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Title Page

Effects of warming and increased precipitation on soil heterotrophic respiration and its temperature sensitivity in the desert steppe

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Abstract

Background Feedback between climate change and soil carbon emissions plays an important role in the grassland carbon cycle. However, the response mechanism of soil heterotrophic respiration (Rh) and its temperature sensitivity (Q_{10}) to long-term warming, increased precipitation and their interaction in the desert steppe remain unclear, and the effects of monitoring frequency on Rh and Q_{10} remain unquantified.

Methods After eight years of warming (ambient temperature, T0; warming 2 ℃, T1; warming 4 ℃, T2) and increased precipitation (natural precipitation, W0; precipitation enhancement 25%, W1; precipitation enhancement 50%, W2), soil samples were

collected and physical and chemical properties, Rh and Q_{10} were monitored.

Results Warming significantly increased soil water content, and the interaction between warming and precipitation also significantly affected soil water content. The response of Rh and Q_{10} to warming and precipitation showed clear frequency dependence. Specifically, warming significantly reduced high and low frequency Rh. For Q_{10}, except for T2, warming and precipitation increased significantly reduced high-frequency Q_{10}, while warming and precipitation increase and their interaction reduced low frequency Q_{10}. Compared with low-frequency monitoring, high-frequency monitoring resulted in lower Rh and higher Q_{10}. Rh in the desert steppe is mainly regulated by SOC, and Q_{10} is mainly regulated by soil bulk density.

Conclusions High-frequency monitoring is more conducive to accurate assessment of changes in Rh and Q_{10} in desert steppe. SOC and soil bulk density are the dominant factors affecting Rh and Q_{10} in the desert steppe under future climate change.

Keywords desert steppe; climate change; soil characteristics; soil heterotrophic respiration; temperature sensitivity

1. Introduction

Global warming, along with shifts in regional precipitation regimes, has profoundly altered the structure, functioning, and biogeochemical cycles of terrestrial ecosystems. These changes now constitute a central focus of research in global change ecology (Calvin et al. 2023). The desert steppe, one of the most widespread ecosystem types in arid and semiarid regions, is characterized by environmental fragility, low resilience, high sensitivity to hydrothermal fluctuations, and a small soil carbon pool with rapid turnover. It is among the most sensitive ecosystem types to climate change (Mu et al. 2024; Quan et al. 2025). The interactive effects of warming and increased precipitation will directly alter the soil hydrothermal regime, physical structure, and carbon cycling processes in desert steppes. Elucidating these response mechanisms is critical for understanding the stability of ecosystems in arid regions in the context of climate change (Guo et al. 2022; Bao et al. 2025).

Soil physical and chemical properties are the core basis for regulating soil ecological processes. Soil water content, bulk density, organic carbon and total nitrogen jointly determine soil aeration, nutrient availability and the microbial living environment (Kang et al. 2024), which are the key links between climate change and soil carbon cycle (Adhikari and Hartemink 2016; Zhao et al. 2019). The desert steppe ecosystem is known to be highly sensitive to water and heat availability, as documented in numerous previous studies. Precipitation changes can directly change soil water content and nutrient availability. Warming exerts a complex water-heat-nutrient interaction effect by accelerating evaporation and organic matter mineralization (Liu et

al. 2014; Zhang et al. 2024). Under short-term climatic disturbance, the physicochemical properties of arid soils exhibit strong overall stability, whereas soil water content is a key property sensitive to hydrothermal changes. This observation provides an important basis for understanding the climate adaptability of the carbon cycle in the desert steppe ecosystem (Xu et al. 2016; Yu et al. 2020).

Soil respiration is the main pathway of soil carbon release in the desert steppe, and its rate and temperature sensitivity determine the intensity of feedback of the ecosystem carbon cycle to climate warming (Bond-Lamberty and Thomson 2010; Feng et al. 2018). To date, numerous studies have been carried out related to climate change in the desert steppe. Studies have found that warming can increase soil enzyme activity and promote respiration rate, while increasing precipitation can alleviate drought stress and enhance microbial activity , with the interaction between the two often shows a non-additive effect on the soil carbon cycle (Zhou et al. 2013; Su et al. 2020). Other studies suggest that changes in soil physicochemical properties indirectly mediate the response of soil respiration to hydrothermal fluctuations, although the findings remain inconsistent(Wang et al. 2023).

Although progress has been made in climate change research in desert steppe ecosystems, comparative studies on the reliability of Rh and its Q_{10} estimates under different measurement frequencies remain scarce. As the core parameter describing the temperature sensitivity of soil heterotrophic respiration, any deviation in Q_{10} estimation will directly propagate through carbon cycle model outputs. Consequently, whether differences in measurement frequency cause overestimation or underestimation of Q_{10}

will have a direct bearing on the accuracy of regional and global carbon balance assessments.

In a desert steppe, we established a factorial combination of three warming gradients (i.e., no warming, T0; mild warming 2°C, T1; strong warming 4°C, T2) and three precipitation gradients (i.e., natural precipitation, W0; increasing precipitation 25%, W1; increasing precipitation 50%, W2) to investigate how short-term climatic manipulation affects soil physicochemical properties, soil respiration (Rh), and its Q_{10} temperature sensitivity. The goals of this study were: (1) to characterize the response of soil physicochemical properties to short-term hydrothermal fluctuations in a desert steppe; (2) to compare the responses of Rh and Q_{10} to these changes under high- versus low-frequency measurement regimes; and (3) to elucidate the regulatory role of soil physicochemical properties in mediating the temperature sensitivity of respiration, thereby providing a scientific basis for improving carbon cycle projections in arid regions under climate change.

