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Research Advances on the Effects of Freeze-Thaw Cycles on Soil Respiration: Postprint

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Abstract

The “priming effect” of freeze-thaw action on soil respiration has been confirmed to be widespread in high-latitude and high-altitude regions. In the context of climate warming, these regions will experience more frequent freeze-thaw variations, potentially enhancing the contribution of soil respiration to regional carbon cycling. This paper summarizes the “priming effect” of freeze-thaw action on soil respiration and elaborates on its influence mechanisms from the perspectives of soil physical properties, root turnover, microbial activity, and community structure. Future research should: strengthen studies on high-altitude ecosystems; integrate in-situ observations with laboratory freeze-thaw simulations while further optimizing simulation experiments; comprehensively consider the effects of biotic and abiotic factors; and explore the response mechanisms of soil respiration to freeze-thaw variations from the perspective of soil respiration components.

Full Text

Research Progress on the Effects of Freeze-Thaw Processes on Soil Respiration

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Abstract

The “stimulating effect” of freeze-thaw processes on soil respiration has been confirmed to be widespread in high-latitude and high-altitude regions. Against the backdrop of climate warming, these areas will experience more frequent freeze-thaw variations, which may enhance the contribution of soil respiration to regional carbon cycling. This paper summarizes the “stimulating effect” of freeze-thaw processes on soil respiration and elaborates on the underlying mechanisms from the perspectives of soil physical properties, root turnover, microbial activity, and community structure. Future research needs to: (1) strengthen studies on high-altitude ecosystems; (2) emphasize the combination of in situ observations with laboratory freeze-thaw simulations, and further optimize laboratory simulation experiments; (3) comprehensively consider the influences of biotic and abiotic factors; and (4) explore the response mechanisms of soil respiration to freeze-thaw variations from the perspective of soil respiration components.

Keywords: soil respiration; freeze-thaw fluctuation; stimulating effect; biotic factors; abiotic factors

Soil respiration is the primary pathway for carbon output from terrestrial ecosystems, and even slight changes in soil respiration intensity caused by environmental variations can significantly impact ecosystem carbon balance [1-3]. Soil freeze-thaw is a process in which soil alternately freezes and thaws due to seasonal or diurnal heat cycles, and as a natural phenomenon, it is widespread in high-latitude and high-altitude regions [4-5]. Freeze-thaw processes not only directly alter soil hydrothermal conditions but also profoundly influence soil physicochemical properties [6-7], microbial and enzyme activities [8-9], and root turnover [10-11]. The series of physical, chemical, and biological changes that soils undergo during freeze-thaw periods lead to alterations in material and energy cycling processes and rates [12-14].

In recent years, numerous studies have demonstrated that freeze-thaw processes exert a non-negligible influence on soil respiration, with freeze-thaw period soil respiration accounting for a significant proportion of annual total soil respiration and substantially affecting ecosystem carbon budgets [15]. Currently, research on soil respiration has primarily focused on the growing season, while studies on non-growing season processes, particularly soil respiration during freeze-thaw periods, have lagged behind [16]. High-latitude and high-altitude regions where soil freeze-thaw processes commonly occur are often areas highly sensitive to global warming [17]. Against the backdrop of climate warming, these regions will experience more frequent freeze-thaw variations [18-20], which may produce a “stimulating effect” on soil respiration and enhance its contribution to regional carbon cycling [21-22]. Therefore, systematically investigating the response mechanisms of soil respiration processes to freeze-thaw variations is crucial for accurately assessing ecosystem carbon budgets. This paper summarizes the “stimulating effect” of freeze-thaw processes on soil respiration and its main influencing factors, systematically elaborates on the mechanisms through

which freeze-thaw processes affect soil respiration from the perspectives of soil physical properties and aeration, root turnover, and microbial activity and community composition, discusses the shortcomings and improvement directions of current research methods, and finally, based on current research progress, identifies future research priorities.

1 The Stimulating Effect of Freeze-Thaw Processes on Soil Respiration and Its Main Influencing Factors

In recent years, studies on polar and temperate ecosystems such as arctic tundra, boreal forest, alpine meadows, and marsh wetlands have shown that soil respiration often increases substantially during thawing periods, with freeze-thaw period soil respiration accounting for more than 50% of annual total soil respiration in some cases [23-27]. Many scholars refer to this phenomenon as the “stimulating effect” of freeze-thaw processes on soil respiration [21,28]. Given the significant impact of freeze-thaw processes on soil respiration, the response of soil respiration to freeze-thaw variations has become a hot topic in current soil carbon cycle research [29-30].

