Research Article

Five-Year Soil Respiration Reflected Soil Quality Evolution in Different Forest and Grassland Vegetation Types in the Eastern Loess Plateau of China

Soil CO₂ efflux in forest and grassland over 5 years from 2005 to 2009 in a semiarid mountain area of the Loess plateau, China, was measured. The aim was to compare the soil respiration and its annual and inter-annual responses to the changes in soil temperature and soil water content between the two vegetation types for observing soil quality evolution. The differences among the five study years were the annual precipitation (320.1, 370.5, 508.8, 341.6, and 567.4 mm in 2005–2009, respectively) and annual distribution. The results showed that the seasonal change of soil respiration in both vegetation types was similar and controlled by soil temperature and soil water content. The mean soil respiration across 5 years in the forest (3.78 ± 2.68 μmol CO₂ m⁻² s⁻¹) was less than that in the grassland (4.04 ± 3.06 μmol CO₂ m⁻² s⁻¹), and the difference was significant. The drought soil in summer depressed soil respiration substantially. The $Q_{10}$ value across 5-year measurements was 2.89 and 2.94 for forest and grassland. When soil water content was between wilting point (WP) and field capacity (FC), the $Q_{10}$ in both types increased with increasing soil water content, and when soil water content dropped to below WP, soil respiration and the $Q_{10}$ decreased substantially. Although an exponential model was well fitted to predict the annual mean soil respiration for each single year data, it overestimated and underestimated soil respiration, respectively, in drought conditions and after rain for short periods of time during the year. The two-variable models including temperature and water content variables could be well used to predict soil respiration for both types in all weather conditions. The models proposed are useful for understanding and predicting potential changes in the eastern part of Loess plateau in response to climate change.

Keywords: Soil CO₂ efflux; Soil quality evolution; Soil water content; Temperature sensitivity; Vegetation type

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1 Introduction

Soil CO₂ efflux, also known as soil respiration including respiration of plant roots, the rhizosphere, microbes, and fauna, has recently received considerable interest because of its importance in the global carbon cycle and potential feedbacks to climate change and soil quality evolution [1], and its accurate quantification has significant implications for ecosystem carbon balances [2] and climate change [3]. On a global scale, mean soil respiration varies widely within and among major vegetation biomes [4], suggesting that vegetation types influence the rate of soil respiration [5]. Differences in soil respiration observed among vegetation types can be explained largely by differences in temperature and moisture and land use change among vegetation biomes [6]. Soil respiration rates correlate significantly with mean annual air temperatures, mean annual precipitation, and with the interaction of the two variables. In addition to soil temperature and soil water content, landscape structure, soil texture, stand characteristics, and substrate quality as well as forest age all affect soil respiration and quality because of their difference in soil carbon and nutrient accumulation as well as soil enzyme activity [7–14].

By collecting the data from published studies where soil respiration rates were measured simultaneously in two or more plant communities located on the same soil type and in similar topographic positions, Raich and Tufekcioglu [5] found no predictable differences in soil respiration between cropped and vegetation-free soils, between forested and cropped soils, or between grassland and cropped soils. But they found that coniferous forest had ~10% lower rate of soil respiration than did adjacent broad-leaved forests growing on the same soil type, and grassland had ~20% higher soil

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Abbreviations: FC, field capacity; RMSE, root mean square error; WP, wilting point
respiration rates than did comparable forest stands. From a case study over the main climatic zones of China, spanning from alpine to temperate to tropical, Zheng et al. [12] reported that ecosystems of different vegetation types showed different \( Q_{10} \) values, ranging from 1.28 to 4.75, which were primarily determined by soil temperature, soil organic carbon content, and ecosystem types. Small-scale spatial variation in soil respiration was reported by Maestre and Cortina [13]. They found significant differences in \( CO_2 \) efflux between different soil cover types.

Studies on soil respiration have been made in East Asia [14, 15], but there have been comparatively fewer research reports in the Loess plateau of China, especially in the eastern part of the plateau. As the second largest geographic unit in China, the plateau is characterized by its non-uniform land cover. In recent years, the shifts from arable land to forest and grassland in the region have affected to a certain extent vegetation type, soil succession [16], soil physical properties [17], and eventually soil respiration. However, there is little knowledge of the effectiveness of vegetation on soil respiration. In a previous study based on 1-year’s observations, we examined the role of soil temperature and soil water content on soil respiration in 11 sites of differing vegetation types and elevations [18]. In the current study, we presented about 5-year observations of soil \( CO_2 \) efflux from forest and grassland soils and analyzed its sensitivity to temperature. The objectives were (i) to further compare the seasonal, annual, and inter-annual variations in soil respiration and their responses to environmental factors between forest and grassland, (ii) to investigate the response of \( Q_{10} \) to soil temperature, soil water content in two vegetation types, and the depth at which soil temperature was measured. We choose two vegetation types with similar climate and soil properties to assess the impact that differences in precipitation, temperature, and soil water content had on soil respiration and its sensitivity to temperature. The results may give some implications for soil quality evolution and management and climate change research.