2. Materials and Methods

2.1 Experiment site

The experiment site is located in the northeast of Siziwang Banner, Inner Mongolia Autonomous Region (N41°47′18″, E111°53′44″) (Fig.1a). The region has a temperate monsoon climate, and the growing season is concentrated from May to October every year, with the vigorous growth period in mid-August. The average temperature in the growing season (May-October) of 2023 was 15.5 °C, and precipitation in the same period was 297.7 mm (Fig. S1). According to the soil classification standard of the Food

and Agriculture Organization of the United Nations (FAO), the soil type in the experiment site is Haplic Calcisols.

2.2 Experimental design

This study was based on a long-term warming and precipitation experimental platform in desert steppe established by the Institute of Botany of the Chinese Academy of Sciences in Spring 2014. A 2 × 3 factorial experiment was used to set up a total of 9 treatment combinations, with 4 replicates of each treatment, making a total of 36 experimental plots (Fig.1b). Open Top Chambers (OTCs) were used to simulate the warming gradient. The bottom of each OTC is a regular hexagon with an area of 5.85 m^2. The targets of no warming (T0), mild warming of 2 °C (T1), and strong warming of 4 °C (T2) were achieved by different OTC heights (i.e., 0.2 m, 1 m, 2.3 m). The light transmittance of the OTCs is more than 90%. Each is equipped with two air circulation fans and one inlet and outlet door to ensure the gas exchange and enable observations. The precipitation enhancement treatment is realized by precipitation interception devices. The bottom areas of the devices are 25% and 50% of the OTC bottom area, respectively, corresponding to a 25% increase in natural precipitation (W1) and a 50% increase in natural precipitation (W2). When natural precipitation occurs, the interception device collects rainwater into the storage bucket and evenly sprays it into the corresponding OTC to simulate the precipitation enhancement scenario.

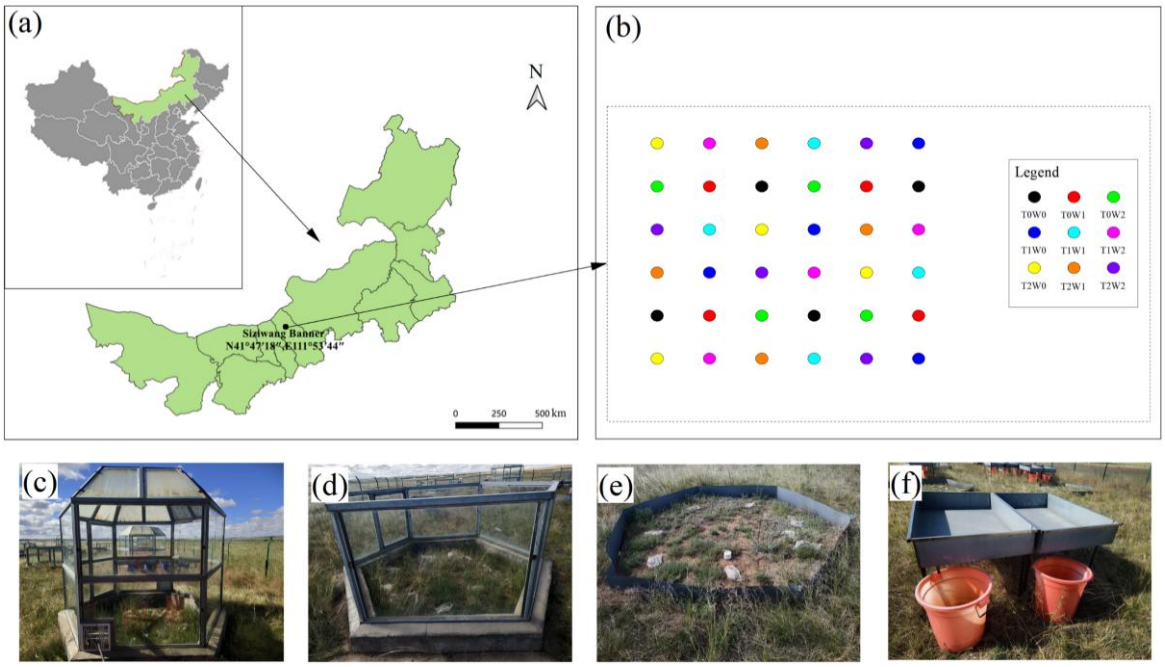


Fig. 1 Experimental site (a); plot distribution (b); warming 4 ℃ (c); warming 2 ℃ (d); no warming (e); rainfall collection (f); T0 represents surface temperature; T1 represents 2 ℃ warming; T2 represents 4 ℃ warming; W0 represents natural precipitation; W1 indicates a 25% increase in precipitation; W2 indicates a 50% increase in precipitation.

2.3 Soil sampling and determination

Soil samples were collected in mid-August 2023. The specific determination process was as follows. Determination of soil physical and chemical properties: The undisturbed soil samples from the 0-10 cm surface soil in each OTC were sampled using a 100 cm 3-ring knife. Soil water content, bulk density and field water holding capacity were calculated by measuring the fresh weight, saturated water absorption weight and drying weight of the soil in the ring knife. At the same time, HH2 thermometers (Delta-T Devices Ltd., UK) were used to record the surface soil

temperature of each OTC in real time. To measure soil chemical properties, a 2.5 cm diameter soil auger was used to collect surface soil samples from the 0-10 cm surface soil in each OTC using a five-point sampling method. The samples from the same OTC were mixed and divided into three equal parts. Part of the soil was air-dried, ground (of which part was acid-treated for the determination of soil organic carbon), and then placed in an elemental analyzer (Vario Isotope Select, Elementar, Germany) to determine soil total carbon, total nitrogen content and soil organic carbon content. Soil available nitrogen was determined by the alkali diffusion method.