Although the stimulating effect of freeze-thaw processes on soil respiration has been confirmed to be widespread across ecosystems, the magnitude of increase in soil respiration varies considerably among different ecosystems. Vestgarden and Austnes [31] found in a simulated freeze-thaw study in Norwegian peatlands that soil respiration rates increased by an average of 48% after freeze-thaw treatment. For some arctic tundra and alpine tundra ecosystems, however, the increase in soil respiration rates can reach more than 50-fold, with distinct peaks [29]. Compared with tundra ecosystems, forest ecosystems generally have higher soil respiration rates during freeze-thaw periods [15]; studies in temperate forests have shown that forest soil respiration rates also increase several-fold during thawing periods and can last for extended durations, with multiple distinct emission peaks [26,32].

Changes in soil respiration during freeze-thaw periods are also influenced by factors such as freezing temperature, pre-freezing soil moisture content, and freezing duration. Neilsen et al. [33] were among the first to use simulated freeze-thaw experiments to investigate the response of boreal forest soil respiration to freezing temperature variations, finding that soils frozen at -13°C emitted significantly more CO_2 during thawing than those frozen at -8°C , which in turn emitted more CO_2 than soils frozen at -3°C . Subsequently, Goldberg et al. [34] and Wei et al. [26] also found in Norwegian spruce forests and larch plantations in northeastern China that lower freezing temperatures led to higher soil respiration rates during thawing. Regarding the effects of pre-freezing soil moisture content variations on soil respiration processes during freeze-thaw periods, Wu et al. [35-36] and Chu et al. [37] conducted studies on typical ecosystems including forests, grasslands, marshes, and croplands, demonstrating that soil respiration rates were significantly higher under high moisture conditions than under low moisture conditions. However, the mechanisms through which soil

moisture changes during freeze-thaw processes affect soil respiration remain unclear. These studies also found that with prolonged freezing duration, soil respiration was more likely to peak during thawing. The number of freeze-thaw cycles is another important factor influencing the response of soil respiration processes to freeze-thaw variations [5]. Some studies have found that distinct peaks in soil respiration generally occur during the thawing periods of the first several freeze-thaw cycles, but as the number of cycles increases, the magnitude of increase in soil respiration rates gradually diminishes until stabilization [38-40]. It is generally believed that lower freezing temperatures, longer freezing durations, and higher pre-freezing soil moisture content make it more likely for soil respiration to peak during thawing, but the magnitude of increase gradually decreases with increasing numbers of freeze-thaw cycles.

Soil freeze-thaw is typically accompanied by snowfall. Changes in snow cover thickness and duration can affect freeze-thaw period soil respiration rates by altering surface soil temperature and increasing or decreasing the number of freeze-thaw cycles [15,32,41]. Yang et al. [42] conducted a snow removal experiment in a subalpine spruce forest in western Sichuan and found that snow removal increased the amplitude of soil temperature fluctuations, adding 39 freeze-thaw cycles to surface soils in winter and reducing soil respiration rates by 21.02%. In contrast, Li et al. [43] found through meta-analysis that increased snow cover thickness raised soil respiration rates by an average of 15.5%. Zhu et al. [44] observed similar phenomena in alpine wetlands and croplands. They also found that longer snow cover duration led to greater increases in soil respiration rates during thawing periods, though emission peaks were delayed. Current research on the effects of freeze-thaw processes on soil respiration has primarily focused on mid- to high-latitude regions, while studies on high-altitude areas—where permafrost and seasonally frozen soils are widely distributed and highly sensitive to climate change—remain relatively scarce.

2 Mechanisms of Freeze-Thaw Effects on Soil Respiration

Soil respiration is primarily composed of microbial respiration and root respiration [45-47]. It is generally believed that freeze-thaw processes affect soil respiration by altering soil physical properties and aeration, root turnover, and microbial activity and community structure [9,39,48].

