Effects of Moss and Litter on Soil Respiration in Qinghai Spruce Forests of the Qilian Mountains (Postprint)

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Abstract

During the 2012-2014 growing seasons, a study was conducted in a Qinghai spruce forest to investigate the effects of surface cover (moss and litter) on soil respiration rates. The LI8100 automated soil CO2 flux system was used to monitor soil respiration under moss cover, litter cover, and bare soil (with surface cover removed), and comparative analyses were performed on soil respiration differences among the three cover treatments. The results showed that the annual mean respiration rates of moss-covered soil, litter-covered soil, and bare soil were (3.88±0.26) mol m-2s-1, (3.31±0.19) mol m-2s-1, and (2.28±0.31) mol m-2 s-1, respectively, with extremely significant differences among the three. No significant differences were observed in surface relative humidity, soil water content, soil temperature, or surface temperature among the three treatments; however, soil temperature in the moss and litter groups was 8.13% and 10.24% higher than in the bare soil group, respectively. Soil respiration rates in all three treatments showed significant exponential correlations with temperature (0.53 R2 0.91), with stronger correlations observed with soil temperature. The temperature sensitivity (Q10) of soil respiration under moss cover and litter cover was 5.47 and 3.67, respectively, both higher than that of bare soil (2.23). Bare soil respiration exhibited a Gaussian function relationship with soil water content (VWC), with VWC=34% serving as the critical threshold, while respiration rates of moss-covered and litter-covered soils showed linear negative correlations with soil water content. The monthly average contribution rates of moss and litter to bare soil respiration were 29.33% and 24.06%, respectively, indicating that moss and litter play important roles in ecosystem respiration in Qinghai spruce forests.

Full Text

Effects of Moss and Litter on Soil Respiration in a Spruce Forest in the Qilian Mountains, Qinghai

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Abstract: Soil respiration (Rs) is an important component of the terrestrial ecosystem carbon cycle and the main pathway for carbon transfer from ecosystems to the atmosphere. Until recently, research has focused on the relationship between Rs and environmental factors, but the effect of litter and moss on Rs remains poorly understood. Litter and moss are common forest-floor components, particularly in northern conifer forests, and may affect soil respiration by regulating soil temperature, moisture, and carbon input. Understanding the effect of litter and moss is fundamental to accurately evaluate the global carbon budget. To evaluate the contribution of litter and moss to total Rs, we selected the Tianlaochi catchment in the Qilian Mountains, Qinghai as our study area. The Rs of soil under the spruce forest was observed for three years using an LI-8100 automatic soil CO flux measurement system. Simultaneously, soil temperature and moisture at a depth of 10 cm were recorded using temperature and moisture sensors on the LI-8100. The results showed obvious monthly and diurnal variations in Rs during the growing season—the monthly maximum Rs occurred in August and minimum in May, and the daily maximum value occurred at 13:00h, except for the moss treatment, whose maximum was at 15:00h. There was a significant exponential relationship between temperature and Rs among the three treatments ($p < 0.01$). The correlation coefficient between Rs and soil temperature was higher than that between Rs and surface temperature. The annual mean Rs values for moss-covered soil, litter-covered soil, and bare soil were (3.31 ± 0.19) mol m ² s ¹, (2.28 ± 0.31) mol m ² s ¹, and (3.88 ± 0.26) mol m ² s ¹, respectively, with highly significant differences among the three treatments. Soil temperature and surface temperature did not differ significantly among treatments, but moss and litter treatments increased soil temperature by 8.13% and 10.24%, respectively, compared to bare soil. Rs showed a significant exponential correlation with temperature in all treatments, with higher correlation to soil temperature. The temperature sensitivity (Q) values for moss-covered, litter-covered, and bare soils were 5.47, 3.67, and 2.23, respectively. Bare soil Rs showed a Gaussian function relationship with soil water content (VWC), increasing with VWC when VWC < 34% and decreasing when VWC > 34%. In moss-covered and litter-covered soils, Rs showed a linear negative correlation with VWC. The monthly contribution rates of moss and litter to bare soil Rs were 29.33% and 24.06%, respectively. We conclude that litter and moss are important factors affecting forest ecosystem Rs, and it is fundamental to consider their effects when calculating Rs in forest ecosystems.

