and 1.54 g kg⁻¹ yr⁻¹, respectively. In contrast, lower values were recorded at humidity levels of 0–30 (−1.73%; −0.2 g kg⁻¹ yr⁻¹) and greater than 50 (0.34%; 0.69 g kg⁻¹ yr⁻¹) (Figure 5a,b). Furthermore, both the percentage change ($p > 0.05$) and the rate of SOC change ($p = 0.028$) showed positive relationships with increasing humidity index values (Figure 5c,d).

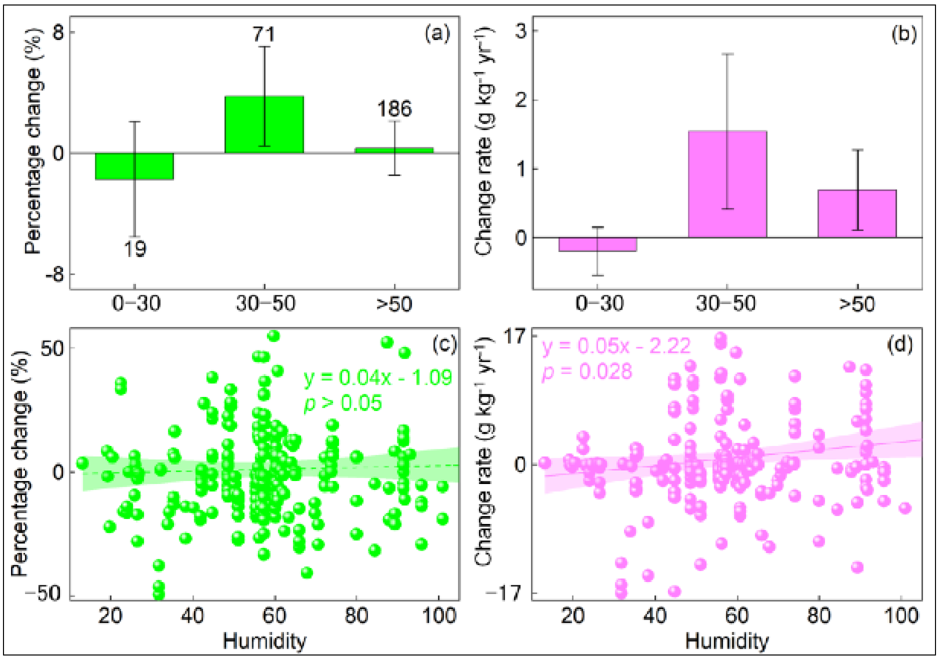

Fig 5: Effects of humidity index on (a) the percentage change in soil organic carbon (SOC), (b) the rate of SOC content change, and the relationship between (c) the percentage and (d) rate of SOC content and humidity index values

Discussion

1. Dynamics of SOC Content

In agreement with earlier research [10], the present study indicates that warming leads to an increase in SOC content within forest soils at depths of 0–20 cm or 0–30 cm on a global scale. Climate warming influences SOC accumulation mainly through its effects on plant development, microbial processes, and soil respiration [4, 30, 31].

Rising temperatures enhance photosynthetic activity and stimulate plant growth, which subsequently increases litter production and root turnover rates [7, 32]. For instance, a recent global meta-analysis reported that warming results in increases of 15.7%, 4.4%, 6.8%, and 7.0% in plant photosynthesis, net primary productivity, and above-ground and below-ground carbon pools, respectively [33]. As a result, higher inputs of fresh organic material into soils contribute to greater SOC accumulation [34].

Warming also regulates litter decomposition by influencing the activity of decomposer organisms [14, 34]. Temperature strongly affects soil microbial populations and enzyme activities, both of which are crucial for the decomposition and transformation of soil organic matter [35, 36]. When temperatures rise, microbial activity often increases [10, 37], which accelerates litter breakdown and enhances SOC formation [38]. In addition, warming may alter plant community composition and improve vegetation productivity as well as leaf quality [39], further contributing to increases in SOC levels.

