# Seasonal Variation Characteristics of Soil Respiration Under Different Biological Soil Crust Types in the Mu Us Sandy Land (Postprint)

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## Abstract

In 2018, using well-developed moss crusts and algal crusts in the southwestern Mu Us Sandy Land as research subjects, with shifting sand as a control, soil carbon flux measurements were employed to systematically observe the diurnal dynamics of biological soil crust-soil respiration across different seasons, explore the relationship between biological soil crust-soil respiration and environmental factors, and analyze the effects of seasonal variation on CO2 efflux and temperature sensitivity of biological soil crust-soil. The results showed: (1) The biological soil crust-soil respiration rates in different seasons all exhibited a "unimodal" curve, but the timing of peak occurrence differed. In spring and summer, the peak occurrence time for different types of biological soil crust-soil respiration rates was around 13:00, whereas in winter and autumn, the respiration rates of algal crust-soil and shifting sand appeared around 15:00, lagging 2 h behind those in spring and summer. (2) Across different seasons, the daily CO2 efflux of different types of biological soil crust-soil followed the order: moss crust > algal crust > shifting sand, reaching a significant level ($P < 0.05$). (3) From spring to winter, the daily CO2 efflux of biological soil crust-soil showed a trend of first increasing and then decreasing, exhibiting the order: summer > spring > autumn > winter, reaching a significant level ($P < 0.05$). (4) Through principal component analysis of biological soil crust-soil respiration rates and environmental factors across different seasons, compared with 5 cm soil temperature, 2 cm soil temperature was the main influencing factor for biological soil crust-soil respiration in different seasons, followed by near-surface air humidity. (5) The relationship between biological soil crust-soil respiration rates and 2 cm soil temperature in different seasons could all be well described by an exponential model. Based on this function, the temperature sensitivity of respiration was calculated, and it was found that the temperature sensitivity ranged from 1.33 to 3.85; with seasonal changes, the temperature sensitivity showed a trend of first decreasing and then increasing: winter > autumn > spring >

summer, indicating that the higher the temperature, the lower the temperature sensitivity of biological soil crust-soil respiration.

## Full Text

## Abstract

Biological soil crusts represent an important surface cover type in arid and semi-arid regions and constitute a crucial component of carbon cycling in desert ecosystems. However, research on seasonal variations in biological soil crust-soil system respiration remains scarce, making it difficult to accurately assess carbon cycle processes in desert ecosystems over time. This study examined well-developed moss crusts and algae crusts in the southwestern Mu Us Sandy Land in 2018, using moving sand as a control. Using a soil carbon flux measurement system, we observed the daily dynamics of biological soil crust-soil system respiration across different seasons, explored the relationship between biological soil crust-soil system respiration and environmental factors, and analyzed the effects of seasonal changes on $CO_2$ release and temperature sensitivity of biological soil crust-soil respiration. The results showed that: (1) The respiration rate of biological soil crust-soil systems exhibited a single-peak curve in different seasons, but the timing of peak values varied. In spring and summer, the peak respiration rates for different types of biological soil crust-soil systems occurred around 13:00, while in winter and autumn, the respiration rates of algae crust-soil systems and moving sand peaked around 15:00, lagging 2 hours behind spring and summer. (2) In the same season, daily $CO_2$ release differed among different biological soil crust-soil systems: moss crust > algae crust > moving sand ($P < 0.05$). With seasonal changes, the daily $CO_2$ release from biological soil crust-soil systems first increased and then decreased, following the pattern: summer > spring > autumn > winter ($P < 0.05$). (3) Principal component analysis of biological soil crust-soil system respiration rates and environmental factors revealed that compared with 5 cm soil temperature, the 2 cm soil temperature was the primary influencing factor on biological soil crust-soil system respiration across seasons, followed by near-surface air humidity. (4) The relationship between biological soil crust-soil system respiration rate and 2 cm soil temperature in different seasons was well described by an exponential model. Based on this function, the temperature sensitivity of respiration was calculated, revealing a range of 1.33–3.85. With seasonal changes, temperature sensitivity first decreased and then increased: winter > autumn > spring > summer, indicating that higher temperatures correspond to lower temperature sensitivity of biological soil crust-soil system respiration.

