Soil Respiration and Its Influencing Factors in Hedysarum mongolicum Shrublands of Different Stand Ages in the Mu Us Sandy Land (Postprint)

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Abstract

To investigate the variation trends of soil respiration rate and flux and their main influencing factors in forest lands during the desertification reversal process, this study selected artificial Hedysarum mongolicum shrub plantations with stand ages of 9 a, 18 a, and 30 a, as well as unaffixed mobile sandy land (CK) in the Mu Us Sandy Land. In-situ observations of soil respiration rate were conducted using the Li-8100A soil carbon flux monitoring system, and the main environmental influencing factors were measured. The results showed that: (1) Both soil respiration rate and flux exhibited a unimodal curve pattern of initially increasing and then decreasing during the plant growing season from May to October, with the maximum value occurring in July. (2) Soil respiration rate and flux showed a continuous increasing trend with the stand age of Hedysarum mongolicum, while the temperature sensitivity of respiration rate (Q10) showed a continuous decreasing trend. During the growing season from May to October, the average soil respiration rates of the Hedysarum mongolicum plantation plots were in the order of: 30 a (2.16 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) > 18 a (1.98 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) > 9 a (1.41 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) > CK (0.24 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$); the soil respiration carbon flux values were in the order of: 30 a (365.74 g $\text{C} \cdot \text{m}^{-2}$) > 18 a (313.63 g $\text{C} \cdot \text{m}^{-2}$) > 9 a (218.66 g $\text{C} \cdot \text{m}^{-2}$) > CK (40.08 g $\text{C} \cdot \text{m}^{-2}$). (3) The seasonal variation of soil respiration rate in CK, 9 a, and 18 a plots was mainly controlled by the coupling effect of soil temperature and moisture ($P < 0.01$), while the main controlling factor in the 30 a plot was soil temperature ($P < 0.01$). (4) Soil respiration carbon flux showed significant positive correlations with vegetation biomass, soil organic carbon, and total nitrogen content ($P < 0.05$).

Full Text

Soil Respiration and Its Influencing Factors in Hedysarum laeve Shrublands of Different Stand Ages in the Mu Us Sandy Land

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Abstract

To investigate the variation trends of soil respiration rate and flux and their main influencing factors during desertification reversal, this study selected Hedysarum laeve artificial shrublands of different stand ages and unaffixed mobile sand dunes (CK) in the Mu Us sandy land. Using the Li-8100A soil carbon flux monitoring system, we conducted continuous observations of soil respiration rate during the plant growing season and measured the main environmental influencing factors. The results showed that: (1) Both soil respiration rate and flux exhibited a single-peak pattern of first increasing then decreasing during the growing season, with the highest values appearing in July. (2) Soil respiration rate and flux showed continuous increasing trends with stand age of Hedysarum laeve shrublands, while the temperature sensitivity of respiration rate (Q_{10}) showed a continuous decreasing trend. From May to October, the order of average soil respiration rates was: 30 a (2.16 $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) > 18 a (1.98 $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) > 9 a (1.41 $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) > CK (0.24 $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). The soil respiration carbon flux values were 30 a (365.74 g $\text{C}\cdot\text{m}^{-2}$) > 18 a (313.63 g $\text{C}\cdot\text{m}^{-2}$) > 9 a (218.66 g $\text{C}\cdot\text{m}^{-2}$) > CK (40.08 g $\text{C}\cdot\text{m}^{-2}$). (3) The seasonal variation of soil respiration rate in CK, 9 a, and 18 a plots was mainly controlled by the coupling effect of soil temperature and moisture ($P < 0.01$), while the main controlling factor in 30 a plots was soil temperature ($P < 0.01$). (4) Soil respiration carbon flux was significantly positively correlated with vegetation biomass, soil organic carbon, and total nitrogen content ($P < 0.05$).