Keywords: moss; litter; soil respiration; soil temperature; volumetric water content

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1 Study Area Overview

The experimental site is located in the Tianlaochi watershed in the upper reaches of the Heihe River in the Qilian Mountains (38°20 -38°30 N, 99°44 -99°59 E). The region has a typical continental alpine semi-humid mountain climate, characterized by long, cold, dry winters and short, cool, wet summers. The study area covers 3083 m^2 at an elevation of 99°56 E, 38°26 N. Annual precipitation ranges from 400–500 mm, concentrated in June–September, with potential evaporation of 1051.7 mm. Annual mean temperature is -0.6 to 2.0°C, with 1892.6 hours of sunshine and mean annual relative humidity of 51.96%. Qinghai spruce (*Picea crassifolia*) forests are distributed on shady slopes at 2600–4450 m elevation, covering 89.2% of the watershed. The selected spruce forest is a moss-spruce forest type with simple community structure. The soil is silty loam, with an upper layer of spruce litter (thickness 0.83 cm, biomass 369 g/m^2) and a lower moss layer (thickness 6.5 cm, biomass 1935 g/m^2). Litter consists mainly of spruce twigs and needles. The dominant moss species is *Hylocomium splendens*, with moss coverage reaching 99.3% of the forest floor and accounting for 9.95% of total biomass (2418 g/m^2).

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2 Research Methods

Within the sample plot, we randomly established three treatment types: (1) Moss treatment—maintaining the original moss cover, measuring moss-covered soil respiration; (2) Litter treatment—retaining spruce litter on the surface while removing moss, measuring litter-covered soil respiration; and (3) Bare soil treatment—removing both moss and litter from the soil surface, measuring bare soil respiration. To minimize soil disturbance from collar installation, collars were inserted 2–3 cm into the soil one week before measurements, with positions remaining fixed throughout the observation period.

Soil respiration rates were measured using an LI-8100 automatic soil carbon flux measurement system (LI-Cor, Inc., NE, USA). The system simultaneously measured surface temperature (Ta) and surface relative humidity (RH) using built-in probes, and soil temperature at 10 cm depth (Ts) and volumetric water content (VWC) using external sensors. Daytime measurements were conducted from 7:00 to 19:00 at 2-hour intervals. Diurnal measurements of bare soil respiration were performed on selected days in May, July, and September, with data recorded every 2 minutes. Measurements were taken under clear weather conditions whenever possible.

2.1 Data Processing

Parallel samples were averaged to obtain soil respiration rates and environmental factors under different treatments. Hourly data were averaged to analyze diurnal variation dynamics, and daily averages were calculated for monthly variation analysis. Monthly averages were obtained by averaging daily means within each month.

2.2 Relationship Between Respiration Rate and Temperature

We used an exponential model to simulate the relationship between respiration rate and temperature:

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

where R_s is the respiration rate (mol m ^{2} s ^{1}), T is soil temperature or surface temperature (°C), a is the respiration rate at 0°C, and b is the temperature sensitivity coefficient representing the multiple change in respiration rate per 10°C temperature increase. Parameters a and b were derived from observed temperature and soil respiration data.

2.3 Contribution of Moss and Litter to Soil Respiration

The contribution rate was calculated using:

$$LCD = \frac{CKD - NLD}{CKD} \times 100\%$$

where LCD represents the contribution rate of surface litter or moss, CKD is the mean R_s of moss or litter treatment groups, and NLD is the mean R_s of the bare soil group.

2.4 Statistical Analysis

One-Way ANOVA (SPSS 18, Chicago, IL, USA) was used to analyze significant differences among treatments. Sigmaplot software was used for graphing.

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3 Results and Analysis

3.1 Diurnal Variation of Bare Soil Respiration and Environmental Factors

Soil respiration and environmental factors showed significant diurnal variation. Soil respiration exhibited a single-peak curve, gradually decreasing from the start of observation at 7:00, reaching a minimum at 15:00 (52.25% of maximum), then increasing to a maximum at 15:00 before decreasing again until 7:00 the next day. Surface temperature (Ta) and soil temperature (Ts) showed similar trends to Rs, reaching maxima at 15:00. Surface relative humidity (RH) showed the opposite pattern, reaching a maximum at 7:00.