2 Materials and methods

2.1 Site description

The study site is located in the Tianlong Mountain natural reserves area (37°44′N, 112°22′E) in Taiyuan City, Shanxi Province, China. The area is characterized by a monsoon continental climate: cold winter and dry spring, hot-humid summer and cold-humid autumn. The mean annual precipitation, based on a 31-year climate record from 1978 to 2008, is 413.9 mm, ranging from 234.6 mm in 1997 to 586.6 mm in 1996. Sixty percent of the annual precipitation falls during the period from July to August. The annual mean temperature is 10°C, with a mean daily minimum of –6.4°C in January and a mean daily maximum of 23°C in July. The annual precipitation was 320.1, 370.5, 508.8, 341.6, and 567.4 mm in 2005–2009, respectively. The dominant tree species are pine (Pinus tabulaeformis Carr. and P. bungeana Zucc. ex Endl.) and arborvitae (Pseudotsuga orientalis L.) Franco, and they cover over 80% of the total area. Grasslands and shrub lands in this area are sparsely located above sea level of 1350 m, and account for about 20% of the total area. The herbaceous plants consist of Artemisia sacrorum Lede., Bupleurum angustissimum Kitag., and Artemisia lavandulaefolia DC. The experimental sites have never been managed, and have never been grazed or fertilized. Further details concerning natural vegetation in the area have been described by Cheng et al. [19].

2.2 Soil respiration and environmental factors measurements

Two forest types (P. tabulaeformis Carr. and P. bungeana Zucc. ex Endl.) and two grassland types (Carex rigescens (Franch.) V. Krecz. and Artemisia gmelinii Web. ex Stechm.) were chosen from dominant vegetation covers. One plot in each forest (20 m × 20 m) and grassland (10 m × 10 m) was established for performance of experiments. The forest is a secondary forest about 25 years old. The four plots were located in a flat area within a distance of 100 m in diameter, and were on the same soil parent material and in similar topographic positions. Soil in the forest and grassland is sandy loams with a clay fraction (<0.002 mm) of 35.2 and 35.5%, a silt fraction (0.02–0.002 mm) of 23.9 and 23.7%, and a sand fraction (>0.02 mm) of 40.9 and 40.8%, respectively. The soil organic carbon of the forest and grassland is 2.61 ± 0.41, 3.11 ± 0.60 g kg⁻¹, respectively. In each plot, four to five PVC collars with approximately 2 m spacing were inserted into the soil surface 2–3 cm depth. Insertion took place at least 1 wk prior to initial \( CO_2 \) efflux measurements, and the collars were left in the place where there is no living above-ground vegetation for the duration of the experiment. Leaf litter within the collars was not removed during the measurement. The collars were used to avoid disturbing the soil with the soil chamber when a measurement was made. Soil respiration was measured using a LI-6400 IR gas analyzer (LI-Cor, Lincoln, NE, USA) equipped with a LI-6400-09 dynamic soil respiration chamber. The measurement was carried out from April of 2005 to November of 2009 with two to three sampling times every month, and a total of 102 measurements were made across the 5 years for each vegetation type. Measurements were done during snow free and frost free period (March–December) between 10:00 and 12:00 on rainless days.

Simultaneously with soil respiration sampling, soil temperature at 10 cm depth was measured with a thermocouple probe (6400-09TC2) the system inserted in the soil adjacent to the PVC collars to a depth of 10 cm. In addition, we made soil temperature measurements at 5 and 15 cm depths using the probe during 2007–2009. At the time of the efflux measurement, soil moisture measurements, expressed as percentage of dry soil mass, were taken from 0 to 10 cm soil depth adjacent to the PVC collars and oven-dried (105°C) until a constant mass. Soil bulk density and soil field capacity (FC) were measured using the volumetric core method. Wilting point (WP) of the soil was calculated as 40% of FC [20]. The litters and roots biomass were also measured.

2.3 Data analysis

The data of two sampling plots within each vegetation type were averaged and used for analysis. All results were represented as mean value ± standard error. Pair wise test was used to compare difference of the measured \( R_a, T_a, W_a \) data between the forest and the grassland. Statistical significance was established at the 0.05 level, unless otherwise mentioned. As for the relationship between seasonal \( R_a \) and \( T_a \) and \( W_a \), linear and nonlinear regression model analyses were performed as follows:

\[
R_a = a e^{bT_a} \quad (1)
\]

\[
R_a = a W_a^b \quad (2)
\]

\[
R_a = a W_a + b \quad (3)
\]
\[ R_i = a(T_i, W_i) + b \]  
\[ R_i = a e^{bT_i} W_i^c \]

Temperature sensitivity \( (Q_{10}) \) of soil respiration and the soil respiration at soil temperature of 10°C \( (R_{10}) \) were calculated, respectively, by:

\[ Q_{10} = e^{10b} \]  
\[ R_{10} = a e^{10b} \]

where \( R_i, T_i, \) and \( W_i \) are average of the measured soil respiration rate (\( \mu \text{mol m}^{-2} \text{s}^{-1} \)), soil temperature (°C), and soil water content (dry weight %) in two plots for each vegetation type, respectively, and \( a, b, \) and \( c \) are regression coefficients, and \( b \) in Eqs. (6) and (7) is from Eq. (1). We use root mean square error (RMSE = \( \sqrt{\sum (\hat{y}_i - y_i)^2/n} \)); \( \hat{y}_i \) and \( y_i \) represent the estimated and measured \( R_i \) values, respectively, to compare fitted models. The total soil CO\(_2\) efflux between March through December from each vegetation type was the sum of \( R_i \) of each month. The monthly soil respiration value was calculated as the \( R_i \) average of two measurements per month multiplied by the respective day number of the month.