Determination of soil heterotrophic respiration rate (Rh): Five soil samples were collected in each OTC using the five-point sampling method with a 2.5 cm diameter soil auger, and mixed into a representative sample, which was stored at low temperature for Rh determination. According to the water content and water holding capacity of the soil in each OTC, distilled water was added to adjust the soil water content to 50-60 % of water holding capacity, based on the optimum moisture range of Rh (Howard and Howard 1993; Zhang and Zhou 2018).The culture flask was sealed with perforated cling film and weighed, and pre-cultured in a LHP-250E constant temperature and humidity incubator (Henan Brothers Instrument, China) for seven days to activate microorganisms and eliminate the pulse effect. Soil moisture was corrected every two days during pre-incubation.After incubation, the culture flask was placed in a PRI-8800 automatic temperature-controlled soil flux measurement system (Beijing PRI-ECO Company, open system) to determine Rh. During the measurement, nitrogen was continuously introduced to avoid the inhibition of respiration by high CO_2 concentration.

160 The temperature gradient was set to 5-35 °C (High frequency intervals of 2 ℃; low
161 frequency intervals of 5 ℃). Each sample was continuously measured for 180 s, and
162 the Rh rate was calculated according to the slope of the CO_2 concentration change.

163 The calculation formula for Rh was (Li et al. 2017; Liu et al. 2018):

164 $$R_h = \frac{C \times V \times \alpha \times \beta}{22.4 \times m}$$

165 where Rh represents soil heterotrophic respiration rate (μg CO_2-C g^{-1} soil d^{-1}); c
166 represents the slope of CO_2 concentration change; v represents the volume of the culture
167 flask; α and β represent the conversion coefficients of CO_2 mass and time, respectively;
168 m denotes soil weight; and 22.4 is the standard gas volume (L mol^{-1}).

169 The following exponential equation was used to calculate Q_{10} (Taylor 1994):

170 $$R_h = a \times e^{bT}$$

171 $$Q_{10} = e^{10b}$$

172 where Rh represents soil heterotrophic respiration rate (μg CO_2-C g^{-1}soil d^{-1}); *a*
173 represents the net heterotrophic respiration rate of soil at 0 ℃; *b* denotes the temperature
174 sensitivity coefficient; *t* represents soil temperature during the measurement; and Q_{10}
175 represents the temperature sensitivity of Rh.

176 **2.4 Data analysis**

177 Before further analysis, we tested normality of the data using the Shapiro-Wilk
178 test in IBM SPSS Statistics 27. Results showed that all the data were normally
179 distributed. First, a generalized linear model (GLM) was used to analyze the
180 independent and interactive effects of temperature and precipitation increase on soil
181 physical and chemical properties, soil heterotrophic respiration rate and temperature

sensitivity. The GLM was as follows:

$$Y = T + P + T \times P + I$$

where Y represents the soil index; T represents the temperature rise; P indicates an increase in precipitation; $T \times P$ represents the interaction between temperature increase and precipitation increase; and I is the intercept.

Second, one-way analysis of variance (one-way ANOVA) was used to examine the differences in soil indicators under nine treatments and Rh and Q_{10} under different measurement frequencies. In addition, redundancy analysis was performed in Canoco 5 (Biometris, Netherlands) to explore the relationship between soil physical and chemical properties and Rh and Q_{10}. Microsoft Excel 2019, Origin 2021 (Origin Lab, U.S.), and QGIS Desktop 4.0.3 were used to create tables and charts.

3. Results and Analysis

3.1 Soil physical properties

The GLM showed that warming, precipitation and their interactions had no significant effects on soil temperature, bulk density or field capacity (p 0.05) (Fig. 2). However, warming had a significant effect on soil water content (p = 0.042), and the interaction between warming and precipitation enhancement was also significant (p = 0.022), while the effect of precipitation enhancement alone was not significant (p = 0.688). This shows that the interaction is the dominant factor regulating soil water content.

