Soil Respiration Dynamics and Influencing Factors under Two Vegetation Types in the Horqin Sandy Land: Postprint

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Abstract

Taking the Horqin sandy land-meadow interlaced region as the study area, soil respiration and its associated factors were measured in artificial poplar forests in the sand dune-meadow ecotone and in Caragana microphylla communities on fixed sand dunes using the LI-6400 soil respiration measurement system. The results indicated that: (1) During both the growth and late growth periods, the diurnal variation of soil respiration in the artificial poplar forest, with and without litter retention, exhibited a "multi-peak pattern". (2) The seasonal peaks of soil respiration, with and without litter retention, in both the artificial poplar forest and Caragana microphylla community occurred in August, with soil respiration rates in the artificial poplar forest being significantly higher than those in the Caragana microphylla community. (3) The seasonal variation of soil respiration in the artificial poplar forest was significantly correlated with 0-10 cm soil temperature ($P<0.01$), and soil respiration with litter retention was lower than that with litter removal. (4) The seasonal variation of soil respiration in the Caragana microphylla community was significantly correlated with 0-10 cm soil moisture content ($P<0.01$), and contrary to the artificial poplar forest, soil respiration with litter retention was greater than that with litter removal. (5) Soil respiration in the artificial poplar forest showed a significant exponential relationship with soil temperature, whereas soil respiration in the Caragana microphylla community showed a significant power function relationship with soil moisture content. Using the normalization method, a dual-factor regression model of soil respiration LnRs with soil temperature T and soil moisture content Ln was established to determine the respective contribution rates of soil temperature and soil moisture content to soil respiration with and without litter retention.

Full Text

Preamble

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Title: Dynamic Changes in Soil Respiration of Two Vegetation Types and Their Influencing Factors in the Horqin Sandy Land

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Abstract

This study investigated soil respiration and associated environmental factors in an artificial poplar forest located in the dune-meadow transitional zone of the Horqin Sandy Land and in a natural *Caragana microphylla* community on fixed dunes. Using the LI-6400 soil respiration measurement system, we monitored soil respiration under two litter treatments (litter retained vs. litter removed) throughout the growing season. Results revealed five key patterns: (1) Daily soil respiration in the poplar forest during both the growth and late-growth periods exhibited multiple peaks for both litter treatments. (2) Seasonal peaks for all treatments occurred in August, with soil respiration rates in the poplar forest significantly exceeding those in the *C. microphylla* community. (3) Seasonal variation in poplar forest soil respiration showed significant exponential correlation with soil temperature (0–10 cm depth) ($p < 0.01$), while the magnitude of variation was smaller in the litter-retained treatment compared to the litter-removed treatment. (4) In contrast, seasonal variation in the *C. microphylla* community displayed significant power-function correlation with soil moisture content (0–10 cm depth) ($p < 0.01$), with litter-retained plots showing greater variation than litter-removed plots. (5) A two-factor regression model was developed using normalized data to quantify the relative contributions of soil temperature and moisture to soil respiration under both litter conditions. These findings provide theoretical support for soil carbon management strategies in arid and semi-arid regions with different vegetation types.

Keywords: Horqin Sandy Land; litter; soil respiration; soil temperature; soil water content

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Introduction

Soil respiration represents a major source of atmospheric CO and constitutes a critical component of the global terrestrial ecosystem carbon cycle, playing a pivotal role in regulating atmospheric CO concentrations at regional and global scales. Even minor alterations in soil respiration can trigger significant changes in atmospheric CO, thereby influencing global climate patterns. Arid and semi-arid regions cover approximately two-fifths of the Earth' s land surface and store substantial organic carbon—estimated at 1,500 Pg C—despite their relatively low soil organic carbon content, accounting for over 15% of total terrestrial ecosystem carbon storage. Consequently, soil respiration serves as one of the primary processes of soil carbon loss in these regions and represents an ecosystem characteristic highly sensitive to climate change.

Soil respiration is a complex biochemical process influenced by the combined effects of abiotic factors, biotic factors, and human activities. Research indicates that soil temperature and moisture content can explain most of the observed variation in soil respiration. When soil moisture is not limiting, soil respiration is primarily controlled by temperature; however, under moisture stress conditions, soil respiration becomes constrained by moisture availability even as temperature continues to drive variation. Litter, located at the soil surface, represents another critical factor affecting soil respiration. Its quantity and decomposition rate significantly influence soil organic matter formation and nutrient supply to plants, while also directly affecting soil carbon fluxes by modifying hydrothermal conditions.