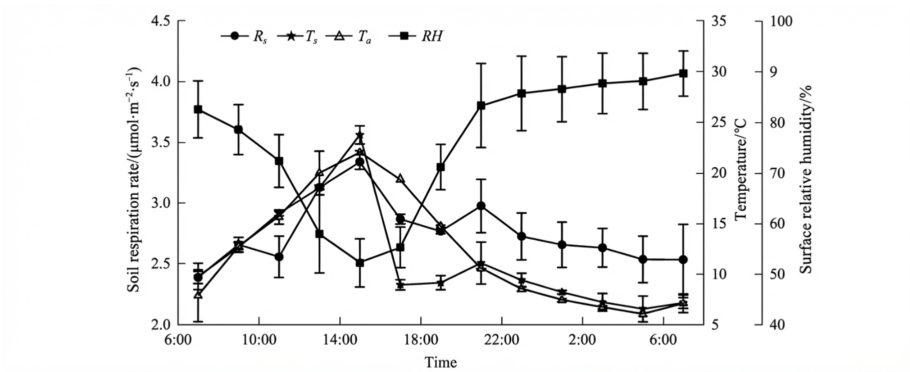

Figure 1: Figure 1

Temporal variation of soil respiration and environmental factors in bare soil. Rs: soil respiration rate in bare soil; Ts: soil temperature at 10 cm depth; Ta: surface temperature; RH: surface relative humidity.

3.2 Diurnal Variation of Respiration Rates and Environmental Factors in Moss-Covered and Litter-Covered Soils

Due to different surface covers, the diurnal variation patterns of respiration and environmental factors in moss-covered and litter-covered soils were similar to bare soil, all showing single-peak curves. However, the timing of maximum respiration rates differed among treatments. Bare soil and litter-covered soil reached maximum Rs at 13:00–15:00, while moss-covered soil reached maximum Rs at 15:00. Ta and Ts peaked at 13:00–15:00, with a lag observed between Ta and Ts.

[FIGURE:2] Diurnal variation of soil respiration rate and environmental factors in June 2012. The meaning of Ta and RH is the same as in Figure 1. " ", " ", and " " represent bare soil treatment, moss treatment, and litter treatment, respectively.

3.3 Monthly Variation Dynamics

During the growing season, respiration rates and soil temperatures showed significant monthly variations, increasing with temperature. Monthly mean values revealed that maximum Rs for all treatments occurred in August, while minimum values appeared in May. The ranking of monthly mean respiration rates was: litter-covered soil (3.48 ± 0.53 mol m ^{2} s ^{1}) > moss-covered soil (3.06 ± 0.41 mol m ^{2} s ^{1}) > bare soil (2.24 ± 0.22 mol m ^{2} s ^{1}). Monthly variation ranges were 1.67-2.85, 1.73-4.63, and 1.77-4.15 mol m ^{2} s ^{1} for bare, moss-covered, and litter-covered soils, respectively.

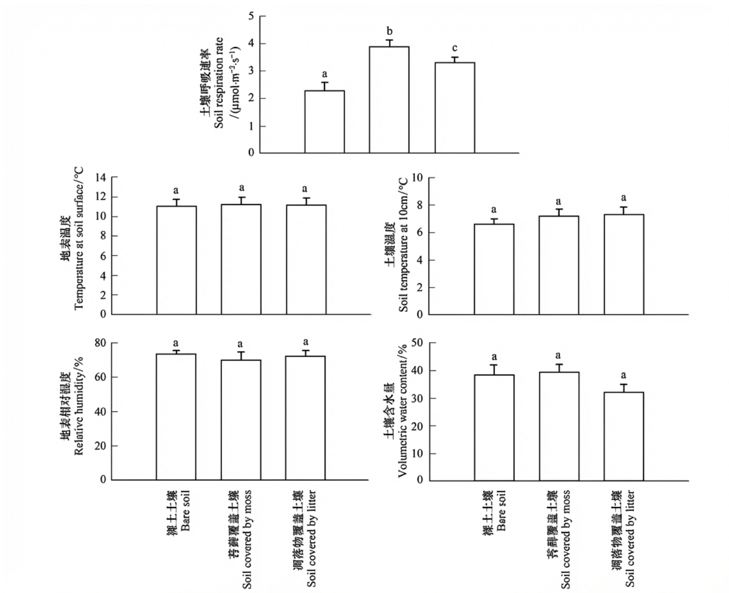

Figure 2: Figure 3

Monthly variation of Rs, Ta, Ts, and RH in three treatments.