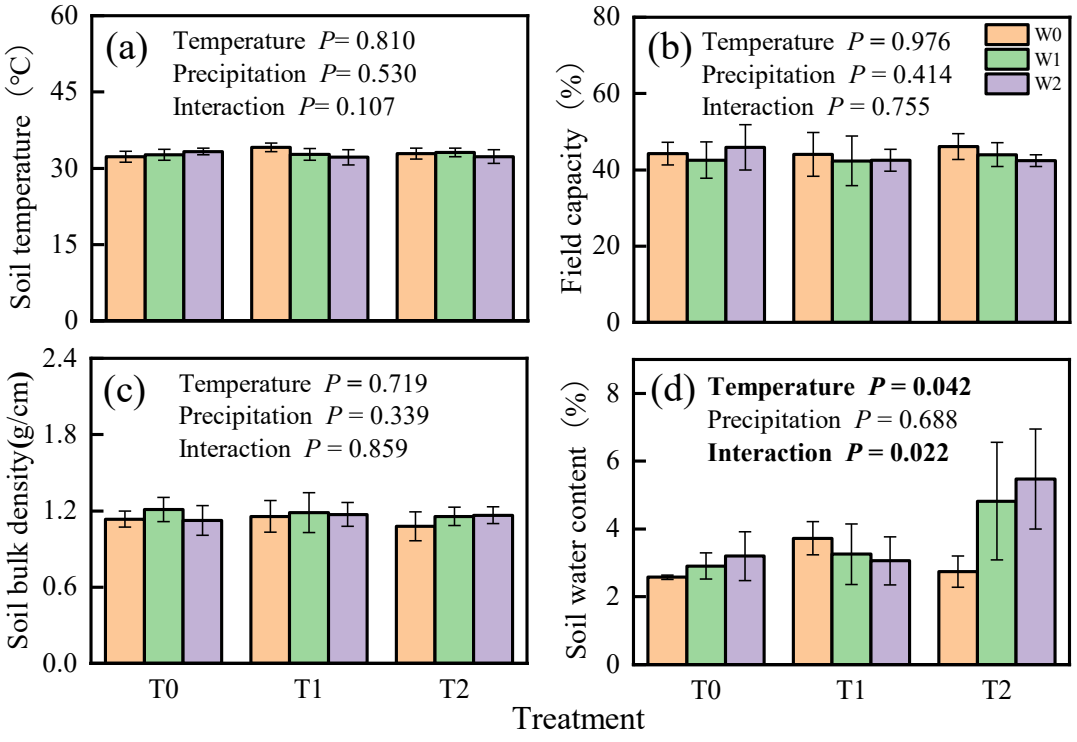


Fig. 2 General linear model and one-way analysis of variance for the effects of warming, precipitation and their interactions on soil physical properties. T0 represents surface air temperature, T1 represents surface air temperature increased by 2°C, T2 represents surface air temperature increased by 4°C; W0 represents natural precipitation, W1 represents natural precipitation increased by 25%, and W2 represents natural precipitation increased by 50%. The same below.

3.2 Soil chemical properties

Warming, precipitation and their interaction had no significant effects on soil total carbon, total nitrogen, organic carbon or alkali-hydrolyze nitrogen (p 0.05) (Fig. 3), indicating that soil chemical properties were not sensitive to the response of warming and precipitation.

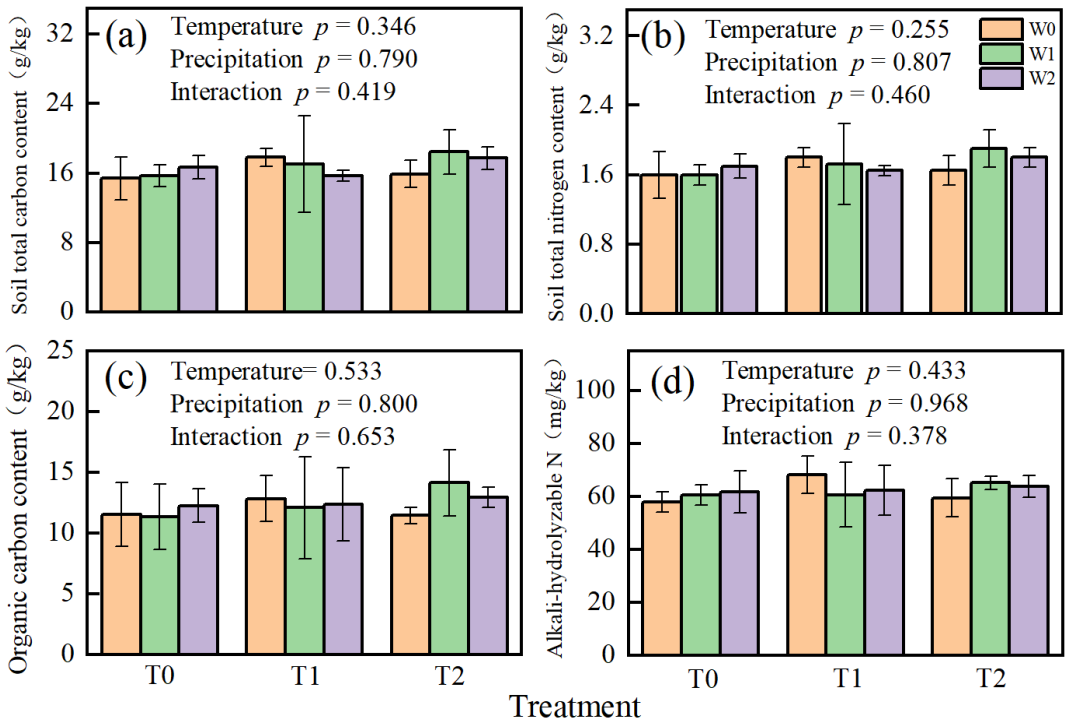


Fig.3 Effects of warming and precipitation enhancement and their interaction on soil physical properties

3.3 Soil heterotrophic respiration (Rh) and its temperature sensitivity (Q_{10})

The general linear model showed that high-frequency and low-frequency Rh and their Q_{10} displayed significantly different response patterns under different treatments (Fig. 4). For high-frequency Rh, temperature had a significant effect (p = 0.004), while precipitation and their interaction were not significant (p = 0.812 and 0.227). Low-frequency Rh was only significantly regulated by temperature (p = 0.034), while precipitation and their interaction had no significant effect (p = 0.787 and 0.651). In terms of Q_{10}, high-frequency Q_{10} was significantly affected by temperature ($p < 0.001$), and precipitation also had a significant effect (p = 0.029), but the interaction was not significant (p = 0.209). However, low-frequency Q_{10} had significant responses to temperature, precipitation and their interaction (p = 0.007,0.003 and 0.037). In summary,

the Rh and Q_{10} of the low-frequency process are more sensitive to hydrothermal conditions and their synergistic effects, while the high-frequency process is mainly regulated by temperature, indicating that the respiratory components of different frequencies may be controlled by different environmental mechanisms.