3 Results

3.1 Seasonal and inter-annual fluctuations of \( T_s, W_s, \) and \( R_s \)

Both single year and 5-year averages of \( T_s, W_s, \) and \( R_s \) (mean ± SE) and paired-sample t-test result were presented in Tab. 1. The averages of the measured \( T_s \) for single and 5 years in the grassland are significantly larger than those in the forest, and no significant difference for the measured \( W_s \) was observed in all years except in 2006 and 2009. The measured \( R_s \) value across 5 years was significantly larger in grassland than that in forest (Tab. 1). The seasonal variations in \( W_s \) (Fig. 1b) depletion and associated \( T_s \) in both vegetation types (Fig. 1a) were representative of the continental monsoon type climate conditions on the eastern Loess plateau of China, as indicated in Fig. 1c. The seasonal patterns of \( T_s, W_s, \) and \( R_s \) over a year in both vegetation types showed a similar trend with a correlation coefficient of 0.98, 0.84, and 0.92 across 5 years, respectively. \( T_s \) ranged from around 0°C in winter and early spring to >20°C in summer, with mean \( T_s \) values ranging from 10.17 to 14.97°C in the forest and 12.16 to 17.95°C in the grassland (Tab. 1). The peak values of \( T_s \) mostly appeared between mid-July and mid-August (Fig. 1a). The highest \( T_s \) among 5 years occurred in 2009 due to intense drought in early summer, although this year had the highest annual rainfall among 5 years (Fig. 1c). The mean \( T_s \) at 10 cm depth in the grassland in 2005, 2006, 2007, 2008, and 2009 was, respectively, 1.09, 1.67, 1.84, 1.87, and 2.98°C higher than that in the forest.

Uneven yearly distribution of precipitation (Fig. 1c) resulted in clear fluctuations of \( W_s \) over a year from less than WP to more than FC of the soils (Fig. 1b). The soil water deficit mostly developed in late-spring and early summer followed by recharge of summer rain (Fig. 1c). The annual mean \( W_s \) ranged from 15.16 to 19.88% in the forest and 15.61 to 19.86% in the grassland. The summertime minimum \( W_s \) in 2009 occurred from May 10 through July 5, in comparison with the other 4 years, indicating that summer drought was at its most severe in 2009 among the 5 years (Fig. 1c). Contrasting seasonal variations in \( W_s \) were highlighted when compared between 2008 and the other years. In 2008, a distinct down trend of \( W_s \) appeared over the year, but in other 4 years a distinct increasing trend began from the middle of the growing season (Fig. 1b and c). Controlled by \( T_s \) and \( W_s, \) \( R_s \) generally showed a unimodal distribution over a given year with maximums in the summer months when \( W_s \) was not limiting, and minimums occurred during the winter months or in early spring (Fig. 1d). The measured mean \( R_s \) during the 5-year measurements ranged from 3.27 to 4.58 \( \mu \text{mol} \text{m}^{-2} \text{s}^{-1} \) in the forest and from 3.33 to 5.42 \( \mu \text{mol} \text{m}^{-2} \text{s}^{-1} \) in the grassland (Tab. 1). The peak time and value of \( R_s \) over a year mostly occurred in summer months whenever both \( W_s \) and \( T_s \) were high, depending on timing and amount of precipitation. When the \( W_s \) in summer months dropped to <10% (corresponding to a soil water matric potential of ~1.5 MPa), the \( R_s \) substantially decreased. Soil water stress strongly restricted \( R_s \), confirming a potential for soil water levels to decouple \( R_s \) from variations in \( T_s \), High rain events in the summer unusually resulted in boosting of \( R_s \), and low \( W_s \) restricted \( R_s \) (Fig. 1c and d).

The annual soil effluxes ranged from 882 to 1215 and from 931 to 1380 g C m\(^{-2}\) for the forest and grassland, with an overall mean of 1051 g C m\(^{-2}\) (forest) and 1097 g C m\(^{-2}\) (grassland) across 5 years.

<table>
<thead>
<tr>
<th>Year</th>
<th>n</th>
<th>Soil temperature(^{a})</th>
<th>Soil water content</th>
<th>Soil respiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>2005</td>
<td>22</td>
<td>11.43 ± 1.28(^{a})</td>
<td>15.91 ± 0.87(^{a})</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>24</td>
<td>11.00 ± 1.30(^{a})</td>
<td>15.16 ± 0.96(^{a})</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>23</td>
<td>10.32 ± 1.36(^{a})</td>
<td>19.88 ± 0.63(^{a})</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>16</td>
<td>10.17 ± 1.62(^{a})</td>
<td>19.19 ± 1.41(^{a})</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>17</td>
<td>14.97 ± 1.39(^{a})</td>
<td>16.13 ± 1.64(^{a})</td>
</tr>
<tr>
<td>Grassland</td>
<td>2005</td>
<td>22</td>
<td>12.52 ± 1.39(^{b})</td>
<td>15.61 ± 0.96(^{b})</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>24</td>
<td>12.67 ± 1.53(^{b})</td>
<td>16.62 ± 1.13(^{b})</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>23</td>
<td>12.16 ± 1.62(^{b})</td>
<td>19.86 ± 0.62(^{b})</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>16</td>
<td>12.04 ± 1.88(^{b})</td>
<td>18.46 ± 1.56(^{b})</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>17</td>
<td>17.95 ± 1.58(^{b})</td>
<td>17.35 ± 1.69(^{b})</td>
</tr>
<tr>
<td></td>
<td>2005–2009</td>
<td>102</td>
<td>13.30 ± 0.73(^{b})</td>
<td>17.55 ± 0.59(^{b})</td>
</tr>
</tbody>
</table>

\(^{a}\) Result of pair wise test for difference between the forest and the grassland of the measured \( R_s, T_s, W_s \) data for single year and 5-year averages. Mean values followed by the same letter do not have significant differences between the two types at the 0.05 level. Capital and lowercase letters represent the result across 5 years and a single year, respectively.
Paired t-test showed that no significant difference of total soil CO₂ efflux was found between the two types.