2.1 Effects of Freeze-Thaw Processes on Soil Physical Properties

Freeze-thaw processes influence soil respiration through changes in soil physical properties in the following ways: (1) During freezing, ice films form on soil particle surfaces, hindering the outward diffusion of CO₂ produced by soil microbial metabolism and root autotrophic respiration, causing CO₂ to accumulate in the soil and creating emission peaks during thawing [35,49]; (2) When liquid water in soil pores freezes into ice, volume expansion destroys soil aggregate structure, subsequently releasing large amounts of labile organic carbon that can be utilized by microorganisms, thereby increasing soil respiration rates

[5,50]. Generally, freeze-thaw processes can destroy soil structure and affect aggregate stability, with the degree of destruction primarily related to soil water content, freezing temperature, number of freeze-thaw cycles, and aggregate size [51-55]. The essence of soil freeze-thaw processes is soil water phase transition caused by temperature changes; therefore, the effects of freeze-thaw on aggregates are closely related to soil water content and temperature. Wang et al. [56] demonstrated that under the same temperature conditions, freeze-thaw processes caused the strongest damage to aggregates when soils reached saturated water content; under the same water content conditions, aggregate stability showed a quadratic functional relationship with temperature. Xu et al. [57] also found that soil water content was an important factor affecting aggregate stability during freeze-thaw processes, and that as water content increased, water-stable aggregates with particle sizes >2 mm showed a decreasing trend, while aggregates with particle sizes <1 mm showed an increasing trend. Li et al. [55] found that freeze-thaw processes could break large soil aggregates into smaller ones, and that lower freezing temperatures and more freeze-thaw cycles led to more pronounced fragmentation of large aggregates. Xiao et al. [58] further revealed that the destruction of soil aggregates by freeze-thaw processes mainly resulted from reduced content of hydrophobic glycoproteins such as glomalin that participate in aggregate formation. Additionally, freeze-thaw processes can increase soil porosity and improve soil aeration, promoting CO_2 emissions during thawing [59].

2.2 Effects of Freeze-Thaw Processes on Root Turnover

The most direct effect of freeze-thaw processes on roots is physical damage leading to root mortality. The decomposition of dead roots increases the content of labile substrates available to microorganisms in the soil, promoting soil microbial respiration [11,60-62]. Studies by Cleavitt et al. [10] and Tierney et al. [62] in secondary broadleaf forests in the United States confirmed this understanding and estimated that fine root mortality during freeze-thaw periods could lead to the release of more than $1.5 \text{ g C} \cdot \text{m}^{-2}$ and $0.5 \text{ g N} \cdot \text{m}^{-2}$. In situ studies by Wu et al. [63] in spruce forests in western Sichuan further demonstrated that freeze-thaw processes not only increased fine root mortality rates but also enhanced rhizosphere microbial activity during later freeze-thaw stages by promoting the release of elements such as C, N, P, and K from dead fine roots, thereby facilitating the decomposition of fine root residues. Freeze-thaw processes can also affect root autotrophic respiration by altering fine root growth processes. The effects of freeze-thaw processes on root growth are mainly manifested in the following aspects [11,64]: (1) Freezing hinders water and nutrient exchange at the root-soil interface, causing some roots to experience difficulty in normal growth due to water and nutrient limitations; (2) When soil freezes, anaerobic respiration dominates in roots, and the accumulation of harmful secretions produced by anaerobic respiration inhibits root growth. Due to the suppression of fine root growth by soil freezing, the stimulating effect of freeze-thaw processes on root autotrophic respiration is limited [11].

2.3 Effects of Freeze-Thaw Processes on Microbial Activity and Community Structure

Similar to chloroform fumigation and wet-dry alternation processes, freezing also causes soil microbial death. The C, N, P, and other nutrients released from dead microorganisms enhance the activity of surviving microorganisms, promoting soil microbial respiration during thawing [65-69]. Some studies have found that a single freeze-thaw cycle can cause the death of more than 50% of microorganisms [40]. Using ^{14}C tracer technology, Herrmann and Witter [38] discovered that 65% of CO_2 emitted from soils during thawing originated from microbial residues. Furthermore, the destruction of aggregates and the release of labile organic carbon from fine root mortality caused by freeze-thaw processes further increase substrate availability for microorganisms in the soil, enhancing microbial activity. Gao et al. [70] found in a study of major temperate forests in the Changbai Mountains that both microbial activity and quantity in surface soils significantly increased after multiple freeze-thaw cycles. Other studies have indicated that soil microorganisms in alpine regions may exhibit certain adaptability to freeze-thaw cycles due to their adaptation to low temperatures [71].