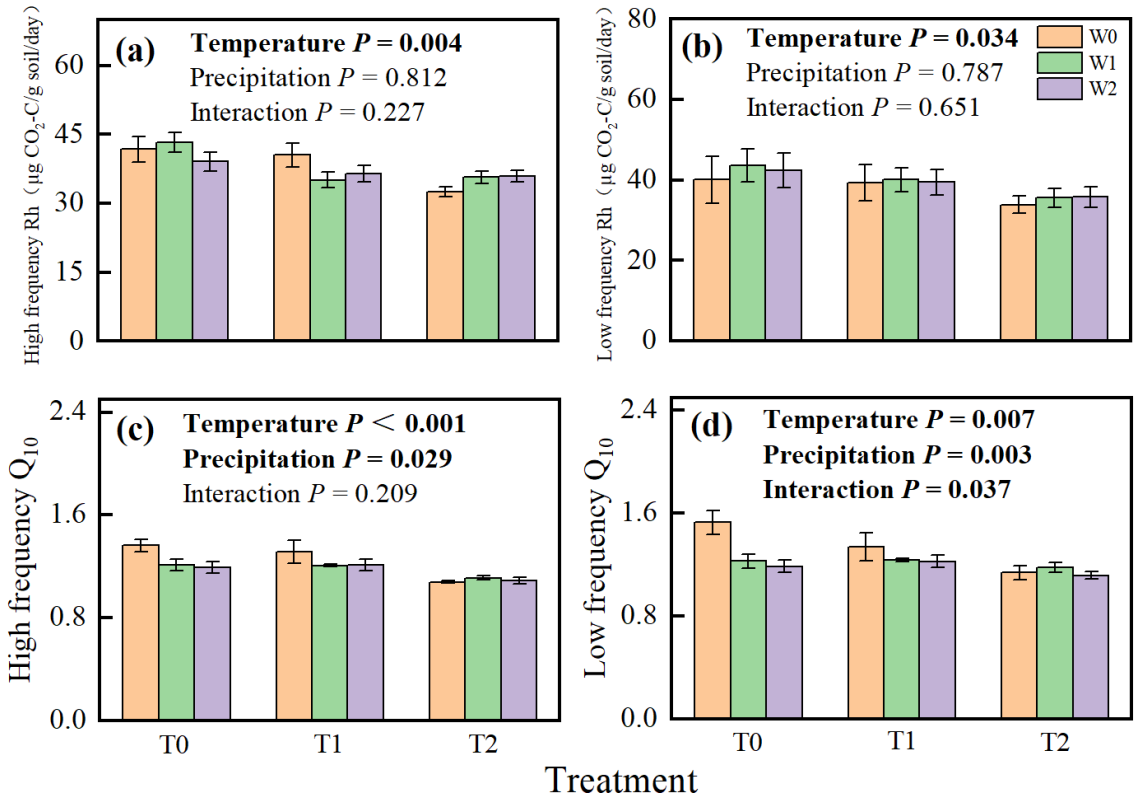


Fig. 4 Variation in Rh and Q_{10} under different treatments

3.4 Differences in Q10 and Rh at different temperature monitoring frequencies

Analysis of variance showed that the average value of Rh was similar under high frequency and low frequency monitoring conditions, and the difference between treatment groups was not significant (NS)(Figure 5a). However, the difference in Q_{10} between the two monitoring frequencies reached a significant level ($p<0.05$)(Figure 5b), indicating that monitoring frequency had a significant effect on the estimation of Q_{10}.

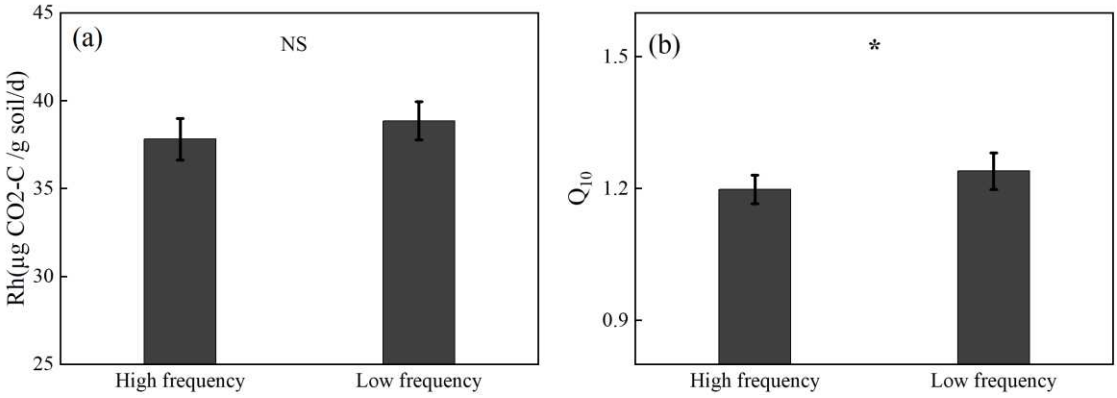


Fig. 5 Difference of Q_{10} under different temperature monitoring frequencies

Note: NS indicates not significant; * indicates significant at $p<0.05$.

The results of redundancy analysis showed that there were significant differences in the composition and contribution of environmental factors affecting Rh and Q_{10}. For Rh (Figure 6a), the first RDA axis explained 45.29 % of the variation, and the factor contribution (Figure 6b) was dominated by soil organic carbon (SOC), with a contribution rate of 63.1 % ($p < 0.01$), followed by soil moisture (SWC, 17.1 %) and soil bulk density (SDB, 16.8 %), while the remaining factors contributed less than 2 %. For Q_{10} (Figure 6c), the first RDA axis explained 43.64 % of the variation. The largest contributing factors (Figure 6d) were soil bulk density (SBD) at 54.2 % ($p < 0.01$) and soil moisture (SWC) of 29.3 % ($p < 0.01$), and the remaining factor contributions were 7.7 %, 4.1 %, 3.6 % and lower. The overall explanatory power was more dispersed for Q_{10} than for Rh. In summary, Rh was mainly controlled by organic carbon, and Q_{10} was dominated by soil bulk density and water, and the composition and contribution structure of the two environmental factors were significantly different.