Previous studies have yielded contrasting results regarding litter effects. Some researchers found that litter removal significantly reduces soil respiration, while others concluded that litter exerts a shielding effect on soil respiration. Research on soil respiration in arid and semi-arid regions remains limited, and studies examining litter effects are particularly scarce. To date, no studies have quantified soil respiration in the Horqin region or determined the relative contributions of influencing factors. This research addresses this gap by investigating soil respiration dynamics and their driving mechanisms in both an artificial poplar forest in the dune-meadow transitional zone and a natural *C. microphylla* community on fixed dunes in the Horqin Sandy Land.

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1. Study Area Overview

The study area is located in A' gula Town, Keerqin Left Wing Rear Banner, Tongliao City, Inner Mongolia Autonomous Region, within the southeastern margin of the Horqin Sandy Land (122°33 00 -122°41 00 E, 43°18 48 - 43°21 24 N). The region features a typical dune-meadow landscape with alternating sand dunes and lakes, with elevations ranging from 186 to 232 m. The climate is characterized by a mean annual precipitation of 389 mm concentrated in the summer months, mean annual evaporation of 1,412 mm, mean annual temperature of 6.6°C (with July mean of 23.8°C and extreme temperatures of 36.2°C and -33.9°C), mean annual relative humidity of 55.8%, and mean annual wind speed of 3-4 m/s (lowest in July–September).

The vegetation community is relatively simple with low species diversity. Dominant plants include *Artemisia halodendron*, *Agriophyllum squarrosum*, *Leymus chinensis*, *Cenchrus pauciflorus*, *Artemisia frigida*, *Salix gordejevii*, *Ulmus pumila*, *Populus* spp., and *Caragana microphylla*. Vegetation growth primarily depends on natural precipitation, though meadow vegetation also utilizes groundwater. Both zonal and azonal soils are well-developed, with sandy loam and loamy sand being the dominant soil types.

This study focused on two vegetation types: (1) an artificial poplar forest in the dune-meadow transitional zone on low-relief dunes, and (2) a natural *C. microphylla* community on fixed dunes. The geographic location and sampling sites are shown in [Figure 1: see original paper].

1.1 Vegetation Characteristics

Vegetation surveys within the selected sample plots revealed that the artificial poplar forest had trees aged 11–19 years, with mean height of 11.9 m, mean diameter at breast height of 11.2 cm, and spacing of 2.5 m × 2.5 m. The forest also contained other low-stature trees and herbs, including *Broussonetia papyrifera*, *Prunus padus*, *Artemisia selengensis*, *Conyza canadensis*, *Polygonum divaricatum*, *Setaria viridis*, and *Incarvillea sinensis*. Litter thickness averaged 1.2–2.1 cm, humus layer thickness approximately 1.6 cm, and groundwater depth 0.996 m.

The *C. microphylla* community consisted of shrubs averaging 2.2 m in height and 0.9 cm in root diameter, with root systems concentrated in the 0.89–1.69 cm range. Associated species included *Artemisia sieversiana* and *Artemisia siversiana*. Litter thickness under shrubs was 0.5–1.5 cm, with no humus layer present and groundwater depth at 3.79 m. Basic soil properties and other site information are summarized in .

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2. Experimental Design

Three soil respiration measurement points were established in each vegetation type. In the artificial poplar forest, a 20 m × 20 m plot was established around a Campbell automatic weather station, with three points forming an approximate equilateral triangle with 5 m sides. At each point, two custom-made plastic rings (10 cm diameter, 5 mm height) were placed side by side: one with litter removed and one with litter retained.

In the *C. microphylla* community, a 20 m × 20 m plot was established around another Campbell weather station, with three measurement points similarly distributed. At each point, two plastic rings were placed adjacent to each other near the root base of a *C. microphylla* shrub (within the canopy area), with one ring having litter removed and the other retaining litter. The experimental layout is illustrated in [Figure 2: see original paper].