**Keywords:** biological soil crusts; different seasons; respiration; Mu Us Sandy Land; temperature sensitivity

## 1 Introduction

The carbon cycle serves as the link connecting the atmosphere and lithosphere, occupying a central position in Earth' s material cycling system. As a major component of the global carbon cycle, terrestrial ecosystem carbon budgets primarily transfer carbon from soil to the atmosphere through soil respiration, which accounts for 68–100 Pg C $yr^{-1}$ globally, representing approximately 10% of atmospheric $CO_2$. Currently, most soil respiration research focuses on croplands, forests, and grasslands, with relatively few studies conducted in desert ecosystems due to their harsh ecological conditions and sparse human populations. Desert ecosystems, as important components of arid and semi-arid regions, store 10$×10^{15}$ kg of carbon, yet the lack of research on soil respiration in these areas creates uncertainties in global carbon budget assessments.

Biological soil crusts (also called biocrusts or microbiotic crusts) are composite structures formed by cryptogamic plants (such as mosses, green algae, cyanobacteria, and lichens) and soil microorganisms through their hyphae, rhizoids, and extracellular secretions that bind with surface soil particles. These crusts cover 60%–80% of arid and semi-arid regions worldwide and participate in and regulate numerous ecological processes by improving soil erosion resistance and ameliorating soil conditions, making them crucial for desert ecosystem restoration and maintenance. Located at the soil-atmosphere interface, biological soil crusts simultaneously conduct respiration and photosynthesis, influencing carbon cycling in desert ecosystems.

Current research on biological soil crust-soil respiration in desert ecosystems primarily focuses on European temperate grasslands, American and Israeli deserts, and polar regions, with most studies examining relationships between biotic factors (biological soil crust types and composition) and environmental factors (such as water, temperature, and photosynthetically active radiation). Research areas in China mainly include the Shapotou region of the Tengger Desert, the Gurbantunggut Desert, and the Loess Plateau, focusing on responses to simulated rainfall and warming, relationships between biological soil crust types and soil respiration, and responses to climate change. However, most studies concentrate on the high-temperature growing season (May–October), often ignoring soil respiration during the colder winter and spring periods and assuming zero carbon exchange between biological soil crust-soil systems and the atmosphere during these times. Related research indicates that algae crusts in Mediterranean regions can still respire even when temperatures drop to -22°C, demonstrating that biological soil crust respiration at low temperatures cannot be neglected. Currently, research on seasonal variations in daily dynamics of biological soil crust-soil respiration remains rare, with insufficient long-term field observation data. Therefore, studying seasonal variations in daily dynamics of biological soil crust-soil respiration will provide reliable data support for carbon estimation in desert ecosystems.

This study, conducted in the Mu Us Sandy Land, examined different types of biological soil crust-covered soils to observe daily dynamics of biological soil crust-soil respiration across seasons. Combining relevant environmental factors, we analyzed the main influencing factors on biological soil crust-soil respiration in different seasons, explored how temperature sensitivity of biological soil crust-soil respiration responds to seasonal changes, and elucidated variation characteristics of biological soil crust-soil respiration across seasons, aiming to provide a scientific basis for accurate assessment of carbon sources and sinks in desert ecosystems.