3.2 Relationships between soil respiration, soil temperature, and soil water content

3.2.1 Soil temperature

The fitted exponential relationship of $R_s$ and $T_s$ confirmed that $R_s$ generally varied with $T_s$ when $W_s > WP$ (a value of about 40% of FC; corresponding to a soil water matric potential of −1.5 MPa) (Fig. 2). Below this water content value, $R_s$ was significantly decoupled from $T_s$, and $W_s$ became a major control on $R_s$ (Fig. 2). The $Q_{10}$ value (an indicator of temperature sensitivity of $R_s$) for 5-year data was 2.89 and 2.94 for the forest and grassland, and $R_{10}$ ($R_s$ at 10°C $T_s$) value for 5-year data was 2.36 and 1.93 μmol m⁻² s⁻¹, respectively. The $Q_{10}$ values for each year data ranged from 2.92 to 3.49 and 2.62 to 3.54 for the forest and grassland, respectively; and the $R_{10}$ values ranged from 1.38 to 2.90 μmol CO₂ m⁻² s⁻¹ for the forest and from 1.33 to 2.72 μmol CO₂ m⁻² s⁻¹ for the grassland. No significant difference was found between the two vegetation types.

In order to examine the effect of drought on $Q_{10}$ and $R_{10}$ values, we fitted equation of $R_s$ to $T_s$, respectively, for all data, the data of $W_s > WP$ and $W_s < WP$, and conducted further analyses (Fig. 2). The results showed that the $Q_{10}$ and $R_{10}$ values as well as the coefficients of determination of the fitted equations increased to some extent when dry data were exclude from analysis (Fig. 2), and that the

Figure 1. Annual and inter-annual variations in (a) soil temperature at 10 cm depth, (b) soil water content in the top 10 cm soil, (c) daily precipitation, and (d) soil respiration. Symbols ● and ○ represent the forest and grassland, respectively; and dotted line and solid line in (b) represent WP and FC, respectively.
Q₁₀ and R₁₀ values decreased for the data of Wₛ < WP. This indicated that the drought soil conditions masked the relationship between Rₛ and Tₛ, Q₁₀ and R₁₀ values.

The Q₁₀ values calculated from the fitted parameters for all data of 2007–2009 at Tₛ of 5, 10, and 15 cm depths showed that Q₁₀ increased with increasing measurement depth (Tab. 3). The Q₁₀ values at 5 cm depth were less than those at 10 and 15 cm depth, but there was a little difference in Q₁₀ values at 10 cm versus 15 cm depth. For data from both vegetation types across 5 years, a Q₁₀ value of 2.53 at 5 cm depth increased to 2.90 at 15 cm depth, a 0.1 increase for each degree of Tₛ increase, while from 10 to 15 cm depth there was only a 0.07 increase. The R₁₀ values also showed an increase with depth from 5 to 10 cm depth, but little difference between 10 and 15 cm depth. This indicated that in our study site the temperature at both 10 and 15 cm depth could be good used to fit the relationship between Rₛ and Tₛ, and to calculate Q₁₀ and R₁₀ values.

We pooled all 5 years’ worth of data for both vegetation types, and regrouped them with respect to Wₛ (fraction of FC, <0.4, 0.40–0.6, 0.6–0.8, 0.8–1, 1–1.2, and >1.2). For each soil moisture class we fitted Rₛ against Tₛ data, respectively, and calculated Q₁₀ and R₁₀ values. Then, using the calculated Q₁₀ and R₁₀ values as dependent variables and the corresponding soil water class as the independent variable, the quadratic relationships of Q₁₀ and R₁₀ to Wₛ class were established (Fig. 3). The Q₁₀ value increased with Wₛ to a maximum at Wₛ about 80–90% of FC, and when Wₛ was <40% of FC and above FC the Q₁₀ decreased. The R₁₀ value was at maximum when the Wₛ reached close to FC (90–100% of FC).

3.2.2 Soil water content

As expected, compared with the relationships of Rₛ against Tₛ for both single year and 5-year data (Fig. 2), the ones of Rₛ against Wₛ was

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**Table 2. Monthly soil CO₂ effluxes (g C m⁻² month⁻¹) from the two communities in 2005–2009, respectively**