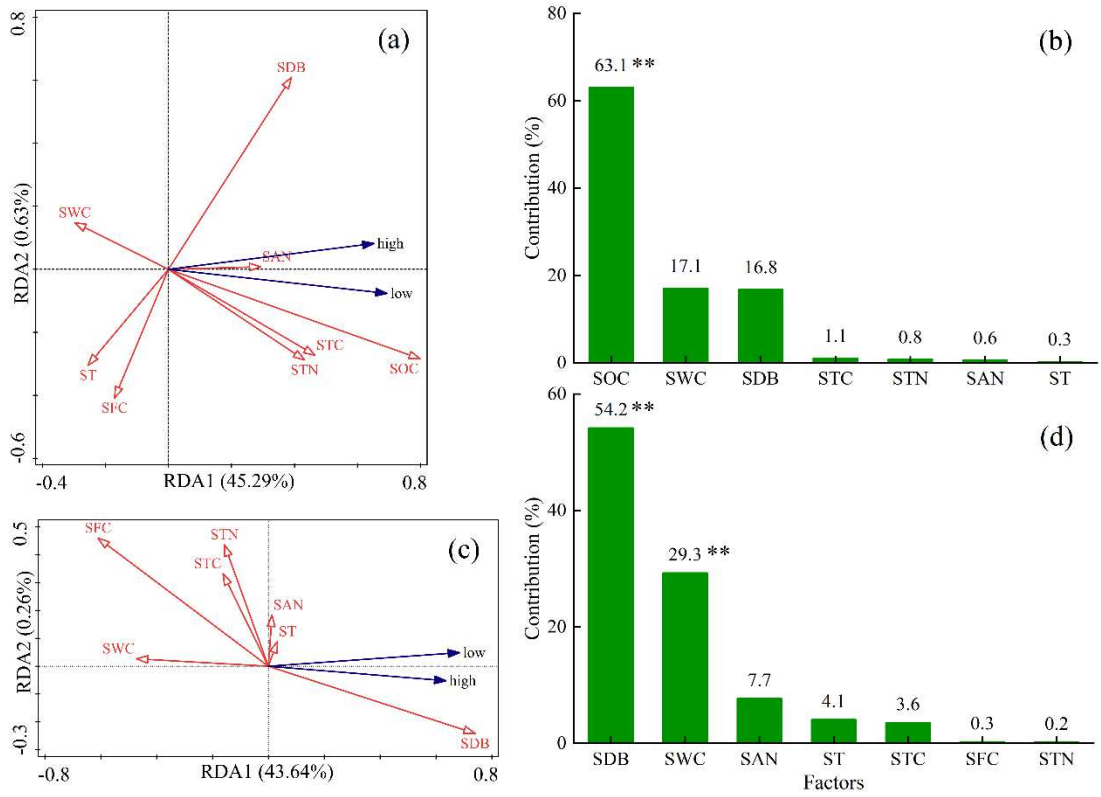


Fig. 6 Redundancy analysis of Rh and Q_{10} with soil physical and chemical properties

Note: Figure (a) is Rh redundancy analysis; figure (b) indicates contributions to the Rh factor; figure (c) is Q_{10} redundancy analysis; figure (d) shows the Q_{10} factor contributions; * * is extremely significant at $p < 0.01$; * is significant at $p < 0.05$.

4. Discussion

4.1 Responses of soil physical and chemical properties to climate change

Soil physical and chemical properties are an important basis for material circulation and energy flow in desert grassland ecosystems, and their response patterns to warming and precipitation increase directly affect the stability and sustainability of the ecosystem (Yin et al. 2023). In this study, there were no significant differences in soil bulk density, soil temperature or field water holding capacity under different

warming and precipitation treatments (p 0.05), indicating that short-term warming and precipitation increase did not change the overall level of soil pore structure, water holding potential and the thermal environment, suggesting strong stability of the soil physical system. This is consistent with the research results of Luo et al. (2017) in a temperate grassland. Short-term climate disturbance does not easily disturb the steady state of soil aggregate structure and pore distribution. Therefore, physical indicators such as bulk density, field water holding capacity and soil temperature show strong buffering capacity. In terms of soil chemical properties, the main nutrient indexes such as soil organic carbon and total nitrogen did not show significant differences under different treatments in this study, indicating that the soil nutrient pool in the desert steppe had strong resistance to short-term climate change. Due to the low organic matter content, slow decomposition rate and long-term water limitation in the desert steppe, short-term warming and precipitation increase were insufficient to change the overall balance of soil organic matter accumulation and mineralization, so soil chemical properties remained stable as a whole. This phenomenon is consistent with relevant findings from the temperate desert steppe of Inner Mongolia, where soil carbon and nitrogen respond weakly and conservatively to short-term climate fluctuations in arid areas. (Mu et al. 2024).

In terms of soil water status, this study found a significant interaction between warming and precipitation increase (p = 0.022), resulting in a significant warming-dependent response of soil water content. In the non-warming T0 treatment, soil water content increased significantly with increasing precipitation intensity, and SWC

293 followed the order W2 (+50%) W1 (+25%) W0 (natural precipitation), as one
294 would expect after direct supplement of soil moisture by exogenous precipitation.
295 However, under moderate warming (T1), SWC decreased with increasing precipitation
296 intensity, and the water content of the W2 treatment was slightly lower than that of W0
297 and W1. This result is likely due to increased soil evaporation and vegetation
298 transpiration potential under warming conditions. When the increase in precipitation is
299 insufficient to offset the water consumption caused by warming, there will be a reverse
300 response of SWC to precipitation intensity, which is consistent with the hydrothermal
301 interaction regulation mechanism proposed by Nielsen et al (Nielsen et al. 2024). Under
302 strong warming (T2), SWC increased with increased precipitation intensity, and the
303 overall level of SWC was significantly higher than that under T0 and T1, indicating that
304 high-intensity precipitation can effectively offset the water loss caused by severe
305 warming and re-dominate the process of soil water recharge.