## 2 Methods

### 2.1 Study Area

The Mu Us Sandy Land is located at the junction of Yulin City, Shaanxi Province and Ordos City, Inner Mongolia Autonomous Region, in the farming-pastoral ecotone of northern China, covering an area of approximately 4.22$×10^{4}$ km$^2$. This study was conducted in Otog Front Banner, Ordos City, Inner Mongolia (38°05 54 N, 107°50 51 E), in the southwestern part of the Mu Us Sandy Land, at an elevation of 1300–1500 m. The region has a temperate arid and semi-arid continental climate with strong wind-sand activity, an average annual wind speed of 3.6 $m \cdot s^{-1}$, average annual evaporation of 2514.8 mm, average annual precipitation of 265 mm, average annual sunshine duration of 2900 h, average annual air temperature of 7.5°C, maximum monthly average temperature of 22.6°C, minimum monthly average temperature of -10.4°C, and average annual relative humidity of 51%. The soil is primarily aeolian sandy soil with loose texture and rich nutrient content.

In recent decades, changes in human activity patterns and scope have intensified desertification in China. Since the 1950s, desertification control efforts in the Mu Us Sandy Land have significantly reduced desertified land area, forming a desert ecosystem dominated by shrubs and annual herbs with perennial herbs as secondary components, accompanied by extensive biological soil crust distribution. Shrubs are mainly *Rhamnus parvifolia*, *Caragana korshinskii*, *Sabina vulgaris*, *Artemisia ordosica*, *Artemisia sieversiana*, *Artemisia desertorum*, and *Salix cheilophila*. Annual herbs include *Chenopodium glaucum*, *Agriophyllum squarrosum*, *Bassia dasyphylla*, *Eragrostis pilosa*, *Celosia argentea*, *Allium mongolicum*, and *Corispermum hyssopifolium*. Perennial herbs include *Ixeris gracilias*, *Orostachys fimbriatus*, *Cynanchum atratum*, *Stipa capillata*, *Euphorbia esula*, *Cleistogenes squarrosa*, and *Melilotus officinalis*. Basic characteristics of biological soil crusts in the study area are shown in Table 1.

### 2.2 Sample Plot Setup

Observations were conducted in winter (January 15), spring (April 15), summer (July 15), and autumn (October 15) of 2018. Based on successional patterns of biological soil crusts and local development conditions, we selected well-developed biological soil crusts (moss crust and algae crust with coverage maintained above 80%) in areas with minimal human disturbance as experimental subjects, using moving sand as a control. To avoid influences from plant roots on biological soil crust respiration, experimental plots were established more than 2 m from plant bases, away from root distributions. Within each plot, three 2 m × 2 m quadrats were randomly established: moss crust quadrat, algae crust quadrat, and moving sand quadrat. Stainless steel rings (diameter 20 cm, height 10 cm) were used for in-situ measurement of biological soil crust-soil respiration rates. When placing the rings, to prevent structural damage to biological soil crusts, a certain amount of water was sprayed on the crust surface until completely soaked, then the rings were vertically pressed into the soil to a depth of approximately 10 cm. Experimental plot setup was completed one week before measurements.

### 2.3 Measurement of Biological Soil Crust-Soil Respiration Rate

In winter, spring, summer, and autumn, a portable soil carbon flux measurement system (LI-8100A, LI-COR, USA) connected to a dark chamber was used to measure biological soil crust-soil respiration rates. On clear days in each season (with no precipitation for 7 days prior to measurement to avoid rainfall effects), measurements were taken from 8:00 daily to 8:00 the next day, with 12 measurements per day for each treatment. Each measurement lasted 3.5 min, with 2 min for gas exchange inside the main unit before and after measurement, resulting in an actual soil respiration measurement duration of 1.5 min. The average respiration rate of biological soil crust-soil systems from 11:00–13:00 was used as the daily average respiration rate.