2. Dynamics of SOC Content as Affected by Warming Magnitude

Contrary to the pattern described above, Yan *et al.* [38] found that warming may reduce SOC content when examined using integrated global datasets. Such contrasting results may arise from differences in the magnitude of temperature increase across studies [10], which can influence plant community characteristics and microbial activity patterns [40].

Our results show that stronger warming intensity is associated with a significant decline in the percentage change of SOC content in forest soils within the 0–20 or 0–30 cm layer on a global scale. The rate of SOC change also exhibited a similar downward tendency, although the decline was not statistically significant (Figure 3 and Figure 6). These results suggest that moderate warming may stimulate SOC accumulation, whereas excessive warming can weaken this positive effect and may even suppress SOC formation.

This pattern may occur because moderate temperature increases promote plant growth within a certain thermal range. Enhanced plant biomass increases organic matter inputs to the soil surface, which stimulates microbial growth and activity [41]. As a consequence, microbial processes accelerate the decomposition and transformation of litter, ultimately contributing to increased SOC content in forest soils [5].

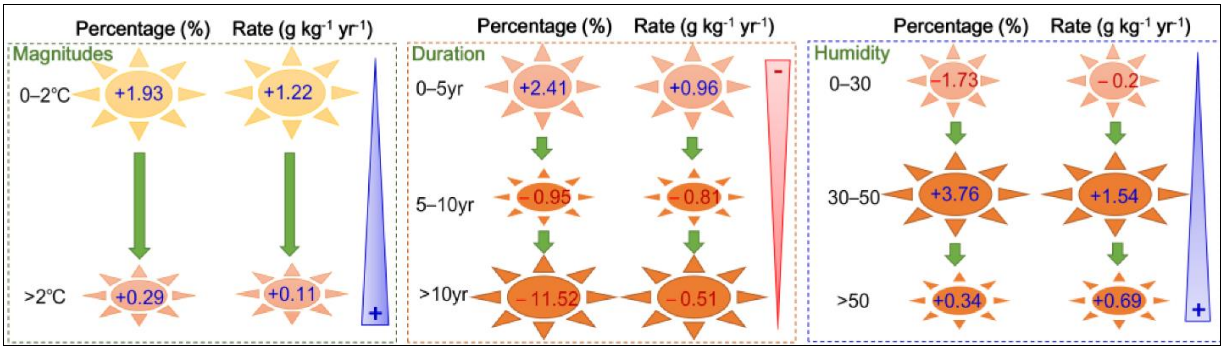

Fig 6: Conceptual framework of the effects of warming on the percentage and change rate of soil organic carbon (SOC) content

Soil moisture is an important factor controlling soil carbon storage and carbon loss under warming conditions [42]. Rising temperatures elevate soil surface temperature and often reduce soil moisture availability [43]. Soil water conditions strongly influence the growth and development of both plants and soil microorganisms [22]. When soils become dry, plant productivity and microbial growth are constrained. Such drying can suppress microorganisms that contribute significantly to carbon sequestration while stimulating microbial groups and enzyme activities associated with carbon decomposition. Together, these processes lead to a decline in SOC levels [10, 44]. Within a suitable temperature range, increasing warming intensity enhances microbial metabolism and speeds up the breakdown of easily decomposable compounds in plant residues. This process promotes the accumulation of more resistant organic compounds derived from plant material and microbial residues [44, 45]. However, excessive warming can weaken this process, eventually shifting SOC dynamics from positive accumulation to net loss [12, 46].

3. Dynamics of SOC Content as Affected by Warming Duration

Earlier research has suggested that prolonged warming does not result in a continuous increase in SOC accumulation. Instead, SOC levels tend to rise initially and subsequently decline over time [10]. In the present study, an increase in warming duration was associated with a significant rise in the percentage change of SOC content in forest soils within the 0–20 or 0–30 cm layer. However, the rate of SOC change showed a declining trend that was not statistically significant (Figure 3 and Figure 6). Notably, when warming persisted for more than five years, the calculated rate of SOC change became negative.