3.4 Comparison of Respiration Rates and Environmental Factors Among Treatments

Significant differences in Rs were found between moss-covered and litter-covered soils ($p = 0.001$). Surface relative humidity between bare soil and moss-covered soil was marginally significant ($p = 0.059$). No significant differences were observed in Ta, Ts, or VWC among the three treatments. Annual mean Rs values were (3.31 ± 0.19), (2.28 ± 0.31), and (3.88 ± 0.26) mol m ^{2} s ^{1} for moss-covered, bare, and litter-covered soils, respectively. Annual mean Ts values were (11.06 ± 0.68)°C, (11.20 ± 0.76)°C, and (11.15 ± 0.74)°C, respectively. Annual mean Ta values were (6.64 ± 0.35)°C, (7.18 ± 0.51)°C, and (7.32 ± 0.52)°C, respectively.

Moss and litter treatments increased Rs by (38.64 ± 3.38)% and (39.25 ± 3.07)%, respectively, compared to bare soil. Moss and litter treatments increased Ta by (32.00 ± 2.98)% and (45.18 ± 2.91)%, respectively, and increased Ts by 8.13% and 10.24%, respectively.

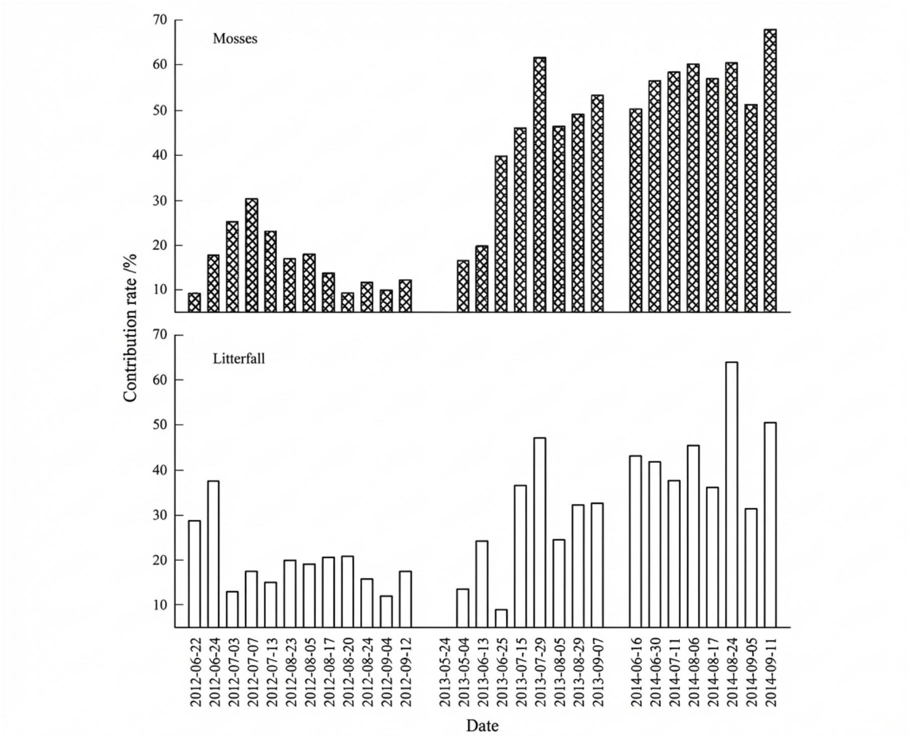

Figure 3: Figure 4

Significant differences of Rs, Ta, Ts, and RH among three treatments across three years.

3.5 Contribution of Moss and Litter to Soil Respiration

Moss and litter contributions to bare soil Rs showed distinct monthly variation. In May, contributions were only 3.93% for moss and 5.63% for litter, rising sharply in June to reach maximum values in August (67.96% for moss, 63.96% for litter). Monthly contribution rates ranged from 3.93%-30.92% for moss and 3.93%-39.01% for litter. The mean monthly contributions were 29.33% for moss and 24.06% for litter.

[FIGURE:5] Contribution rates of moss and litter to total soil respiration.