### 2.4 Measurement of Related Environmental Factors

Previous studies indicate that air temperature and humidity, photosynthetically active radiation, and soil temperature and moisture significantly influence biological soil crust-soil respiration. During the experiment, soil temperature and moisture at 2 cm and 5 cm depths were measured using temperature sensors (5TM, METER, USA) in summer and autumn. In spring and winter, since soil temperature could drop below 0°C and the sensors could not accurately measure soil water content, soil temperature at 2 cm and 5 cm was measured using temperature sensors, while soil water content at these depths was determined using the weighing method. Simultaneously with soil respiration measurements, soil samples were collected at 2 cm and 5 cm depths and immediately weighed using an electronic balance with 0.01 g precision. After weighing, samples were taken to the laboratory and oven-dried at 105°C to constant weight. Photosynthetically active radiation and near-surface air temperature and humidity were measured using a photosynthetically active radiation sensor (PAR, METER, USA) and air temperature sensor (VP-4, METER, USA). All data were collected using an EM50 data logger (METER, USA) at 1-min intervals.

### 2.5 Data Processing and Analysis

Daily $CO_2$ release from biological soil crust-soil systems in different seasons was calculated as follows:

$$\text{Daily } CO_2 \text{ release} = \frac{(R_1 + R_2 + \cdots + R_{12}) \times 2 \times 3600 \times 10^{-6}}{2}$$

where $R_1, R_2, \ldots, R_{12}$ are the respiration rates of biological soil crust-soil systems measured 12 times daily.

In calculating temperature sensitivity ($Q_{10}$) of biological soil crust-soil respiration, the relationship between soil respiration and temperature was first fitted using the van' t Hoff exponential model:

$$R_s = ae^{bT}$$

where $R_s$ is soil respiration, $T$ is temperature, $a$ is basal respiration (soil respiration at 0°C), and $b$ is the temperature response coefficient. After fitting to obtain coefficient $b$, temperature sensitivity was determined by:

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

Data analysis was performed using SPSS 19.0 for statistical analyses (regression analysis, significance testing, and factor analysis). Figures were prepared using Excel 2016.

## 3 Results

### 3.1 Daily Dynamics of Biological Soil Crust-Soil Respiration Rate in Different Seasons

The respiration rates of biological soil crust-soil systems in different seasons all exhibited single-peak curves, showing the pattern: moss crust-soil > algae crust-soil > moving sand. However, the timing of maximum values differed. In spring and summer, the peak respiration rates of different biological soil crust-soil systems occurred around 13:00. In autumn and winter, moss crust-soil respiration peaked around 13:00, while algae crust-soil and moving sand respiration peaked around 15:00, lagging 2 hours behind spring and summer. Minimum values occurred at 3:00–5:00. With seasonal changes, respiration rates of different biological soil crust-soil systems first increased then decreased, with maximum respiration rates following: summer > spring > autumn > winter, and minimum values showing: summer > spring > autumn and winter. Overall, the pattern was: summer > spring > autumn > winter.

[Figure 1: see original paper]

### 3.2 Daily $CO_2$ Release from Biological Soil Crust-Soil Systems

Daily $CO_2$ release from biological soil crust-soil systems in different seasons showed the pattern: moss crust-soil > algae crust-soil > moving sand, reaching significant levels in winter, spring, and summer ($P < 0.05$). In autumn, daily $CO_2$ release from moss crust-soil was greater than from algae crust-soil but not significantly different. From spring to winter, daily $CO_2$ release from different biological soil crust-soil systems first increased then decreased, following: summer > spring > autumn > winter, reaching significant levels ($P < 0.05$).

[Figure 2: see original paper]

### 3.3 Daily Dynamics of Related Environmental Factors

Daily dynamics of 2 cm soil temperature showed single-peak curves in all seasons, while 5 cm soil temperature showed similar patterns. Photosynthetically active radiation and near-surface air temperature peaked around 13:00 daily and reached minimum values around 21:00. Near-surface air humidity showed relatively constant daily dynamics across seasons. Seasonal mean values were higher in summer for photosynthetically active radiation and near-surface air temperature. Daily mean soil moisture at 2 cm and 5 cm depths followed: summer > spring > autumn > winter.

[Figure 3: see original paper]

Daily mean values of related environmental factors in different seasons are shown in Table 2.