Keywords: soil respiration; influencing factors; Hedysarum laeve; Mu Us sandy land

Introduction

Soil respiration refers to the process of carbon dioxide production and release from undisturbed soils, representing a critical component of ecosystem carbon cycling that regulates atmospheric CO_2 concentrations at regional and global scales [?]. Global soils release approximately 60–98 Pg of carbon to the atmosphere annually through respiration, equivalent to about 10 times the carbon emissions from human activities [?]. Consequently, even minor changes in soil respiration can significantly alter atmospheric CO_2 concentrations and potentially influence global climate change [?, ?].

In arid and semi-arid regions of northern China, characterized by poor vegetation and soil stability and relatively low soil organic carbon content, soil respiration constitutes a major pathway for ecosystem carbon loss and represents one of the most sensitive responses to climate change [?, ?]. As artificial forests establish and develop, changes in species composition, community structure, biomass accumulation, and soil properties with stand age lead to significant differences in soil respiration processes [?, ?]. Previous studies have reported varying patterns: research on Leucaena plantations in downstream areas showed decreasing soil respiration rates with increasing stand age [?], while studies on Populus davidiana plantations in dust storm source areas reported similar results [?]. In contrast, investigations of rubber plantations in Xishuangbanna found that soil respiration rates first increased then decreased with stand age [?]. However, in the arid and semi-arid sandy regions of northern China, research on basic patterns of soil respiration rate and flux during sustainable restoration of windbreak and sand-fixation vegetation, as well as the response mechanisms to changes in vegetation, soil hydrothermal factors, and physicochemical properties, remains relatively limited. Particularly, the coupling relationships between soil respiration and multiple influencing factors are not well understood.

Hedysarum laeve is a pioneer species for windbreak and sand-fixation in sandy areas of northern China, with afforestation methods including artificial seedling planting and direct seeding (primarily aerial seeding) [?]. Since the 1970s, large-scale sand-fixation afforestation projects using H. laeve have been implemented in the Ordos region of the Mu Us sandy land, creating extensive artificial vegetation restoration areas after nearly 50 years of management. Previous research has investigated water physiological ecology [?], soil moisture dynamics [?, ?], root characteristics [?, ?], and community spatial heterogeneity [?] of H. laeve. This study focuses on H. laeve artificial shrublands in the Mu Us sandy land, conducting dynamic observations of soil respiration at different temporal scales of plantation community development to elucidate the variation patterns of soil respiration rate and flux during the growing season with vegetation restoration years and their response characteristics to major environmental factors. The results provide scientific guidance for carbon sequestration management of H. laeve windbreak and sand-fixation forests and assessment of carbon sink functions in sandy ecosystems.

1.1 Study Area Overview

The Mu Us sandy land (107°20 E–111°30 E, 37°27.5 N–39°22.5 N) is one of China' s four major sandy lands, spanning southern Ordos City in Inner Mongolia, northern Yulin City in Shaanxi Province, and northeastern Yanchi County in Ningxia, with a total area of 3.8×10^4 km^2. This research was conducted at the Wulantaolegai Sand Control Station and Wushenzhao Sand Control Station in Uxin Banner, Ordos City, Inner Mongolia. The region has a temperate semi-arid continental monsoon climate, with average annual precipitation of 270–350 mm concentrated in June–August, average annual evaporation of 1800–2500 mm, mean annual temperature of 7.2 °C, total annual sunshine hours of 2900 h, frost-free period of approximately 156 days, and average elevation of 1300 m. The soil type is aeolian sandy soil. Dominant plant species include Salix cheilophila, Hedysarum laeve, Hedysarum scoparium, Caragana korshinskii, and Artemisia ordosica [**?**].

1.2 Experimental Plot Setup and Investigation

Plot setup. We selected H. laeve windbreak and sand-fixation forests established in 1990, 2003, and 2012, setting up two 20 m × 20 m fixed plots for each stand age. All plots were established on mobile sand dunes before afforestation and have remained under long-term enclosure without watering, weeding, or other management measures. No pest, disease, or fire disturbances have occurred, and natural regeneration of H. laeve populations is good. Two additional plots were established on unafforested mobile sand dunes as controls.