<table>
<thead>
<tr>
<th>Types</th>
<th>Year</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>2005</td>
<td>34.3b</td>
<td>53.2</td>
<td>142.4</td>
<td>110.9</td>
<td>195.7</td>
<td>235.6</td>
<td>236.1</td>
<td>157.6</td>
<td>37.1</td>
<td>12.0</td>
<td>1215</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>18.1</td>
<td>59.2</td>
<td>95.1</td>
<td>96.5</td>
<td>144.0</td>
<td>225.8</td>
<td>155.8</td>
<td>97.8</td>
<td>42.9</td>
<td>26.0</td>
<td>961</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>44.1</td>
<td>104.9</td>
<td>65.9</td>
<td>122.8</td>
<td>252.3</td>
<td>268.3</td>
<td>186.1</td>
<td>95.4</td>
<td>41.4</td>
<td>17.5</td>
<td>1199</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>34.7</td>
<td>53.7</td>
<td>66.3</td>
<td>186.1</td>
<td>194.2</td>
<td>155.2</td>
<td>158.5</td>
<td>105.7</td>
<td>31.1</td>
<td>13.2</td>
<td>999</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>40.3</td>
<td>15.6</td>
<td>48.6</td>
<td>51.4</td>
<td>221.7</td>
<td>182.2</td>
<td>150.0</td>
<td>114.1</td>
<td>44.0</td>
<td>17.2b</td>
<td>882</td>
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<tr>
<td>Grassland</td>
<td>2005</td>
<td>33.0b</td>
<td>57.3</td>
<td>83.7</td>
<td>113.5</td>
<td>201.6</td>
<td>213.4</td>
<td>177.3</td>
<td>113.6</td>
<td>39.3</td>
<td>17.2</td>
<td>1051</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>12.3</td>
<td>59.3</td>
<td>118.1</td>
<td>123.1</td>
<td>130.5</td>
<td>191.4</td>
<td>158.1</td>
<td>91.4</td>
<td>26.5</td>
<td>20.5</td>
<td>931</td>
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<tr>
<td></td>
<td>2007</td>
<td>41.4</td>
<td>159.7</td>
<td>103.6</td>
<td>141.0</td>
<td>243.5</td>
<td>290.7</td>
<td>134.0</td>
<td>65.1</td>
<td>19.9</td>
<td>7.4</td>
<td>1206</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>34.9</td>
<td>58.3</td>
<td>119.8</td>
<td>182.9</td>
<td>200.4</td>
<td>148.0</td>
<td>143.8</td>
<td>76.8</td>
<td>16.7</td>
<td>5.5</td>
<td>987</td>
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<tr>
<td></td>
<td>2009</td>
<td>43.4</td>
<td>29.1</td>
<td>55.8</td>
<td>67.7</td>
<td>243.4</td>
<td>246.4</td>
<td>149.0</td>
<td>92.4</td>
<td>45.3</td>
<td>10.0b</td>
<td>983</td>
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<tr>
<td></td>
<td>2005–2009</td>
<td>33.0</td>
<td>72.4</td>
<td>111.2</td>
<td>125.1</td>
<td>209.1</td>
<td>245.3</td>
<td>165.3</td>
<td>96.7</td>
<td>29.1</td>
<td>10.0</td>
<td>1097</td>
</tr>
</tbody>
</table>

a) Total represents CO₂ efflux amount (g C m⁻² period⁻¹) from March to December.

b) The value is mean value of other four years.

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**Table 3. The Q₁₀ and R₁₀ variations with increasing temperature measuring depth of 5, 10, and 15 cm, respectively**

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth (cm)</th>
<th>Forest Q₁₀</th>
<th>K₁₀</th>
<th>R²</th>
<th>Grassland Q₁₀</th>
<th>K₁₀</th>
<th>R²</th>
<th>Both types Q₁₀</th>
<th>K₁₀</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007–2009</td>
<td>5</td>
<td>2.52</td>
<td>2.01</td>
<td>0.54</td>
<td>2.75</td>
<td>1.38</td>
<td>0.71</td>
<td>2.53</td>
<td>1.71</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.76</td>
<td>2.17</td>
<td>0.55</td>
<td>2.96</td>
<td>1.68</td>
<td>0.67</td>
<td>2.83</td>
<td>1.95</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>2.79</td>
<td>2.17</td>
<td>0.57</td>
<td>3.07</td>
<td>1.78</td>
<td>0.68</td>
<td>2.90</td>
<td>1.98</td>
<td>0.62</td>
</tr>
</tbody>
</table>

a) R² is the coefficient of determination of the fitted equation at corresponding depth of soil temperature measurement.
significant only in 2009 (linear, \( p < 0.01 \) for both forest and grassland in 2009). This indicated that effect of \( W_s \) on \( R_s \) is less than that of \( T_s \) on \( R_s \) on most of years. However, when combining 5-year data during the summer (June through August), we found that \( R_s \) showed significant positive correlation with \( W_s \) (for both types, \( p < 0.01 \); Fig. 4). In contrast, the relationship between \( R_s \) and \( T_s \) during the same period was not significant (\( p > 0.05 \); Fig. 4). This indicated that in the summer, it is \( W_s \) and not \( T_s \) that controlled \( R_s \) and that if we were to use \( T_s \) to predict \( R_s \) in summer months, it could result in a greater margin of error.

### 3.3 Combined relations between soil respiration, soil temperature, and soil water content

For measurements in the field over the season it is possible that the empirically derived \( Q_{10} \) temperature function is confounded with an effect of \( W_s \) [21]. Including a water variable in the \( Q_{10} \) function or using a new multiple variable for both \( T_s \) and \( W_s \) could improve predictive accuracy for \( R_s \). Compared with a single exponential function, two two-variable models strongly improved the predictability of \( R_s \) (Tab. 4). For example, for a single year of data (2009), the exponential equation explained only 40 and 49% of variance of \( R_s \) for forest and grassland, respectively. Adding the relationship with water as a power component to the exponential equation increased the \( R^2 \) values to 81 and 84%, respectively. The percents of variance of seasonal variation in \( R_s \) that could be explained by the product and exponential-power equations ranged from 72 to 87% and 81 to 91%.

