



Diurnal and seasonal variations of soil respiration rate under different row-spacing in a *Panicum virgatum* L. field on semi-arid Loess Plateau of China

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Abstract: Soil respiration (SR) in crop field is affected by environmental factors, agronomic practices and crop types. To clarify how planting density affects the SR dynamics in switchgrass (*Panicum virgatum* L.) field on the semi-arid Loess Plateau, this research investigated diurnal and seasonal changes of soil respiration rate (R_s) under three different row-spacing treatments (20, 40 and 60 cm) in the fourth growing year of switchgrass. Results showed that R_s presented a pronounced seasonality under all row-spacing treatments. The highest daily average R_s values appeared in August, while the lowest ($P < 0.05$) were in September for each row-spacing. Diurnal variations of R_s exhibited single-peak curves in each month. Daily average R_s increased significantly as row-spacing enlarged during May and August but there was no significant difference among row-spacing treatments in September. Soil water storage in the depth of 0–100 cm had no significant difference ($P > 0.05$) among the row-spacing treatments, and similar results were found for soil temperature in 0–15 cm soil depth. Soil respiration temperature sensitivity (Q_{10}) values were 1.0–3.7 during the growing months, which were strongly correlated with air temperature in May and June and the soil temperature at 15 cm depth in August. Higher aboveground biomass production and lower R_s in most growth months indicated that 20 cm row-spacing treatment was beneficial for increasing the carbon fixation in switchgrass field. Results also implied that it is necessary to take into account the influence of phenology and root growth of switchgrass on soil respiration for accurately evaluating the carbon cycle in the region.

Keywords: switchgrass; row-spacing; soil temperature; soil water; Q_{10} value

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Soil respiration (SR) is the second largest C flux between the terrestrial system and the atmosphere, with a magnitude of 10 times greater than anthropogenic carbon dioxide production (Curiel-Yuste et al., 2004; Dornbush and Raich, 2006). Because it originates from autotrophic root respiration and heterotrophic microbial respiration in the rhizosphere and bulk soil, including the respiration from roots, the symbiont and microbial, SR is a comprehensive measurement of soil activity (Dornbush and Raich, 2006). Researches showed that SR can be affected by soil water (Jia et al.,

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2004), soil temperature (Curiel-Yuste et al., 2004), soil aeration (Han et al., 2007) and root activity (Dornbush and Raich, 2006). Agronomy practices and cropping system, such as row-spacing, tillage method and fertilization, may affect soil physical and biological environments (i.e. soil water content, soil temperature and soil properties) and plant growth, which in turn impacts SR (Sun et al., 2009; Lü et al., 2011; Zhang et al., 2014). Soil respiration has been widely investigated in different vegetation and land uses, such as temperate desert (Huang et al., 2015), coastal wetland (Han et al., 2014), natural grassland (Peri et al., 2015) and crop land (Jiang et al., 2015). Agricultural farmland fields are important sources of atmospheric CO₂ concentration and global C cycle (Zhang et al., 2014; Jiang et al., 2015), but limited information is available on SR characteristics in agro-ecosystems, especially in artificial grassland under different planting densities (i.e. row-spacing).

Switchgrass (*Panicum virgatum* L.) is a highly productive, perennial C₄ warm-season bunchgrass, native to North America prairie (Lee et al., 2007). The high aboveground and underground biomass production make switchgrass a valuable bioenergy crop with the potential to increase soil C sequestration (Wright and Turhollow, 2010). In early 1990s, switchgrass was introduced and planted in semi-arid loess hilly-gully regions on the Loess Plateau and exhibited great eco-adaptability to different habitats in the area (Xu et al., 2005, 2008). However, plant or vegetation productivity should be moderately developed due to the limited water availability in the region, (Shan and Chen, 1993). It is also important to identify appropriate plants/crops with moderate biomass production and water consumption level in appropriate density (Shan and Chen, 1993; Xu et al., 2008). In recent decades, intensive researches about switchgrass focused on variety selection, method establishment, water and nitrogen use, biomass production and management, and environmental impacts (McLaughlin and Kszos, 2005; Monti et al., 2007; Xu et al., 2008). Few studies measured soil respiration in switchgrass field, especially in water-limited regions (Wagle and Kakani, 2014). Thus, the objectives of this study were to: (1) clarify the seasonal variation characteristics of soil respiration, and its relationships with environmental factors; and (2) address the influence of soil temperature and moisture on soil respiration variations under different row-spacing treatments.