306 In this experiment, soil temperature (ST) did not exhibit a strong gradient across
307 treatments and ST was not regulated by precipitation. Neither T1 nor T2 increased ST
308 to a level significantly higher than the T0 no-warming control, and there were no
309 significant differences in ST between different precipitation treatments at the same
310 warming level (p 0.05). This indicates that the warming amplitude and precipitation
311 intensity of this study did not significantly change the soil thermal environment, and
312 that the response of ST to short-term climate disturbance was limited. Overall, the short-
313 term climate change simulated in this study mainly affected SWC through interaction
314 between warming and precipitation, but had no significant effect on other physical

315 indicators such as bulk density, field water holding capacity or soil temperature,
316 reflecting the strong buffering capacity of the soil physical system to short-term climate
317 disturbance.

318 **4.2 Response of Rh to climate change**

319 High-frequency Rh only responded significantly to temperature, while low-
320 frequency Rh responded significantly to both temperature and precipitation, while the
321 interaction between temperature and precipitation was not significant. This difference
322 indicates that Rh at different frequencies is controlled by different environmental
323 mechanisms. High-frequency Rh, corresponding to the rapid response of the microbial
324 community in the active carbon pool, was mainly driven by temperature, which may be
325 due to the fast turnover of the active carbon pool and the high availability of substrates,
326 while the microbial respiration process was less limited by water. The significant
327 response of low-frequency Rh (corresponding to the decomposition process of the inert
328 carbon pool) to water reflects the essential role of water as a medium for substrate
329 diffusion and microbial movement in the decomposition process (Vidya et al. 2012;
330 Chenu et al. 2017).

331 The significant response to water is also reflected in the wetting pulse effect.
332 Studies have shown that heterotrophic respiration under drought conditions will have a
333 strong impulse response to rewetting events, and thatdrier soil before rewetting and
334 greater moisture change during rewetting are associated with stronger pulse respiration
335 (Oikawa et al. 2014; Manzoni et al. 2020). The significant response of low-frequency
336 Rh to precipitation in this study may be related to the wet pulse during the dry-wet

alternation, but more high-frequency continuous monitoring data are needed to distinguish the contribution of continuous respiration and pulse respiration in the future. A global arid region study has shown that soil microbial respiration rate decreased with increasing annual average temperature, and its temperature sensitivity exhibited adaptive adjustment (Dacal et al. 2019). The temperature sensitivity (Q_{10}) of Rh decreases with increasing annual average temperature, which suggests that in the long-term, the microbial community may achieve thermal adaptation to temperature through physiological and community evolutionary adjustment (Dacal et al. 2019). This may partially explain the relatively stable temperature sensitivity of high-frequency active carbon pool components of Rh in this study in the context continuous warming.

Comprehensive analysis of global arid regions has also revealed a significant secondary temperature response of soil respiration, with a clear temperature threshold beyond which respiration shifted from temperature-driven to water-limited (Raich et al. 2023; Almagro et al. 2025). Different types of vegetation have different abilities to regulate the temperature threshold. Shrub and grassland systems have higher temperature thresholds than forest systems, which reflects differences in their adaptability to drought stress (Almagro et al. 2025). This study was conducted in a desert steppe. In this system, the secondary temperature response is triggered only when temperature attains a certain threshold. Since the warming treatment in the present experiment may have remained below that threshold, the secondary response failed to emerge and the hydrothermal interaction was not activated. This could partly account for the insensitivity or low sensitivity of Rh to precipitation observed in this area.On a

global scale, regions with lower annual precipitation tend to show higher Rh temperature sensitivity, indicating that soil carbon decomposition in arid regions may respond more strongly to temperature changes (Liu et al. 2016; Chen et al. 2020). Chen et al. (2020) also confirmed that average annual precipitation was significantly negatively correlated with Q_{10}, which was related to the particularity of hydrothermal conditions in arid areas.

The results of redundancy analysis (RDA) support the above conclusions from the perspective of environmental factors. The main influencing factors for Rh were soil organic carbon (SOC, 63.1 %), soil moisture (SWC, 17.1 %) and soil bulk density (SDB, 16.8 %). This ranking first confirms the core position of soil organic carbon as a source of heterotrophic respiration substrates. At the same time, it is worth noting that the cumulative contribution of water and bulk density reached 33.9 %, indicating that the physical environment has a non-negligible role in regulating Rh. Data-driven analysis based on 90 soil samples showed that there were significant interactions between soil properties (such as texture, organic carbon content and bulk density) and water, and these interactions significantly affected the response function of Rh to water (Moyano et al. 2012). Chenu et al. (2017) further pointed out that soil properties such as soil organic carbon, texture and bulk density affected the wet response function of soil microbial respiration by changing water retention capacity and pore connectivity. Incorporating the interaction effects of the above soil characteristics into the carbon cycle model can significantly improve the prediction accuracy of Rh.

In addition, under the synergistic effect of warming and precipitation changes, the

long-term response of heterotrophic respiration faces microbial thermal adaptation and substrate depletion constraints (Sun et al. 2023). A warming experiment conducted in an alpine meadow on the Qinghai-Tibet Plateau found that continuous warming significantly enhanced heterotrophic respiration (which contributed more than 90 % of the increase in soil respiration) in the early growing season, but this warming effect gradually weakened in the middle and late growing season (Chen et al. 2016). This phenomenon indicates that the activation effect of Rh in the early stage of short-term warming may be restricted by substrate limitation or microbial physiological adaptation, and the long-term response of soil heterotrophic respiration to warming may not be linear. In this study, the insignificant response of high-frequency Rh to the interaction between precipitation and temperature and precipitation may be related to this mechanism whereby the substrates in the active carbon pool are easily rapidly consumed, and the microbial community has physiological adaptation potential under the background of continuous warming, resulting in Rh showing no significant association with precipitation or the interaction of temperature and precipitation.