#### Figure 3. Relations of both \( Q_{10} \) and \( R_{10} \) values with \( W_s \) and \( W_s \) were represented by a fraction of FC. The relations both \( Q_{10} \) (●) and \( R_{10} \) (■) with \( W_s \) could be expressed well by quadratic curves (\( Q_{10} = -8.51W_s^2 + 15.32W_s - 3.17, R^2 = 0.93; R_{10} = -1.88W_s^2 + 4.27W_s + 0.15, R^2 = 0.79 \)). The solid line represents a fitted regression line for 5-year data combined for two vegetation types.

#### Figure 4. Relationships between soil respiration rate and soil water content (●) at the top 10 cm, and soil temperature (■) at 10 cm depth during the summer (June through August) measurements in the forest (a) and the grassland (b) across 5 years. Dotted and solid lines represent fitted line of \( R_s \) against \( T_s \) and \( W_s \), respectively.

#### Table 4. Regression coefficients of the exponential equation and the combined relationships between soil respiration and soil temperature and soil moisture

<table>
<thead>
<tr>
<th>Equation types</th>
<th>( R_s = ae^{bT_s} ), Eq. (1)</th>
<th>( R_s = a(T_sW_s) + b ), Eq. (4)</th>
<th>( R_s = ae^{bT_s}W_s^c ), Eq. (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>( n )</td>
<td>( a )</td>
<td>( b )</td>
</tr>
<tr>
<td>Forest 2005</td>
<td>22</td>
<td>0.8666</td>
<td>0.1208</td>
</tr>
<tr>
<td>Forest 2006</td>
<td>24</td>
<td>0.8045</td>
<td>0.1073</td>
</tr>
<tr>
<td>Forest 2007</td>
<td>23</td>
<td>0.7743</td>
<td>0.125</td>
</tr>
<tr>
<td>Forest 2008</td>
<td>16</td>
<td>0.7837</td>
<td>0.1136</td>
</tr>
<tr>
<td>Forest 2009</td>
<td>17</td>
<td>0.4673</td>
<td>0.1084</td>
</tr>
<tr>
<td>Forest 2005–2009</td>
<td>102</td>
<td>0.8132</td>
<td>0.1061</td>
</tr>
<tr>
<td>Grassland 2005</td>
<td>22</td>
<td>0.7682</td>
<td>0.1263</td>
</tr>
<tr>
<td>Grassland 2006</td>
<td>24</td>
<td>0.6754</td>
<td>0.1018</td>
</tr>
<tr>
<td>Grassland 2007</td>
<td>23</td>
<td>0.4889</td>
<td>0.1339</td>
</tr>
<tr>
<td>Grassland 2008</td>
<td>16</td>
<td>0.5793</td>
<td>0.1181</td>
</tr>
<tr>
<td>Grassland 2009</td>
<td>17</td>
<td>0.5074</td>
<td>0.0961</td>
</tr>
<tr>
<td>Grassland 2005–2009</td>
<td>102</td>
<td>0.6544</td>
<td>0.108</td>
</tr>
</tbody>
</table>

\(^{a)}\) All equations were significant at the 0.01 level. We did not show the results for Eqs. (2) and (3), because the fitted regression equations were not significant at the 0.05 level except for in 2009.
for the forest, and from 77 to 82% and 84 to 91% for the grassland, respectively (Tab. 4), and they are significantly larger than those from the exponential equations.

When we compared the different regression models with measured data using RMSE (Fig. 5) we found that RMSE values for a single variable model (R₀ against Tₛ or Wₛ, Eqs. 1 to (3)) are larger than those for Eqs. (4) and (5). This indicated that in this area the two-variable models are more accurate than the single-variable ones for estimating soil respiration. More detailed comparison over the different measurement periods within a year showed that the exponential model overestimated Rₛ during the soil drought period and underestimate after a rain event in summer month (data not shown).

4 Discussion

4.1 Effect of soil temperature and soil moisture on annual and inter-annual variations in soil respiration

Across 5 years of efflux measurement was significantly higher for grasslands (4.04 μmol m⁻² s⁻¹) compared to forests (3.78 μmol m⁻² s⁻¹; Tab. 1). From a review of published papers, Raich and Tufekcioglu [5] also concluded that under similar growing conditions grassland had ~20% higher Rₛ rates than did comparable forest stands. They attributed the difference partly to physiological and structural differences between forest and grassland. The soil type and climate conditions associated with the two vegetation types in this study were the same, so the difference in canopy may be the reason for the differences observed herein because photosynthetic supply of carbon belowground or root biomass could also be key determinants of Rₛ variations. For example, the higher root biomass (75.69 kg ha⁻¹ in grassland and 31.72 kg ha⁻¹ in forest) and soil organic carbon (3.14 and 2.61%), Tₛ and Wₛ in the grassland than those in the forest were reasons behind the relatively high Rₛ. The exact reasons for high Rₛ in the grasslands still need to explore.