1 Materials and methods

1.1 Site description

A field experiment was conducted at Ansai Research Station (ARS) of Chinese Academy of Sciences (CAS) in Shaanxi province (36°51'30"N, 109°19'23"E; 1,068 m asl). The annual mean temperature is 8.8°C in the region. The mean lowest temperature of the coldest month (January) is -6.9°C, while the mean highest temperature of the hottest month (July) is 22.6°C. The annual active accumulated temperature ($\geq 10^\circ\text{C}$) is about 3,120°C and the frost-free period is 159 days. The mean annual precipitation is about 500 mm, of which about 70% falls in July to September. The soil is wind-deposited loessial parent materials with a homogeneous silty clay loam texture classified as Calcic Cambosols. In the switchgrass field at different habitats, soil water content is about 6% in 0.6–2.0 m soil depth after the switchgrass growing about three years (Jiang et al., 2007).

1.2 Experimental design

Switchgrass seeds were sown on 15 July 2009 at 5 g/m along a row, which was equivalent to 255, 170 and 85 kg/hm² under 20, 40 and 60 cm row-spacing, respectively. The experiment used a randomized block design with three replications. The plot size was 12 m² (3 m×4 m) each. There was no irrigation or fertilization supplement since the experiment was established, and also during the experimental period.

1.3 Soil water content measurement

One aluminum tube (4.0 cm in diameter, 4.0 m in length) was installed at the center of each plot to measure soil volumetric water content (θ_v). In this study, soil water content was only measured down to 100 cm soil depth at 10-cm intervals and was measured monthly from April to October in

2012 using intelligent water neutron meter (CNC-503DR, Beijing Hean Nucleus Co. Ltd., China). Soil water storage (SWS) in the 0–100 cm soil depth was calculated as:

$$\text{SWS} = \sum_{i=1}^{20} \theta_v \times h_i \times 10. \quad (1)$$

Where θ_v is soil volumetric water content (cm^3/cm^3) at a specific soil depth; h_i is soil depth increment (i.e. 10 cm); and the subscript i stands for numbers of the soil depth intervals measured.

1.4 Soil respiration rate and soil temperature measurement

Soil respiration rate (R_s) was obtained with an enclosed-chamber system for soil CO_2 efflux measurement (PP-Systems, Amesbury, MA, USA). Living plants of switchgrass were removed with scissors one day before the measurement to avoid the effects of foliar respiration (Jia et al., 2014). One PVC-collar (20 cm in diameter, 16 cm in height) was installed in each plot thereafter. The R_s measurements were taken with a PP Systems (EGM-4) infrared gas analyzer (IRGA) that recorded CO_2 concentration at 4-s intervals for 30 s. Soil temperature (T_s) was measured at 5, 10 and 15 cm depths with digital thermometers. The measurements were carried out at 2-h intervals from 08:00 to 18:00 on the third sunny day in each month, and the experimental dates were 16 May, 12 June, 20 August and 13 September. Soil respiration and soil temperature were not measured in July due to the consecutive rainy days.

1.5 Aboveground biomass and climatic factors

The aboveground biomass was measured every year in October during 2009–2012. The switchgrass plant was cut by hand-held shears to ground level. The climatic factors, such as daily precipitation, air temperature and relative humidity in the year, were sourced from the meteorological station located close to the field (ca. 200 m).