Investigation and measurement indicators. Within each fixed plot, we established 5 m × 5 m quadrats to visually estimate shrub cover, count shrub species and individuals, measure height with a steel tape, and harvest all above-ground biomass. Within the shrub quadrats, we established 1 m × 1 m sub-quadrats to measure herbaceous cover and aboveground biomass using the same method, collect all litter and measure its standing stock, and finally excavate soil profiles to 60 cm depth. Soil samples were collected from 0–10 cm, 10–20 cm, 20–40 cm, and 40–60 cm layers (300 g each), transported to the laboratory, and analyzed for organic carbon content using the potassium dichromate external heating method and total nitrogen content using the Kjeldahl method [**?**]. Detailed plot information is provided in .

1.3 Soil Respiration Measurement

From May to October 2021, we established 3 m × 3 m soil respiration observation quadrats in each fixed plot (spacing > 5 m between quadrats). PVC collars (20 cm inner diameter, 13 cm height) were inserted 3 cm into the soil 24 hours before measurement. Vegetation inside the collars was clipped at ground level. Using the Li-8100A soil carbon flux observation system (LI-COR, USA), we conducted continuous monthly measurements of soil respiration rate from May to October, with three sunny days selected each month. Daytime measurements were taken from 06:00–18:00 at 2-hour intervals, and nighttime measurements were taken at 18:00 and 06:00. Soil temperature and moisture at 10 cm and 20 cm depths were measured synchronously using automatic sensors with 30-minute recording intervals.

1.4 Data Processing and Analysis

We used exponential regression models to describe the relationship between soil respiration rate and soil temperature [?] and calculated temperature sensitivity (Q_{10}) using:

$$R_s = a \times e^{bT} \quad (1)$$

$$Q_{10} = e^{10b} \quad (2)$$

where R_s is soil respiration rate ($\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), T is soil temperature (°C), and a and b are constants.

Linear regression models described the relationship between soil respiration rate and soil moisture content [?]:

$$R_s = a + bW \quad (3)$$

where W is soil water content (%).

Multivariate linear and nonlinear models described the interactive effects of temperature and moisture on soil respiration [?]:

$$R_s = a + bT + cW \quad (4)$$

$$R_s = a \times T^b \times W^c \quad (5)$$

where a, b, and c are constants.

Growing season soil respiration carbon flux was calculated using the daily flux accumulation method, where daily flux equals the average daily respiration rate multiplied by 86,400 seconds:

$$R_{sy} = \sum R_{smi} \quad (6)$$

where R_{sy} is growing season soil respiration flux (g $\text{C} \cdot \text{m}^{-2}$), and R_{smi} is daily soil respiration flux (g $\text{C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).

To compare respiration rates and fluxes among plots, we fitted single-factor and two-factor models for each plot using continuous automatic measurements of soil temperature and moisture. Respiration rates were calculated at 30-minute intervals, multiplied by time to obtain daily fluxes, and accumulated to obtain growing season fluxes.

One-way ANOVA was used to analyze soil respiration differences among plots, with Duncan' s multiple comparison test for significance. Multiple regression models assessed the relative importance of environmental factors. All analyses were performed using SPSS 22.0, with figures created using Sigmaplot 12.0.

2.1 Seasonal Variation Characteristics of Soil Temperature and Moisture Content

During the growing season, the 0–30 cm soil layer average temperature across all plots ranged from 10.88 to 25.82 °C, showing a pattern of first increasing then decreasing, with maximum temperatures in July and minimum temperatures in October. The 0–30 cm soil layer average moisture content ranged from 1.85% to 13.24%, with maximum values during the rainy season in July–August and minimum values during the dry season in May–June [Figure 1: see original paper]. As H. laeve stand age increased, the monthly amplitude of soil moisture content decreased.