3.6 Correlation Analysis Between Soil Respiration Rate and Environmental Factors

3.6.1 Relationship with Temperature In all three treatments, respiration rates showed highly significant exponential correlations with temperature ($p < 0.01$), with better fit at lower temperatures. Surface temperature could explain 68.80%, 52.91%, and 60.93% of variation in bare, moss-covered, and litter-covered soil respiration, respectively. Soil temperature could explain 79.56%, 91.11%, and 84.66% of variation, respectively, indicating stronger response to soil temperature than surface temperature. Q values ranked as: moss-covered soil (5.47) > litter-covered soil (3.67) > bare soil (2.23).

[FIGURE:6] Relationship between respiration rate and surface/soil temperature.

3.6.2 Relationship with Soil Water Content In bare soil, respiration rate showed a Gaussian relationship with VWC, increasing with water content when VWC < 34% but decreasing when VWC > 34%. In moss-covered and litter-covered soils, respiration rate showed linear negative correlations with VWC. Soil water content could explain 43%–65% of variation in respiration rates.

[FIGURE:7] Relationship between soil respiration and soil water content.

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4 Discussion

4.1 Temporal Dynamics of Soil Respiration Rate

Both moss-covered and litter-covered soils exhibited single-peak diurnal variation curves, consistent with temperature patterns, indicating temperature as the primary control on diurnal variation. Maximum Rs occurred at 13:00–15:00 for bare and litter-covered soils, but was delayed to 15:00–17:00 for moss-covered soil, likely because moss acts as a barrier hindering direct heat transfer to soil. Our results (bare soil: 1.67–2.85 mol m ^{2} s ^{1}; moss-covered: 1.73–4.63 mol m ^{2} s ^{1}; litter-covered: 1.77–4.15 mol m ^{2} s ^{1}) differ from some previous studies, possibly due to spatial heterogeneity, canopy structure differences, moss thickness, species composition, or elevation.

4.2 Relationships with Temperature and Soil Water Content

Temperature and moisture are widely recognized as primary factors controlling soil respiration, especially in arid and semi-arid regions. Our exponential model achieved high correlation coefficients, with soil temperature showing stronger relationships than surface temperature. Moss and litter covers increased soil temperature by 8.13% and 10.24%, respectively, likely contributing to increased respiration rates. The presence of moss and litter promotes faster decomposition and more active microbial metabolism, thereby enhancing respiration.

The relationship between respiration rate and soil water content is complex. In bare soil, we found a Gaussian relationship with a critical threshold at VWC = 34%, beyond which respiration decreased. This threshold effect may be influenced by surface cover, vegetation type, and rainfall patterns. In covered soils, linear negative relationships prevailed, suggesting that cover materials modify moisture effects on respiration.

4.3 Effects of Moss and Litter on Soil Respiration

Moss increased bare soil respiration by 29.33%, consistent with studies showing moss contributions of 10%-55% to soil respiration. The positive effects include: large moss biomass, high autotrophic respiration, accumulation of humus, hosting of decomposer microbes, and improved soil moisture and nutrients. However, some studies report negative effects, suggesting moss can reduce soil temperature and inhibit organic matter decomposition. The net effect requires long-term observation.

Litter increased bare soil respiration by 24.06%, comparable to contributions of 28% reported for tropical forests and 45% for some coniferous forests. Litter affects respiration through multiple pathways: preventing soil cooling, increasing microbial biomass, providing substrate for microbial respiration, and influencing leaching processes. The magnitude of effect depends on litter quantity and decomposition rate.

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5 Conclusion

1. Surface cover affects the timing of maximum respiration rates. Moss cover delayed the peak by 1-2 hours compared to bare and litter-covered soils.
2. Moss and litter significantly increased soil respiration rates, with mean monthly contributions of 29.33% and 24.06%, respectively. Although temperature and moisture differences among treatments were not statistically significant, the effects of cover materials on microclimate were evident.
3. All treatments showed significant exponential relationships between respiration rate and temperature, with stronger correlations to soil temperature than surface temperature. Moss and litter covers increased temperature sensitivity (Q values of 5.47 and 3.67 vs. 2.23 for bare soil).
4. Soil moisture effects on respiration were bidirectional. In bare soil, a critical threshold occurred at VWC = 34%, above which respiration declined. In covered soils, respiration showed linear negative correlations with VWC.

These findings demonstrate that moss and litter are important factors affecting soil respiration in Qinghai spruce forests and must be considered when evaluating forest ecosystem carbon cycling.

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