1.6 Statistical analysis

One-way ANOVA with the least significant differences (LSD) test was employed to compare the parameters (i.e. R_s , soil temperature and soil water content) across growing period or row-spacing treatments. Differences were considered significant at $P \leq 0.05$ level. To compare the relationship between soil CO_2 flux and soil temperature, we used a first-order exponential function ($\text{CO}_2 \text{ flux} = a \times e^{bT}$) to simulate the relationship between soil respiration rate and temperature, where coefficient a is the intercept of soil respiration, coefficient b represents the temperature sensitivity of soil CO_2 flux, and T is the air or soil temperature (Lloyd and Taylor, 1994). Soil CO_2 flux quotient (Q_{10}) was calculated using the formula $Q_{10} = e^{10b}$ (Luo et al., 2001). All statistical tests were performed using SPSS 17.0 (SPSS, Chicago, USA).

2 Results

2.1 Characteristics of environmental factors

In 2012, total precipitation during the growing season (April to October) was 443 mm, which was about 11.74% lower than the 1951–2000 average of 502 mm. The precipitation during July to September was 303 mm, close to the 50-year (1951–2000) average of 318 mm. The precipitation in July, August and September was 118, 72 and 114 mm, respectively (Fig. 1).

The diurnal variations of photosynthetically active radiation (PAR) showed a unimodal pattern, which ranged from 1,700 to 2,400 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$, with the maximum values occurred between 10:00–14:00 in May to September (Fig. 2). Air temperature (T_a) was generally paralleled with PAR, increased from a low value at 8:00 (17°C–28°C) to a peak value (25°C–35°C) between 12:00 and 14:00. The daily maximum and minimum mean air temperature were observed in June (32.1°C) and September (22.05°C), respectively (Fig. 2). The highest relative humidity (RH) appeared at 8:00 in the morning and then decreased gradually during a day. The lowest daily mean RH was recorded on 12 June (Fig. 2).

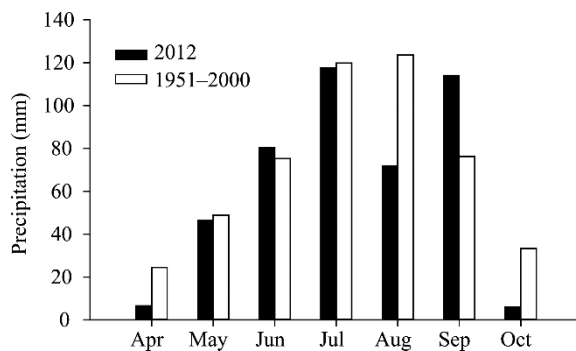


Fig. 1 Monthly precipitation distribution during the growing seasons in 2012 and 1951–2000

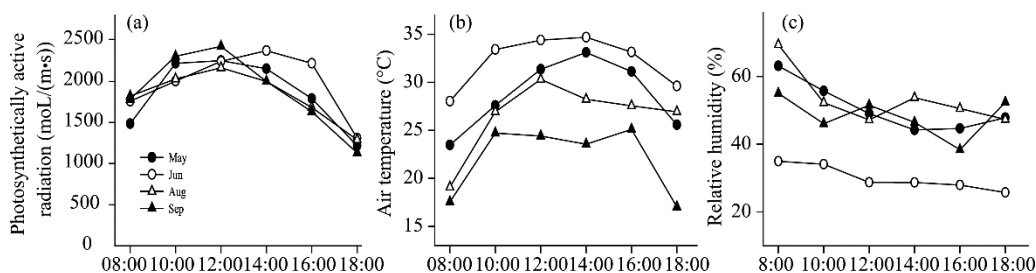


Fig. 2 Diurnal changes of photosynthetically active radiation (PAR), air temperature (Ta), and air relative humidity (RH) in the experimental months of 2012

2.2 Aboveground biomass production

From 2009 to 2012, the aboveground biomass production under each row-spacing increased significantly ($P < 0.05$) along with the age of the switchgrass. In 2009 and 2010, biomass production under the 20 cm row-spacing was significantly higher ($P < 0.05$) than those under the other two row-spacing treatments while there was no significant difference between these two treatments. In 2011 and 2012, biomass production decreased significantly as row-spacing increased. The biomass production was significantly higher under 20 cm row-spacing, while was significantly lower under 60 cm row-spacing (Fig. 3).