Annual variations in Rₛ were controlled by changes in both Tₛ and Wₛ, but their roles differed over the year [21–26]. In the summer, Wₛ was more important than Tₛ because of narrow fluctuations of the later, but in the other seasons, Tₛ was the dominant factor. It is the interactions of Tₛ and Wₛ over the course of a year that drives the majority of annual variations in Rₛ [21, 27, 28]. As expected, Tₛ represents primary controls over Rₛ seasonally, and Wₛ inter-annually [29]. A 6-year study in southern France showed that the year-to-year differences in Rₛ resulted from the difference in Wₛ during summer months [30]. A similar drought-induced decrease in Rₛ was also reported [31, 32]. More recently, Gaumont-Guay et al. [23] demonstrated that Wₛ under drought conditions played a more important role in explaining inter-annual variation of Rₛ and ecosystem respiration compared to Tₛ. Mo et al. [14] also reported that in summer Rₛ was influenced more by Wₛ compared to Tₛ. Rey et al. [22] found that reduce of the annual Rₛ as a result of Wₛ limitation reached 37.4%. We also found a decrease of about 50% in Rₛ during April–June in 2009 compared to the average value of the other 4 years during the same period. Contrast to drought effect, rain events after a drought caused a sudden increase in Rₛ. For example, the Wₛ values in the early growing season in 2009 were significantly lower than that in the other 4 years, resulting in the lowest Rₛ among the 5 years (Fig. 2). After a rain event (95 mm on July 8 and 36 mm on July 17, Fig. 1c) the rate increased to 8.49 and 10.80 μmol CO₂ m⁻² s⁻¹ in the forest and 8.94 and 11.95 μmol CO₂ m⁻² s⁻¹ in the grassland on July 9 and 19 (Fig. 1d), respectively. Similar phenomena were also observed in June of 2005 and 2006, and in August of 2008. Both an increase of Rₛ after a rain event in the summer and a decrease during a drought period were main reason resulting in inter-annual changes of Rₛ [30].

A sharp boosting of Rₛ after the rain events have been reported in other places [22, 25, 28, 33], and it might result from displacement of CO₂-rich air from within the soil, rapid decomposition of microbial biomass and an increase of surface area of organic substrates. Photosynthesis restriction under drought soil and sharp increase in photosynthesis after the rain enlarge the difference of Rₛ between two periods. Additionally, the increase of decomposition from labile materials (litter) and both rhizosphere respiration and carbon assimilation of canopy after a rain event also contributed to Rₛ increase [34]. The effect mechanism of drying and wetting of soils on soil respiration have been reported on some papers [25, 26, 34]. Wₛ limits Rₛ in two ways, either by limiting the diffusivity when it is high or by stressing soil microbial communities and root respiration when it is low [22]. The effects of Wₛ on Rₛ have been mostly divided into three periods: drought (below WP), optimum soil water (WP through FC), and above FC and toward saturation. Our site has a semiarid monsoon continental climate and rain is distributed mostly in summer and drought often occurs in late spring and early summer. During the 5-year study, Wₛ in the two vegetation types seemed to rarely reach a high limiting value (FC) because of their rapidly draining soil with low water holding capacity. However, drought strongly limited Rₛ on some measurement dates in the summer months when Wₛ dropped to below WP (Fig. 2).

Although limitation of low Wₛ on Rₛ has been reported in other places for other vegetation, the threshold value of Wₛ limiting Rₛ did not reach an agreement in different of papers. In some papers a value of about 20% volumetric water content over 0–10 cm depth was used for the low threshold for Rₛ [22, 35]. Gaumont-Guay et al. [23] also used the soil FC (~0.25–0.30 m³ m⁻³) and the WP (0.12 m³ m⁻³) as a threshold value for Wₛ to describe the relationship between Rₛ and Tₛ. More recently, Jassal et al. [26] also found that soil water stress was strongly limiting for both Rₛ and its temperature sensitivity when Wₛ was below WP (0.11 m³ m⁻³, corresponding to 45.8% of FC) and above FC (0.24 m³ m⁻³), and that between these content levels, Wₛ was controlled by Tₛ. To date,
there are still no agreements about low threshold value limiting $R_s$. For example, different $W_s$ (12%, [21]; 20%, [22]; 11%, [26]; 15%, [28]) and different water matric potentials (−2 MPa [26]; −80 kPa [31]; −1.5 MPa [36]) or fractions of FC (1/3 of FC [18]) were used as a low threshold value limiting $R_s$ in different studies. The difference of the used threshold values in different papers mostly resulted from the difference in soil texture in the sites. The agreement of all these papers was that soil water deficit could substantially reduce $R_s$ and its sensitivity to $T_s$.

4.2 Effect of soil temperature and soil water content on $Q_{10}$

As an important parameter, $Q_{10}$ has been widely used in regional and global soil and ecosystem models [35]. Compared with the studies carried out in other regions for other vegetation types, the average $Q_{10}$ value of 2.9 (Tab. 4) from our site are slightly larger than the median value of 2.4 for $R_s$ [4], but in the ranges of the recent reported values in China [12, 37, 38] and in Japan [14]. No significant difference in $Q_{10}$ between the two vegetation types indicated that response of both types was the same for both $T_s$ and $W_s$. We could not determine the reason why different vegetation types would respond to $T_s$ and $W_s$ in the same way because $Q_{10}$ values could be affected by many different factors including soil carbon and stand characteristics [8], substrate quality, and microbial population [39]. We postulated that the differences in $Q_{10}$ between the two vegetation types due to $T_s$ and $W_s$ variation may have been offset by differences in biotic factors, such as canopy construction, fine root density, and organic matter.