### 3.4 Relationships Between Biological Soil Crust-Soil Respiration Rate and Environmental Factors in Different Seasons

Correlation analysis between biological soil crust-soil respiration rates and environmental factors revealed seasonal variations. In winter, moss crust-soil respiration rate was positively correlated with near-surface air relative humidity, 2 cm soil moisture, and photosynthetically active radiation, but negatively correlated with near-surface air temperature, 2 cm soil temperature, and 5 cm soil temperature. Algae crust-soil and moving sand respiration rates were positively correlated with near-surface air temperature, photosynthetically active radiation, 2 cm soil temperature, and 5 cm soil temperature, but negatively correlated with near-surface air relative humidity. In spring, moss crust-soil and algae crust-soil respiration rates were positively correlated with near-surface air relative humidity, photosynthetically active radiation, and 2 cm soil moisture, but negatively correlated with near-surface air temperature, 2 cm soil temperature, and 5 cm soil temperature. Moving sand respiration rate was positively correlated with photosynthetically active radiation, 5 cm soil temperature, and 2 cm soil moisture, but negatively correlated with near-surface air relative humidity and temperature. In summer, moss crust-soil, algae crust-soil, and moving sand respiration rates were positively correlated with near-surface air relative humidity, 2 cm soil moisture, and photosynthetically active radiation, but negatively correlated with near-surface air temperature, 2 cm soil temperature, and 5 cm soil temperature. In autumn, moss crust-soil and algae crust-soil respiration rates were positively correlated with near-surface air relative humidity and photosynthetically active radiation, but negatively correlated with near-surface air temperature, 2 cm soil moisture, 2 cm soil temperature, and 5 cm soil temperature.

[Figure 4: see original paper]

### 3.5 Temperature Sensitivity of Biological Soil Crust-Soil Respiration in Different Seasons

Principal component analysis indicated that 2 cm soil temperature was the main influencing factor on biological soil crust-soil respiration across seasons, followed by near-surface air humidity. From winter to spring, the relationship between 2 cm soil temperature and biological soil crust-soil respiration gradually shifted from positive to negative correlation. Regression equations established between biological soil crust-soil respiration rates and 2 cm soil temperature showed that exponential models well described their relationship ($R^2$ = 0.50–0.85). Based on these relationships, $Q_{10}$ values were calculated, revealing that biological soil crust-soil respiration $Q_{10}$ ranged from 1.33 to 3.85. With seasonal changes, $Q_{10}$ first decreased then increased: winter > autumn > spring > summer. In the same season, biological soil crust-soil respiration $Q_{10}$ showed: moss crust-soil > algae crust-soil > moving sand.

## 4 Discussion

### 4.1 Daily Dynamics of Different Types of Biological Soil Crust-Soil Respiration

Biological soil crusts are widely distributed in arid and semi-arid regions. As composites of plants, microorganisms, and soil at the atmosphere-soil interface, they influence carbon exchange processes and represent important factors affecting carbon flux in desert ecosystems. Studies in the Shapotou region of the Tengger Desert, Gurbantunggut Desert, and Loess Plateau show that biological soil crust-soil respiration rates exhibit single-peak daily dynamics, consistent with our results. However, peak timing differs across regions: peaks occur around 12:00 in the Tengger Desert and Gurbantunggut Desert, and around 13:00–15:00 on the Loess Plateau. In our study, peaks occurred around 13:00 in spring and summer for all crust types, while in autumn and winter, moss crust-soil respiration peaked around 13:00 and algae crust-soil and moving sand peaked around 15:00. These differences are closely related to regional environmental conditions, biological soil crust types, and seasonal water-heat conditions. Compared with algae crust-soil and moving sand, moss crust-soil has higher microbial diversity and abundance and stronger water retention and utilization capacity. Although daily hygroscopic condensation water absorption is higher in moss crust-soil than in algae crust-soil and moving sand, the utilization efficiency of condensation water by biological soil crusts, the influence of crust type on condensation water evaporation, and seasonal differences in water-heat conditions all affect condensation water duration, leading to differences in daily peak timing among different crust types across seasons.