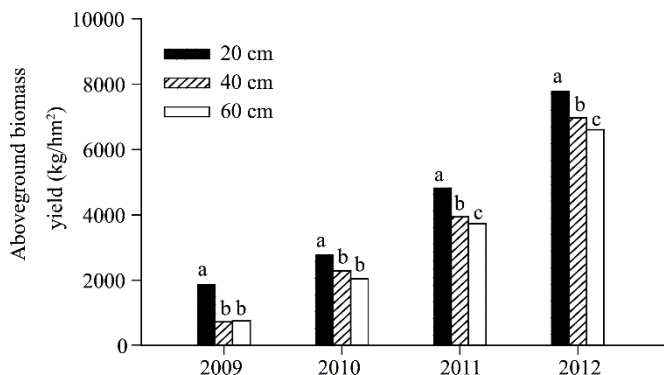


Fig. 3 Aboveground biomass production of switchgrass under each row-spacing treatment in 2009–2012. The letters on top of the bars indicated that there were significant differences among row-spacing treatments in each growth year at $P < 0.05$ level.

2.3 Soil water storage

Soil water storage (SWS) at the 0–100 cm soil depth under different row-spacing treatments changed with time, which decreased gradually from April to June and then increased afterwards till September followed by a final decrease in October (Fig. 4). In April, SWS at the 0–100 cm soil

depth were 120.5, 129.8 and 129.3 mm under 20, 40 and 60 cm row-spacing, respectively. In June, it decreased sharply and reached the lowest values at 75.5, 78.2 and 84.1 mm under 20, 40 and 60 cm row-spacing, respectively. In October, SWS values were 115.0, 124.5 and 124.8 mm for 20, 40 and 60 cm row-spacing treatments which were about 4.6%, 4.1%, and 3.5% lower than those in April. There were no significant difference among the three row-spacing treatments in SWS during the switchgrass growing months in 2012.

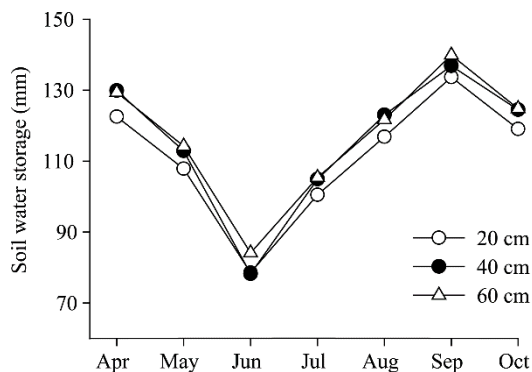


Fig. 4 Monthly mean soil water storage at 0–100 cm soil depth in the switchgrass field under different row-spacing treatments in 2012

2.4 Soil temperature

In each experimental day, soil temperature (T_s) increased gradually from 8:00 in the morning and reached the highest point at 14:00 in May and June, or at 16:00 in August and September, and then declined gradually till 18:00 in the afternoon (Fig. 5). Except at 10 cm soil depth in May and June during 14:00–16:00, there were no significant differences in T_s values among row-spacing treatments or soil depth in each month. The daytime lowest T_s appeared at 8:00 in the daytime for each soil depth except for August, where T_s values were similar at 8:00 and 18:00 in each soil depth. The daily variation of T_s values (i.e. the maximum minus the minimum values in the daytime) decreased as soil depth increased (Fig. 5).