Short-term warming periods (less than five years) generally favor SOC accumulation, whereas medium- and long-term warming (greater than five years) may lead to enhanced SOC emissions. During the early stages of warming, plant growth typically accelerates. Although this growth requires substantial nutrient uptake, the nutrients returned to the soil through plant litter often exceed those consumed by plants, resulting in a net gain in soil nutrients [15, 41]. A recent meta-analysis further demonstrated that short-term warming stimulates increases in soil microbial biomass and enzymatic activity, especially enzymes associated with carbon cycling processes [10]. As a result, although warming initially accelerates litter decomposition, prolonged warming may lead to drought conditions. Such conditions reduce plant photosynthetic activity and limit plant growth, ultimately decreasing the production of plant biomass [18, 19]. This pattern may occur because plants under prolonged warming allocate a greater proportion of their carbon resources toward structures and biochemical compounds that help them tolerate drought stress [46]. In addition, long-term warming can cause soil nutrient depletion and reduce both microbial biomass and microbial activity [10, 18, 19]. These combined effects ultimately generate strong negative feedback on SOC accumulation in forest soils.

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

Changes in SOC levels in response to humidity are closely linked to variations in soil moisture, which are controlled by precipitation and temperature patterns [47, 48]. Our results indicate that, at a global scale, the rate of SOC change in forest soils (0–20 or 0–30 cm) is positively associated with the humidity index. Numerous earlier studies have reported that higher humidity index values correspond to increased soil moisture content. Elevated soil moisture generally promotes the growth and reproduction of soil microorganisms [28, 49]. These microorganisms enhance the ability of plants to utilize soil water and nutrients more efficiently [50]. Consequently, increases in microbial diversity and biological activity accelerate nutrient cycling within soils, which contributes to higher SOC accumulation efficiency [51, 52].

However, the results of this study also suggest that SOC change rates do not continuously increase as the humidity index rises. Instead, the highest SOC change rate occurs when the humidity index lies between 30 and 50. Under optimal soil water and aeration conditions, microorganisms are able to utilize sufficient water resources [53] while also obtaining the oxygen required for metabolic activity. Because SOC dynamics are strongly influenced by microbial decomposition processes, favorable soil moisture conditions can sustain SOC accumulation at relatively high levels [54]. In contrast, both excessively dry and excessively wet conditions can suppress plant root development and microbial activity [55, 56]. Particularly under very high humidity index values, increased soil moisture reduces soil aeration and limits microbial metabolic processes [57, 58]. Moreover, higher humidity levels can promote excessive losses of soil carbon [25], thereby reducing the efficiency of SOC accumulation.

5. Study Limitations

Despite the valuable insights generated by this study, several limitations should be acknowledged. First, the analysis focused only on the influence of warming on the rate of SOC change in forest soils. To obtain a broader understanding of carbon cycling within terrestrial ecosystems, future research should examine the mechanisms controlling SOC dynamics across a wider range of land-use types, including grasslands, shrublands, and wetland ecosystems. Second, this study considered SOC changes primarily within the surface mineral soil layer. Warming may have different effects on SOC accumulation in deeper soil layers compared with surface soils. Therefore, future investigations should evaluate how warming influences SOC dynamics at greater soil depths. Third, soil carbon dynamics in the litter layer also play an important role in regulating carbon cycling within forest ecosystems. The present study examined warming effects only on SOC within mineral soils and did not address potential changes in SOC within the litter layer. Consequently, further studies are needed to explore how warming influences SOC accumulation and transformation within the litter layer of forest ecosystems.

The results indicate that warming has a positive influence on SOC dynamics within the mineral soil layer (0–20 cm or 0–30 cm). Under warming conditions, the rate of SOC change remained positive (0.85 g kg^{-1} yr^{-1}), suggesting that global warming can increase SOC levels in forest soils, rising from 67.47 to 69.90 g kg^{-1}. However, the rate of SOC change declined as both the magnitude and duration of warming increased. Specifically, the rate decreased from 1.22 to 0.11 g kg^{-1} yr^{-1} with stronger warming intensity and from 0.96 to −0.51 g kg^{-1} yr^{-1} with prolonged warming exposure. Notably, SOC change rates became negative when warming lasted longer than five years, indicating that long-term warming may restrict SOC accumulation. Furthermore, higher humidity levels were found to favor SOC storage and enhance the rate of SOC change under warming conditions.

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