Freeze-thaw processes also significantly impact soil microbial community structure [5,72]. Based on high-throughput sequencing methods, Kreyling et al. [11] found that freeze-thaw processes significantly increased fungal activity, particularly that of saprotrophic fungi. Liu et al. [73] discovered that the number and diversity of bacteria in surface soils significantly decreased after multiple freeze-thaw cycles in subalpine forests of western Sichuan. Ollivier et al. [74] and Juan et al. [75] further found that freeze-thaw processes could cause changes in specific bacterial functional groups, significantly affecting microbial functional traits. Overall, freeze-thaw processes can shift soil microbial communities from bacteria-dominated to fungi-dominated [76-77]. Fungi have higher carbon assimilation efficiency than bacteria, meaning they assimilate more carbon and release less carbon during metabolism. Moreover, fungal cell walls are primarily composed of carbon polymers, which are more difficult to decompose than bacterial cell walls (mainly composed of peptidoglycan and phospholipids) [78-80]. Therefore, ecosystems dominated by fungal communities generally have relatively lower soil respiration rates [80-82]. The shift from bacteria-dominated to fungi-dominated microbial communities under freeze-thaw processes is not conducive to CO_2 emission peaks during thawing.

3 Main Research Methods for Studying Freeze-Thaw Effects on Soil Respiration

In situ observation and laboratory freeze-thaw simulation are the primary means for studying the effects of freeze-thaw processes on soil respiration [4,29]. In situ observation generally requires sophisticated field experimental platforms and is susceptible to environmental disturbances [83], whereas laboratory freeze-thaw

simulation experiments are currently more commonly used due to their low cost and strong controllability [40]. Laboratory simulation experiments typically use incubators or refrigerators to control temperature and achieve soil freeze-thaw simulation [4,5]. Because the freeze-thaw environment in which soils are placed differs significantly from natural conditions, research results are easily affected by factors such as sampling time and methods, temperature variation amplitude, freeze-thaw cycle duration, and number of cycles. Therefore, when conducting laboratory freeze-thaw simulations, the following aspects should be noted to approximate natural conditions [4-5]: (1) Soil microorganisms and root turnover exhibit distinct seasonal variation characteristics [10,76]. Soils collected in spring and summer have just experienced freeze-thaw cycles, so incubation results may differ from those for soils collected in autumn and winter [40]. Therefore, soil samples for freeze-thaw simulation experiments should be collected in autumn and winter; (2) Under natural conditions, air temperature changes are gradual processes. Consequently, during laboratory incubation, rapid temperature fluctuations that cause rapid microbial death should be avoided [83]; (3) Under natural conditions, temperature changes during soil freezing and thawing occur from top to bottom. Therefore, during laboratory incubation, soil temperature changes should be ensured to begin from the surface layer as much as possible [26,31]; (4) Snow cover and litter on the soil surface should be considered in freeze-thaw simulations, as they can buffer temperature changes on the one hand and affect changes in soil moisture and nutrient content during thawing on the other [42-43]; (5) In existing studies, freeze-thaw cycles are generally designed to last 1-2 days, and the number of freeze-thaw cycles is typically fewer than 5, which is far less than actual field conditions. Therefore, when conditions permit, freeze-thaw cycle duration and number should be increased as much as possible. Despite the limitations of laboratory freeze-thaw simulation, it remains the primary means for studying the mechanisms of soil respiration response to freeze-thaw variations and serves as an important supplement to in situ research. Combining field in situ research with laboratory freeze-thaw simulation can achieve complementary advantages and mutual validation, thereby contributing to a more accurate and in-depth understanding of the mechanisms through which freeze-thaw processes affect soil respiration.

4 Research Prospects

In summary, research on the response of soil respiration to freeze-thaw variations will exhibit the following development trends:

1. Related studies both domestically and internationally have mainly focused on mid- to high-latitude ecosystems such as arctic tundra, boreal forest, peatlands, and marsh wetlands, while research on high-altitude ecosystems—where permafrost and seasonally frozen soils are widely distributed and highly sensitive to climate change—remains relatively weak. Therefore, studies on the response of soil respiration processes to freeze-thaw variations in high-altitude cold ecosystems need to be strengthened.

2. Due to limitations in research methods, current understanding of the response patterns of soil respiration to freeze-thaw variations shows considerable divergence. Future research should emphasize the combination of in situ observations with laboratory freeze-thaw simulations and further optimize laboratory simulation experimental protocols to better approximate natural conditions.
3. The response of soil respiration to freeze-thaw variations is a comprehensive effect process influenced by multiple factors. Actively exploring new research approaches and comprehensively considering changes in biotic and abiotic factors such as soil hydrothermal conditions, physicochemical properties, microbial processes, and root turnover will help elucidate the mechanisms underlying soil respiration responses to freeze-thaw variations.
4. Although researchers have conducted some exploratory studies on the variation characteristics of soil respiration during freeze-thaw periods, there remains a lack of investigation into the response mechanisms of soil respiration to freeze-thaw variations from the perspective of soil respiration components.

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