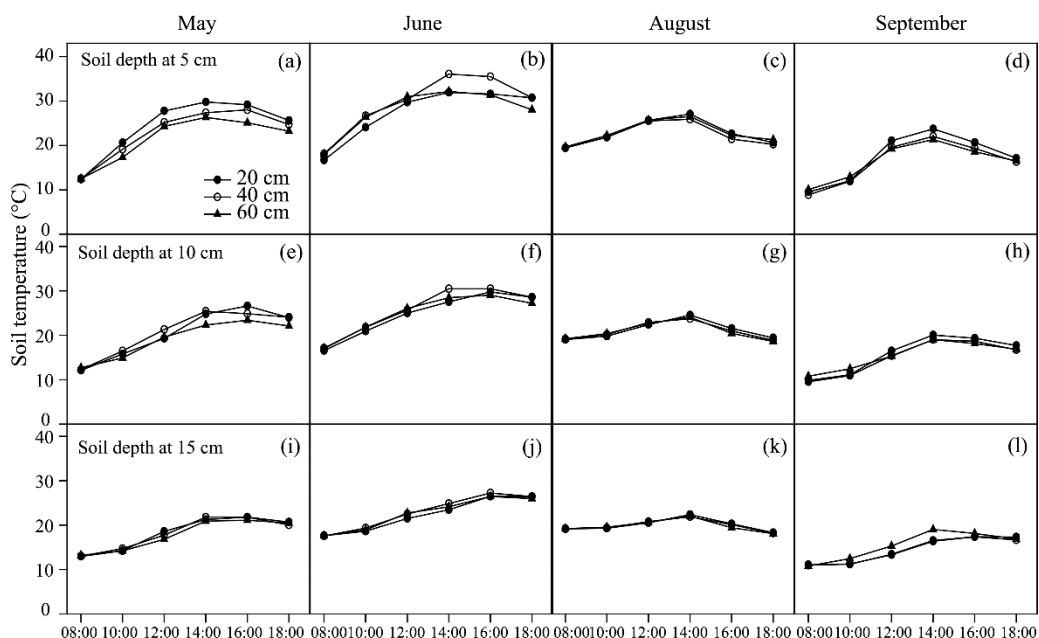


Fig. 5 Diurnal changes of soil temperature in the switchgrass field during the experimental months under row-spacing of 20, 40 and 60 cm in 2012

2.5 Soil respiration

Diurnal variations of R_s exhibited single-peak curves under all treatments over the experimental period (Fig. 6). Daily averaged R_s increased significantly with the increase of row-spacing in May (0.80, 1.13 and 1.37 g CO₂/(m²·h)), June (0.85, 1.10 and 1.27 g CO₂/(m²·h)) and August (1.82, 1.91 and 2.14 g CO₂/(m²·h)) for 20, 40 and 60 cm row-spacing, respectively; while in September, there were no significant difference among row-spacing treatments, and the values were 1.05, 1.10 and 1.06 g CO₂/(m²·h) for 20, 40 and 60 cm, respectively. In August, R_s was about 1.8–2.3 g CO₂/(m²·h) in the morning at 8:00, while in the other three months, it began at about 0.3–1.0 g CO₂/(m²·h). In May and June, the R_s values under all three row-spacing showed similar daily trends, with maximum value appeared at 14:00 in May or at 16:00 in June, respectively. In August, daily maximum values for 40 and 60 cm row-spacing appeared at 14:00, while it was at 16:00 for 20 cm row-spacing. The highest daily averaged R_s appeared in August, and daily maximum R_s values appeared at 12:00 on 13 September for each row-spacing (Fig. 6).