## 4.2 Influence of Temperature on Biological Soil Crust-Soil Respiration

Temperature is an important abiotic factor affecting biological soil crust-soil respiration. Related studies show that temperature increases significantly enhance respiration rates in arid tundra ecosystems and semi-arid desert ecosystems, consistent with our results. With seasonal changes (from winter through autumn, near-surface air temperature and soil temperature first increase then decrease, peaking in summer), biological soil crust-soil respiration rates show the same trend. However, warming reduced respiration rates of moss crust-soil and algae crust-soil in natural vegetation areas of the Tengger Desert' s Shapotou region, differing from our results. Biological soil crust-soil respiration comprises two components: autotrophic respiration (mainly plant root respiration) and heterotrophic respiration (mainly soil microorganisms and fauna). Our study plots were established away from plant root distributions, minimizing root respiration effects. Soil temperature is the main factor influencing soil heterotrophic respiration, which our results confirm. The optimal temperature for biological soil crust-soil respiration is 20–30°C; above or below this range, respiration is inhibited to varying degrees. Different study areas have varying soil structures and water-heat conditions, leading to differences in daily soil temperature dynamics and thus differences in peak respiration timing across regions. In our study area in the Mu Us Sandy Land, with average annual precipitation of 265 mm (significantly higher than Shapotou' s 186 mm), water conditions are less limiting to biological soil crust-soil respiration than in the Tengger Desert. Therefore, respiration rates follow: summer > spring > autumn > winter.

## 4.3 Temperature Sensitivity of Biological Soil Crust-Soil Respiration

The sensitivity of soil respiration to temperature changes is influenced by soil ecosystem composition and climate zone, representing an important factor in feedback relationships between the global carbon cycle and climate change. Studies show that temperature sensitivity decreases with increasing temperature, primarily because higher temperatures inhibit soil microbial and enzyme activities, reduce available soil water, and hinder ecological processes, thereby decreasing temperature sensitivity. This aligns with our results. However, some studies found that temperature sensitivity increases with temperature, differing from our findings because soil respiration is affected by both temperature and moisture. When soil moisture conditions are favorable, good water conditions facilitate soil organic matter decomposition, and the promoting effect of moisture on soil respiration can offset the inhibiting effect of temperature increase, leading to increased temperature sensitivity. Studies in forest ecosystems and subtropical grassland ecosystems also confirmed that poor moisture conditions reduce temperature sensitivity, while increased moisture can significantly enhance it. Our study area in the Mu Us Sandy Land is a typical desert ecosystem, and experiments were conducted one week after rainfall when soil moisture content was low. Therefore, temperature sensitivity followed: winter > autumn > spring > summer.

## 5 Conclusion

Based on measurements of daily dynamics of biological soil crust-soil respiration rates across seasons in the Mu Us Sandy Land and analysis of related environmental factors, we conclude:

1. Daily dynamics of biological soil crust-soil respiration rates in different seasons all showed single-peak curves, with peak times occurring at 13:00–15:00.
2. In the same season, daily $CO_2$ release differed among biological soil crust-soil systems: moss crust > algae crust > moving sand, reaching significant levels ($P < 0.05$). Daily $CO_2$ release across seasons followed: summer > spring > autumn > winter, reaching significant levels ($P < 0.05$).
3. Principal component analysis showed that the main influencing factor on biological soil crust-soil respiration across seasons was 2 cm soil temperature, followed by near-surface air humidity.
4. Temperature sensitivity of biological soil crust-soil respiration differed across seasons, following: winter > autumn > spring > summer, indicating that higher temperatures correspond to lower temperature sensitivity.

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*Note: Figure translations are in progress. See original paper for figures.*