2.2.1 Seasonal Variation of Soil Respiration Rate

Based on optimal regression models, the growing season soil respiration rates in H. laeve plots ranged from 0.34 to 3.07 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. Specifically, CK ranged from 0.14 to 0.67 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, 9 a from 0.67 to 2.14 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, 18 a from 1.26 to 2.69 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, and 30 a from 1.25 to 3.07 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. From May to October, soil respiration rates showed a single-peak pattern, with maximum values in July [Figure 2: see original paper].

2.2.2 Seasonal Variation of Soil Respiration Flux

Growing season soil respiration fluxes from May to October also exhibited a single-peak pattern, with maximum values in July and minimum values in May [Figure 3: see original paper]. ANOVA revealed significant differences in monthly soil respiration fluxes among plots ($P < 0.05$). Total growing season fluxes were 30 a (365.74 $\mathrm{g\ C \cdot m^{-2}}$) > 18 a (313.63 $\mathrm{g\ C \cdot m^{-2}}$) > 9 a (218.66 $\mathrm{g\ C \cdot m^{-2}}$) > CK (40.08 $\mathrm{g\ C \cdot m^{-2}}$). Compared with unafforested mobile sand dunes, the 9 a, 18 a, and 30 a H. laeve plots showed increases of 445.4%, 682.6%, and 812.5%, respectively, indicating that vegetation restoration significantly enhanced soil respiration in sandy lands.

2.3.1 Relationships Between Respiration Rate and Temperature/Moisture

Exponential models showed that soil respiration rate was significantly positively correlated with 0–30 cm soil temperature across all plots ($P < 0.01$) . Linear models revealed that soil respiration rate was extremely significantly correlated with soil moisture content in H. laeve plots ($P < 0.01$), but not significantly correlated in CK plots ($P > 0.05$) .

Two-factor composite models showed that, except for CK plots, the combination of soil temperature and moisture explained 52.1-90.4% of the monthly variation in soil respiration rate, performing better than single-factor models . This indicates that the coupling of soil temperature and moisture significantly influences soil respiration in sandy lands.

2.3.2 Correlations Between Soil Respiration Rate and Other Influencing Factors

With the development of H. laeve shrublands, vegetation biomass, litter stock, root biomass, soil total nitrogen, and organic carbon content all increased significantly with stand age ($P < 0.05$) . Multiple regression analysis showed that growing season soil respiration flux was significantly correlated with vegetation biomass, soil organic carbon content, and total nitrogen content ($P < 0.05$), with relative importance values of 16.8%, 29.6%, and 18.6%, respectively . The regression model was:

$$Y = 39.14 + 0.04X_1 + 15.45X_2 + 0.01X_3 + 96.72$$

where Y is soil respiration flux, X_1 is plant aboveground biomass, X_2 is soil organic carbon content, and X_3 is total nitrogen content ($R^2 = 0.997$, $P < 0.001$).

2.3.3 Variation Characteristics of Temperature Sensitivity (Q_{10})

Based on the soil temperature exponential function model, the seasonal Q_{10} values for different plots ranged from 1.16 to 1.82, showing a trend of first increasing then decreasing with stand age. The 30 a plots had the lowest temperature sensitivity, while the 9 a and 18 a plots showed higher sensitivity than other soil layers . This pattern is similar to findings from the Kubuqi Desert [?], suggesting that vegetation restoration in sandy lands may help stabilize soil carbon pools under climate warming.

3.1 Soil Respiration Rate and Flux

Observations of Caragana korshinskii plantations in the Loess hilly region showed single-peak patterns in soil respiration rates with maximum values in July–August and a mean rate of 3.15 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ [?]. Studies on Caragana shrubs in the Xilin River basin [?] and Tamarix chinensis shrubs in the Yellow River Delta [?] also reported peak respiration rates in summer. In this study, H. laeve shrublands showed growing season respiration rates ranging from 0.31 to 3.42 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, with means of 1.28–2.14 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, generally lower than regional studies but consistent in their seasonal patterns.