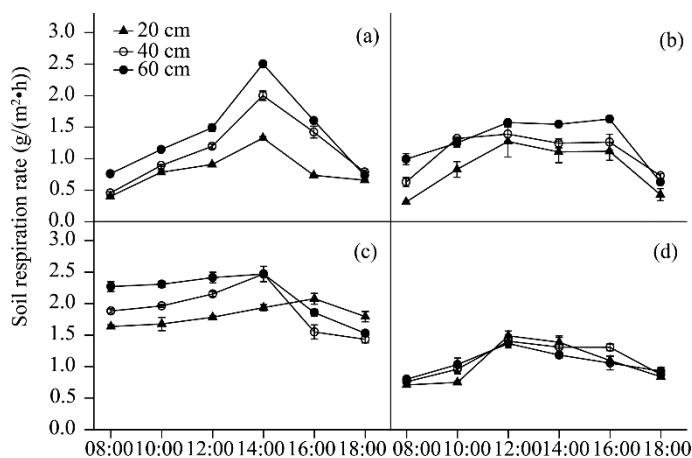


Fig. 6 Diurnal changes of soil respiration rate in switchgrass field under the row-spacing of 20, 40 and 60 cm on 19 May (a), 12 June (b), 20 August (c) and 13 September (d) in the experimental months of 2012

2.6 Soil respiration temperature sensitivity

Soil respiration temperature sensitivity (Q_{10}) values were 1.0–3.7 in switchgrass field during the growing months (Fig. 7). Q_{10} values calculated from air temperature were significantly higher

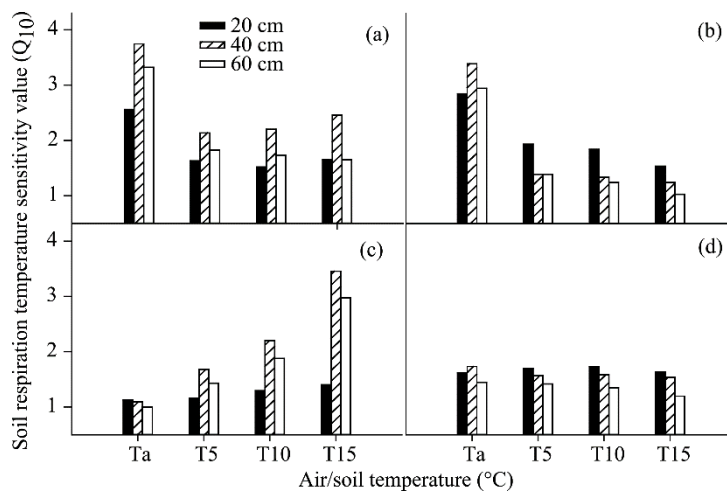


Fig. 7 Q_{10} values in switchgrass field under the row-spacing of 20, 40 and 60 cm. Ta represents the air temperature. T5, T10 and T15 represent the soil temperatures at 5, 10 and 15 cm soil depths, respectively on 19 May (a), 12 June (b), 20 August (c) and 13 September (d) in the experimental months of 2012

($P < 0.05$) than those calculated from soil temperature in May and June, while there were no obvious trends in August and September. Q_{10} values were much higher in May and June, than in August or September for each row-spacing treatment. In August, higher Q_{10} values were found to be more correlated with soil temperature at 15 cm soil depth, and decreased with soil depth. In September, there was no obvious changing trend in Q_{10} values with air temperature or soil temperature at 5, 10 or 15 cm soil depth (Fig. 7). In May and August, soil Q_{10} values calculated with soil temperature were much higher ($P < 0.05$) under 40 cm row-spacing, while in June and September those values were bigger ($P < 0.05$) under 20 cm row-spacing treatments (Fig. 7).

3 Discussion

The diurnal changes of R_s exhibited single peak curves under all row-spacing treatments in each month with the highest value appeared at noon (Fig. 6), which were similar to the results obtained by other researches (Lü et al., 2011; Wang et al., 2015). Soil water content may affect SR because low water content would limit the contact between microorganism and available substrate and therefore microorganisms could be dormant and/or die under low soil water conditions (Conant et al., 2004). In this study, no significant difference was observed in soil water content at 0–10, 10–20 and 20–30 cm soil depths among three row-spacing treatments, suggesting that soil water content was not the main factor inducing the differences of R_s (Figs. 4 and 7).