3. Measurement Methods

Soil respiration was measured using an LI-6400 portable photosynthesis system (Li-Cor Inc., NE, USA) equipped with a soil respiration chamber (LI-6400-09). Measurements were conducted from 08:00 to 18:00 at each point. Prior to measurement, green vegetation within the rings was clipped at ground level, and debris was removed from the litter-removed rings. Soil temperature at 10 cm depth was measured using the system' s built-in thermocouple probe, and soil moisture content was measured using a portable soil moisture meter (Diviner2000, Sentek, Australia) to determine average moisture within the 0–10 cm depth interval.

Continuous observations were conducted during the growth period (August) and late-growth period (October). After the annual experiment, litter thickness was measured at each point. Following completion of all measurements, soil samples (50 × 50 cm × 20 cm) were collected around the respiration rings.

4. Data Processing and Analysis

Data were organized by vegetation type. For analysis of diurnal variation characteristics, all observations from replicate points were averaged to obtain daily means, which were then averaged monthly to analyze seasonal patterns.

4.1 Statistical Models

Soil respiration (R_S) was modeled against soil temperature (T) using an exponential function:

$$R_S = a \cdot e^{bT}$$

where R_S is mean soil respiration (mol m ² s ¹), T is mean soil temperature (°C), and a and b are constants. The temperature sensitivity coefficient Q , defined as the ratio of soil respiration at a given temperature to that at 10°C lower, was calculated accordingly.

Soil respiration was modeled against soil moisture content ( ) using a power function:

$$R_S = c \cdot \theta^d$$

where   is mean volumetric soil moisture content (%) and c and d are constants ($0 < d < 1$). Although a quadratic model was considered for the *C. microphylla* community due to moisture stress, the power function was selected for consistency across analyses, as both models showed similar explanatory power (R^2 values differing by less than 0.06).

4.2 Two-Factor Regression Model

To separate the effects of soil temperature (T) and moisture ( ) on soil respiration (R_S), the following two-factor regression model was applied after normalizing all variables:

$$R_s^* = \gamma + \alpha T + \beta\theta$$

where R*_s, T, and   represent normalized values of ln(R_S), soil temperature, and ln( ), respectively, calculated as (Y - Y_min)/(Y_max - Y_min). The coefficients   and   represent the contribution coefficients of temperature and moisture, respectively.

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5. Results

5.1 Diurnal Variation in Soil Respiration and Temperature in Poplar Forest

Diurnal patterns of soil respiration and temperature varied between growth periods. During the growth period, both litter-retained and litter-removed treatments showed multiple peaks, with minima at 02:00 and 08:00 and maxima at 16:00 and 12:00, respectively. Secondary peaks occurred at 12:00 for litter-retained and 20:00 for litter-removed treatments. During the late-growth period, minima occurred at 06:00 and 22:00, maxima at 18:00 and 20:00, with secondary peaks at 02:00 and 10:00. Mean daily respiration rates were higher during the growth period (8.097 and 11.872 mol m ^{2} s ^{1} for litter-retained and litter-removed, respectively) than in the late-growth period (2.952 and 4.429 mol m ^{2} s ^{1}).

Correlation analysis between diurnal soil respiration and soil temperature revealed that the strongest relationships occurred with temperature shifted forward by 2–4 hours ($p < 0.05$). During the growth period, both treatments showed strongest correlation with temperature shifted forward by 2 hours, while in the late-growth period, the litter-removed treatment correlated best with temperature shifted forward by 4 hours. Soil temperature explained up to 52.9% of the variation in soil respiration [FIGURE:3, FIGURE:4; TABLE:2].

5.2 Seasonal Variation in Soil Respiration and Environmental Factors

Seasonal soil respiration during the growing season showed substantial fluctuations, with both vegetation types peaking in August. In the poplar forest, litter-removed soil respiration consistently exceeded litter-retained respiration, with monthly averages of 5.80 and 4.67 mol m ^{2} s ^{1}, respectively ($p < 0.01$). Conversely, in the *C. microphylla* community, litter-retained respiration was greater than litter-removed (5.82 vs. 7.75 mol m ^{2} s ^{1}; $p < 0.01$) [Figure 5: see original paper].