Drought stress reduces not only $R_s$ but also $Q_{10}$. During our 5 years of study, and periodical drought mostly occurred between May and June, resulting in a decrease in both $R_s$ and $Q_{10}$. In an agreement with other studies [2, 28, 39], also found that $Q_{10}$ increased with increasing soil water up to a maximum at about 80–90% of FC (Fig. 3). Jassal et al. [26] also found that the highest $Q_{10}$ occurred at 83% of FC. In our study site, the fact that $Q_{10}$ increased with exclusion of the lower $W_s$ data and $Q_{10}$ decreased when $W_s$<WP further indicated the dependency of $Q_{10}$ on $W_s$ [40–42].

The $Q_{10}$ value increases with the measured soil depth, owing to the fact that the greatest temperature fluctuations occur at the soil surface. The large range of $Q_{10}$ values reported in the literature may have partially resulted from differences in the measured $T_s$ depth. Khomik et al. [43] reported that for $T_s$ depths of 2, 5, 10, 15, 20, and 50 cm, the corresponding $Q_{10}$ values were 4.2, 5.6, 8.5, 9.8, 11.1, and 12.2, respectively, and the highest $R_s$ of $R_s$ to $T_s$ was at 10 cm depth. Similar reports could be found in other areas [14, 31]. The variations in $Q_{10}$ resulting from different measurement depths make it difficult to compare $Q_{10}$ between different ecosystems. Although $Q_{10}$ derived at seasonal time scales would incorporate the instantaneous control of temperature on the processes controlled by temperature as well as on the long-term phenology control of root growth dynamics and microbial population changes [41], and other variables, like $W_s$ and substrate supply, would also have the potential to influence seasonal changes in $R_s$ and consequently $Q_{10}$ [23, 44], we suggested that the annual $Q_{10}$ from a yearly scale measurement should be used in models for $R_s$ estimate.

4.3 On the models of soil respiration

The measured $R_s$ rates and the modeled values over a given year in the forest and grassland matched well for model 1, 4, and 5 (Fig. 5) than did for model 2 and 3 according to RMSE values, indicating the former three models are better to describe relationships between $R_s$ and $T_s$ and $W_s$ than the latter ones. Single model of $R_s$ to $W_s$ is comparatively poor except for in drought year. From periodic analysis of the measured and modeled data, we also noted some important trends in the behavior of the three models (Eqs. (1), (4), and (5)) under different $W_s$ conditions. The differences were highlighted when we compared the measured and the modeled values between 2007 and 2009. The exponential model overestimated $R_s$ in soil drought conditions and underestimated it in high water conditions in summer of 2009. However, the estimated and measured values were in good agreement in 2007. This confirmed that the exponential equation is a good predictor of $R_s$ only under no water stress conditions [14, 45–49].

$R_s$ has often been modeled using $T_s$ and occasionally $W_s$ as the driving factors for particular sites and vegetation [21, 30, 35, 46, 48], depending on biotic and abiotic factors as well as the climatic conditions of the studied site. Compared with the single variable models of $R_s$ to $T_s$ or to $W_s$, the combined models including both $T_s$ and $W_s$ variables can increase accuracy of prediction of $R_s$ [30, 50]. Combining the exponential soil temperature and quadratic soil water equation as a product in a multiple, the $R^2$ of the fit equation increased from 0.46 (exponential soil temperature equation) and 0.26 (quadratic soil water equation) to 0.52. In a mature spruce forest in southern Germany, researchers [51] also found that $T_s$ alone explained 72% of the variation in the efflux rate, but that including $W_s$ as an additional variable increased the explained variance to about 83%. The coefficients of determination of linear regression between the measured and predicted values using Eqs. (1), (4), and (5) were 0.78, 0.87, and 0.91 for the forest and 0.77, 0.77, and 0.86 for the grassland in 2007, respectively, and 0.52, 0.72, and 0.89 (forest), and 0.56, 0.81, and 0.88 (grassland) in 2009. This indicates that an exponential-power model is the best one to express the relationship between $R_s$ and $T_s$ and $W_s$ compared to other options, and that in our site the two variable models have advantages over the single ones for estimating soil respiration [51–53].

The importance of $T_s$ and $W_s$ in determining soil CO₂ emissions were highlighted based on analysis of 5 years of observational data. The annual and inter-annual variations in $R_s$ in two different vegetation types showed a similar trend because $R_s$ in both types was controlled by the same climate conditions. The $T_s$ was a prevailing factor controlling $R_s$, explaining 75–80% of temporal variations in $R_s$. However, the influence of $W_s$ caused by annual precipitation and its distribution in particular should be considered, especially in summer months because it could lead to great reductions in $R_s$ and $Q_{10}$. The optimal soil water corresponding to maximum $Q_{10}$ was about 80–90% of FC.

The single variable model of $R_s$ and $T_s$ ($R_s = aW_s + b$; $R_s = a(T_s)$) could be widely used to predict $R_s$ during no water stress and the latter in drought years. The two-variable models ($R_s = a(T_s, W_s) + b$; $R_s = aW_s + b$) combining $T_s$ and $W_s$ improved the predicting capacity for $R_s$ for both ecosystems using single year data 5-year data, respectively. The relationship proposed for $R_s$ with $T_s$ and $W_s$ is useful for understanding and predicting potential changes in the eastern part of Loess Plateau of China in response to climate change [54–56].
Acknowledgments

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The authors have declared no conflict of interest.

References