The temperature sensitivity of R_s (Q_{10}) is a critical parameter for quantitatively assessing carbon balance response of the terrestrial ecosystem to soil or air temperature (Wang et al. 2010). Our results clearly showed that Q_{10} values in switchgrass field varied with growth months and row-spacing treatments, and the values were different when calculated with air temperature or soil temperature in different soil depth (Figs. 5 and 7). Q_{10} value was affected by not only air and soil temperature but also the changes in soil water content, root biomass, litter inputs, microbial populations and other seasonally fluctuating conditions and processes (Curiel Yuste et al., 2004). Switchgrass normally reached the yearly highest aboveground biomass production since the third or fourth year of growth, and had the seasonal highest biomass production in August at different habitats in loess hilly-gully regions (Xu et al., 2005; Jiang et al., 2007). Higher aboveground biomass production with higher coverage could weaken the “block and delay effect” of solar radiation and heat conduction into the soil surface, and thus affects soil temperature and Q_{10} values (Pang et al., 2013; Wang et al., 2015). Most empirical models used to calculate the Q_{10} values based on seasonal patterns of SR and temperature, and have a constant Q_{10} , which may over- or underestimate SR when considered its values at small research areas (Xu and Qi, 2001; Janssens and Pilegaard, 2003). Such as in this study, great variations in Q_{10} values calculated from air temperature or soil temperature in different soil depths implied that to choose appropriate temperature index was important in explaining or predicting SR and that Q_{10} values derived from monthly patterns of R_s should be used with caution when using its to evaluate annual variations or predicting future changes of SR (Qi et al., 2010). Although it was found that an exponential model can be used to show R_s response to air temperature or soil temperature in surface depth (Fig. 7), there were no significant differences among row-spacing in soil temperature at 0–15 cm soil depth, thus it could be concluded that the diurnal variation of soil respiration was mainly dominated by air temperature or other factors (Dornbush and Raich, 2006). Diurnal variations of air temperature were closely related with solar radiation, which was generally paralleled with PAR during the growing season (Fig. 2).

The differences in SR may be due to plant eco-physiological process and root activity differences among row-spacing treatments (Zhang et al., 2013; Gao et al., 2015). Several studies suggested that R_s is directly dependent on plant photosynthesis or growth (Yuste et al., 2004; Dornbush and Raich, 2006; Kuzyakov and Gavrichkova, 2010). As an agronomical practice in agricultural cropping systems, row-spacing affects plant canopy structure, light interception, radiation use efficiency, biomass production, and thus consequently the soil environment (Ma et al., 2001; Mattera et al., 2013). Our former research results showed that leaf net photosynthetic rate increased with the increase of row-spacing, which may partially explain the higher R_s for 60 cm row-spacing (Fig. 6)

(Gao et al., 2015). Switchgrass had flexible strategy in root growth and distribution with its annual root biomass production accumulated most before September (Xu et al., 2010). Results showed that switchgrass started turning green in April with the highest growth rate in May, the maximum aboveground biomass production in August, and started to senesce in September (Xu et al., 2005). Thus, the monthly differences among row-spacing treatments in soil respiration may be due to root growth of switchgrass, which was the most active in May and its activity significantly decreased in September.

4 Conclusions

Better understanding of the effects of different row-spacing on soil respiration is important for accurately evaluating carbon cycle of plants/crops in semi-arid regions. Our results showed that both soil respiration rate and Q_{10} values varied with row-spacing and growth month in switchgrass field. Data indicated that aboveground biomass production was significantly higher, and R_s was lower in most months of growing season under 20 cm row-spacing treatment, which implied that 20 cm row-spacing treatment was more beneficial for increasing carbon fixation in switchgrass field. Because switchgrass is a perennial species, row-spacing treatments affect its growth and eco-physiological process. Thus, further research is required to investigate the phenology and root growth differences of switchgrass among the months over the growing season and row-spacing treatments, and their relations with soil respiration rate and Q_{10} values. The findings presented here will be useful to integrate the biogeochemical process into rational planting of this bioenergy crop in large scale on the Loess Plateau regions.

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