Correlation analysis indicated that poplar forest soil respiration was more strongly associated with soil temperature, while *C. microphylla* community respiration correlated more closely with soil moisture content . Single-factor regression models confirmed these relationships: exponential models for poplar forest (R^2 = 0.858-0.908) and power-function models for *C. microphylla* community (R^2 = 0.708-0.778) .

The two-factor regression model using normalized data explained more variation than single-factor models, with R^2 values of 0.872–0.938 for poplar forest and 0.748-0.812 for *C. microphylla* community (all $p < 0.01$) . In poplar forest, temperature contributed 0.881-0.846 to the model, while moisture contributed 0.155–0.223. In the *C. microphylla* community, moisture contributed 0.716–0.749, while temperature contributed 0.171–0.193.

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6. Discussion

6.1 Diurnal Patterns and Temperature Effects The complexity of diurnal soil respiration patterns in the poplar forest reflects the strong influence of hydrothermal conditions. The growth period' s higher respiration rates resulted from favorable moisture and temperature conditions that enhanced root activity and microbial metabolism. The 2–4 hour forward shift in temperature correlation suggests that soil respiration responds to temperature changes with a temporal lag, possibly due to the time required for substrate diffusion and microbial activation. The moderate explanatory power of temperature (52.9%) indicates that other factors, including moisture, substrate availability, and microbial community structure, also substantially influence diurnal dynamics.

6.2 Seasonal Controls on Soil Respiration The divergent controlling factors between vegetation types reflect their distinct environmental conditions. The poplar forest' s strong temperature dependence arises from its higher soil organic matter content, shallower groundwater table, and concentrated root distribution in the 0–50 cm layer, making it more responsive to temperature fluctuations. In contrast, the *C. microphylla* community on fixed dunes experiences moisture stress due to deeper groundwater and lower organic matter, causing soil moisture to become the primary limiting factor. The significant power-function relationship between respiration and moisture in this community indicates strong water limitation on microbial and root activity.

6.3 Litter Effects on Soil Respiration Litter effects differed fundamentally between vegetation types. In the *C. microphylla* community, litter removal reduced soil respiration by 24.22%, consistent with many studies showing litter as a primary carbon source in resource-poor systems. The strong correlation between litter-retained respiration and soil moisture reflects litter' s role in moisture retention and thermal insulation.

Conversely, in the poplar forest, litter removal increased respiration by 25.60%, suggesting a shielding effect where litter insulates the soil, reducing temperature sensitivity and limiting CO efflux. This negative contribution aligns with findings from other temperate forests and grasslands. Several mechanisms may explain this pattern: (1) removal of litter exposes soil to direct solar radiation, increasing surface temperature and stimulating microbial activity; (2) reduced moisture retention capacity after litter removal may paradoxically enhance aerobic conditions for certain microbial groups; (3) the shallow litter layer (1.2–2.1 cm) may have limited decomposition input but significant insulating properties.

The temperature sensitivity coefficient Q was higher for litter-retained (2.97) than litter-removed (2.60) treatments in the poplar forest, indicating that litter buffers soil temperature fluctuations and reduces respiration sensitivity to warming—a critical consideration for predicting climate change impacts.

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7. Conclusion

In the dune-meadow transitional zone of the Horqin Sandy Land, soil respiration in the artificial poplar forest exhibited complex diurnal patterns with multiple peaks for both litter treatments. Seasonal variation peaked in August for both the poplar forest and *C. microphylla* community. The poplar forest showed significantly higher respiration rates than the *C. microphylla* community. Litter removal increased soil respiration in the poplar forest but decreased it in the *C. microphylla* community, highlighting context-dependent litter effects.

Two-factor regression models incorporating both soil temperature and moisture provided superior simulation performance compared to single-factor models, better capturing the ecosystem' s response to environmental variation. Soil temperature was the primary control in the poplar forest, with litter-retained treatment showing higher temperature sensitivity (Q = 2.97) than litter-removed treatment (Q = 2.60). In contrast, soil moisture predominantly controlled respiration in the *C. microphylla* community.

This study provides the first quantitative assessment of soil respiration and its controls in the Horqin Sandy Land. However, the one-year dataset represents a limitation, and longer-term observations combined with laboratory experiments are needed to elucidate the microbial mechanisms underlying litter effects on soil respiration.

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