3.2 Soil Respiration Temperature Sensitivity (Q_{10})

The Q_{10} values in this study (1.16–1.82) were lower than the global average for terrestrial ecosystems (2.03–2.40) [?] and the range reported for Chinese ecosystems (1.80–3.05) [?]. However, Q_{10} is influenced by multiple factors including vegetation changes, environmental hydrothermal conditions, and soil physico-chemical properties, creating uncertainties that require further verification [?].

3.3 Relationships Between Soil Respiration and Hydrothermal Factors

Temperature is a primary factor controlling seasonal variation in soil respiration rate [?]. Our exponential function models showed significant positive correlations between growing season soil respiration rate and 0–30 cm soil temperature, consistent with previous studies [?, ?]. Surface soil temperature changes are most sensitive, enhancing microbial activity and root respiratory enzyme activity, thereby strengthening soil respiration [?].

Soil moisture content is another critical environmental factor affecting soil respiration in arid and semi-arid regions, regulating biological factors closely related to respiration such as aboveground vegetation, root growth, and microbial activity [?]. Studies have reported complex and uncertain relationships between soil moisture and respiration, including positive [?], negative [?], and non-significant correlations [?]. In this study, soil respiration rate was not significantly correlated with moisture in CK plots, consistent with findings from the Mu Us sandy land [?]. However, H. laeve plots showed extremely significant correlations, likely because in water-limited sandy ecosystems, low vegetation cover in CK plots results in rapid precipitation infiltration and evaporation, making soil respiration highly sensitive to moisture changes. In contrast, higher vegetation cover in H. laeve plots slows these hydrological processes, reducing sensitivity.

3.4 Relationships Between Soil Respiration and Vegetation Biomass

Vegetation biomass influences soil respiration through two pathways: (1) input and decomposition of aboveground litter and underground dead roots driving heterotrophic respiration [?], and (2) continuous accumulation of living roots promoting autotrophic respiration [?]. In this study, aboveground biomass in H. laeve plots was 1911.1–4289.2 $kg \cdot hm^{-2}$ and root biomass was 194.3–635.4 $kg \cdot hm^{-2}$, both increasing significantly with stand age. Soil respiration flux was extremely significantly positively correlated with vegetation biomass ($P < 0.01$), consistent with studies on Eucalyptus plantations in Sichuan [?] and tundra vegetation in Changbai Mountain [?].

3.5 Relationships Between Soil Respiration and Organic Carbon/Total Nitrogen Content

Soil organic carbon is the primary nutrient source for microbial decomposition and plant growth, while nitrogen is a component of amino acids, proteins, nucleotides, and coenzymes. Accumulation of carbon and nitrogen effectively enhances soil microbial and enzyme activities, strengthening soil respiration [?]. With increasing stand age, soil organic carbon content in H. laeve plots increased from 0.63 to 1.27 $g \cdot kg^{-1}$ and total nitrogen from 0.12 to 0.15 $g \cdot kg^{-1}$. Regression analysis showed significant positive correlations between soil respiration and both organic carbon and total nitrogen content ($P < 0.05$), confirming that vegetation restoration significantly enhances soil respiration through increased carbon and nitrogen pools.

4 Conclusions

(1) During the plant growing season, soil respiration rates in H. laeve shrublands of different ages in the Mu Us sandy land showed a single-peak pattern, with maximum values occurring in summer (July). The seasonal variation in CK, 9 a, and 18 a plots was mainly controlled by the coupling of soil temperature and moisture, while soil temperature was the dominant factor in 30 a plots.

(2) Growing season soil respiration fluxes were 30 a (365.74 $g\ C \cdot m^{-2}$) > 18 a (313.63 $g\ C \cdot m^{-2}$) > 9 a (218.66 $g\ C \cdot m^{-2}$) > CK (40.08 $g\ C \cdot m^{-2}$). With increasing stand age, the continuous increase in vegetation biomass, soil organic carbon, and total nitrogen content significantly enhanced soil respiration.

(3) The temperature sensitivity of soil respiration (Q_{10}) showed an initial increase followed by a decrease with stand age development. Under climate warming, vegetation restoration in sandy lands may help stabilize soil carbon pools.

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