4.3 Response of Q_{10} to climate change

In this study, high frequency Q_{10} only had a significant response to temperature, while low frequency Q_{10} had significant responses to temperature, precipitation and temperature-precipitation interaction. This difference indicates that Q_{10} at different frequencies is controlled by different environmental mechanisms. High-frequency Q_{10} (corresponding to the rapid response of microbial communities in the active carbon pool) is mainly driven by temperature, which may be due to the rapid turnover of the

active carbon pool and high substrate availability, and the microbial respiration process is less limited by water. The low-frequency Q_{10} (corresponding to the decomposition process of the inert carbon pool) is highly sensitive to temperature and water conditions and their interactions, reflecting that the decomposition of the inert carbon pool requires sufficient water as a medium for substrate diffusion and microbial movement. On a global scale, regions with lower annual average precipitation tend to show higher Q_{10} values, suggesting that soil carbon decomposition in arid regions may respond more strongly to temperature changes (Xu et al. 2015; Chen et al. 2020). In addition, a study specifically investigating whether water affects microbial growth and respiration temperature dependence found that microbial rates decrease with decreasing water content and increase with increasing temperature until the optimal value, but water and temperature are statistically independent of each other as rate regulators (Cruz-Paredes et al. 2021).

The results of redundancy analysis (RDA) further support the above conclusions from the perspective of environmental factors. The main influencing factor for Q_{10} was soil bulk density (SDB, 54.2 %), followed by soil moisture (SWC, 29.3 %). The explanation rate of soil bulk density to Q_{10} variation even exceeded that of climatic factors such as water and temperature, indicating that soil physical structure plays an important role in Q_{10} regulation. This has also been demonstrated in a global meta-analysis across different terrestrial biomes of in situ measurements of Q_{10}, which confirmed that soil bulk density is one of the key factors regulating the spatial variability of Q_{10} (Chen et al. 2020).

The regulation of water content on Q_{10} has bidirectional and threshold effects(Zhang et al. 2026; Lellei-Kovács et al. 2011; He et al. 2024). On the one hand, an appropriate amount of water increase can increase the temperature sensitivity of soil respiration. The mechanism is that moderate humidification can improve substrate diffusion efficiency and activate microbial metabolic activities (Steinweg et al. 2012; Liu 2013; Sihi et al. 2018). On the other hand, insufficient water content will significantly inhibit Q_{10}. A culture experiment found that low water conditions would limit the diffusion of solutes in the soil water film and inhibit microbial activity, thereby significantly reducing the Q_{10} value of soil organic matter mineralization (He et al. 2024b). In addition, the study also found that after the input of exogenous active organic matter, due to the low activation energy required for the decomposition of high-quality carbon components, Q_{10} also decreased (He et al. 2024b). Another field manipulation experiment also found that drought significantly reduced the apparent Q_{10} in autumn, confirming the seasonal regulation of soil moisture on Q_{10} (Vidya et al. 2012). Change in precipitation pattern will also produce a respiration pulse in the soil rewetting process. The contribution of this pulse event to Q_{10} under arid climate and intermittent rainfall conditions cannot be ignored (Manzoni et al. 2020). From this study, the significant effect of the temperature-precipitation interaction ($p = 0.037$) confirms this nonlinear pattern in low-frequency Q_{10}: whether the increase in temperature brings a proportional increase in respiration rate depends on whether the water condition is in an appropriate range. When the moisture deviates from the optimal threshold, the response of microbial metabolism to temperature will be inhibited, showing the warming-inhibition

447 effect of the interaction.

448 In summary, under the conditions of this study, Q_{10} showed a strong treatment-
449 dependent response to gradient warming and gradient precipitation, and the significant
450 response of low-frequency Q_{10} to the interaction of temperature and precipitation
451 deserves special attention. This finding indicates that water changes not only directly
452 affect the size of Q_{10}, but also change the response of Q_{10} to temperature rise by
453 adjusting soil moisture conditions, especially with regard to the decomposition process
454 of the inert carbon pool. This implies that soil carbon models using a constant Q_{10} value
455 (such as 1.5 or 2.0 commonly used in traditional models) that ignore the interactive
456 regulation effect of water on Q_{10} may significantly under- or overestimate the feedback
457 intensity of the soil carbon pool to climate change in arid areas.

458 **5. Conclusion**

459 This study showed that short-term warming and precipitation increase had no
460 significant effect on the physical and chemical properties of desert steppe soil in Inner
461 Mongolia, although soil water content changed significantly. The response of soil
462 heterotrophic respiration (Rh) and its temperature sensitivity (Q_{10}) to warming and
463 precipitation showed obvious frequency dependence. High-frequency Rh was only
464 significantly regulated by temperature, while low-frequency Rh was sensitive to both
465 temperature and precipitation. The contribution of soil organic carbon (SOC) to Rh
466 variation was dominant, which explained more than the sum of other factors. The
467 response of Q_{10} was more differentiated: high-frequency Q_{10} was only related to
468 temperature, while low-frequency Q_{10} was significantly affected by temperature,

precipitation and their interaction, and soil bulk density (SDB) and water (SWC) were the dominant factors explaining most of the variation in Q_{10}. The contribution of bulk density was about 50%, while the contribution of water was about half that of bulk density. In summary, the low-frequency components of soil respiration are more sensitive to hydrothermal conditions and their synergistic effects. The influences of soil moisture, bulk density, and carbon pool heterogeneity should be accounted for in the Q_{10} parameterization approaches of soil carbon models applied to arid regions.

Abbreviations

FAO Food and Agriculture Organization of the United Nations

OTC Open Top Chamber

GLM Generalized linear model

SOC Soil organic carbon

SDB Soil bulk density

SWC Soil moisture

ST Soil temperature

RDA Redundancy analysis

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no conflicts of interest.

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Authors' contributions

Yan Chen: Data curation, Writing - original draft. **Guangyi Lv:** Data curation, Writing – review. **Chengjie Wang** and **Zhanyi Wang:** Funding acquisition, Supervision, Writing - review and editing. **Andreas Wilkes:** review and editing.

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