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RESEARCH ARTICLE

# Photosynthetic performance of switchgrass and its relation to field productivity: A three-year experimental appraisal in semiarid Loess Plateau

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**Abstract**

To reveal photosynthetic characteristics and biomass yield is important for evaluating introduced species adaptation to local environments. A field experiment was conducted over three consecutive years (2011–2013) to evaluate photosynthetic characteristics, soil water content, aboveground biomass accumulation, and water use efficiency (WUE) in switchgrass (*Panicum virgatum* L.) populations exposed to three row spacing (20, 40 and 60 cm) treatments in two growth months (June and August) on the semiarid Loess Plateau of China. Results indicated that net photosynthetic rate ($P_n$), transpiration rate ($T_r$), instantaneous water use efficiency ($WUE_i$) and plant height of switchgrass showed an increased trend, but aboveground biomass production and WUE showed an decreased trend with enlarged row spacings over the three years. The maximum daily mean $P_n$ values (17.9, 18.4 and 19.7 μmol $CO_2$ $m^{-2}$ $s^{-1}$) were observed in 2011, and the highest aboveground biomass production (67 771.8, 6 976.8 and 6 609.2 kg $ha^{-1}$) were recorded in 2012 for 20, 40 and 60 cm, respectively. A close correlation between tiller numbers and aboveground biomass production ($r$=0.907) was observed. $P_n$ was positively and significantly correlated with biomass per tiller, but it showed a negative correlation with aboveground biomass production. Our results confirm that wide row spacing is beneficial for single plant development, while narrow row spacing favors biomass production and water use of switchgrass in the region. It also implies that single leaf growth and performance could explain the switchgrass community density differences, while fails to account for the aboveground biomass production.

**Keywords:** switchgrass, photosynthesis, row spacing, biomass production, water use efficiency

## 1. Introduction

The semiarid loess hilly-gully region on the Loess Plateau of China is well-known for the serious soil erosion and ecologically fragile environment (Wang *et al.* 2011). In order to restore the vegetation and control soil erosion, great efforts have been made to plant trees and grasses on slope land since the end of the 1950s (Chen *et al.* 2008; Jia and

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Shao 2013). However, artificial grassland with short persistence always exists during the process because of the harsh environment and limited species with high adaptation for choice (Shan and Chen 1993; Li *et al.* 1999; Xu *et al.* 2006b). To introduce eminent species from abroad or other places is a good way to enrich plant species and varieties for vegetation construction and developing artificial grassland (Xu *et al.* 2006b). Switchgrass (*Panicum virgatum* L.) is a warm-season perennial $C_4$ grass native to North America, and it can be used as forage crop and soil and water conservation, and has been taken as biomass energy source recently (Sanderson *et al.* 1996; Xu *et al.* 2006b; Wright and Turhollow 2010). It showed great eco-adaptability to the semiarid loess hilly-gully region on the Loess Plateau of China since it had been introduced in 1990 (Xu *et al.* 2008; Gao *et al.* 2015).

Photosynthesis is an important process to form organic yield, and it is closely associated with plant growth and environment conditions, while relationship between photosynthetic rate and plant yield is complex (Buttery *et al.* 1981; Wei *et al.* 2009; Song *et al.* 2012). Researches showed that normally positive correlation was between carbon assimilation and crop yield, while it was affected by growth stages and weather conditions (Guo *et al.* 2002; Li *et al.* 2010). To study plant photosynthetic characteristics are particularly important for selecting and evaluating species for revegetation and site adaptability (Shan and Chen 1993). Row spacing is considered to be an important agronomical practice to control plant density, which significantly affects canopy micro-environment such as light interception, ventilation, air temperature and relative humidity, and consequently plant photosynthesis and yield in plant production (Sharratt and McWilliams 2005; Yang *et al.* 2014; Gao *et al.* 2015). Plants growing in wider rows may not efficiently utilize available resources, while in too narrow rows may intensify the intraspecific competition (Yang *et al.* 2014). Previous studies reported that narrow row spacing causes higher leaf photosynthesis and suppresses weed infestation than wider row spacing, because narrow row spacing leads more leaf coverage per unit area thus produces high leaf area index (LAI), resulting in more light interception and higher biomass production (Liu *et al.* 2011; Wang *et al.* 2015).

To date, researches about leaf photosynthetic characteristics of switchgrass in relation to possible limiting factors, such as cultivars, leaf morphology and leaf environmental conditions have been taken (Xu *et al.* 2005; Ma *et al.* 2011; Guo *et al.* 2013; Gao *et al.* 2015). In those experiments, gas exchange measurements were performed on switchgrass only in one growing stage or in one year. The intra- and inter-annual variations photosynthetic rates and its relation to biomass production and climate variability have not been fully addressed. Therefore, our main objectives in this paper were to: (1) Assess the seasonal and inter-annual variability of leaf photosynthesis over three consecutive years (2011–2013) that were characterized by marked differences in rainfall amount under field conditions. (2) Examine the relationship between photosynthetic characteristics and biomass production of switchgrass. Our final objectives were to investigate the influences of row spacing on photosynthetic characteristics and yield components of switchgrass and to provide a theoretical evidence for rational use and cultivation in the region.

## 2. Materials and methods

### 2.1. Field experimental design

The study was conducted from 2011 to 2013 at the research farm of Ansai Research Station (ARS) of Chinese Academy of Sciences (CAS), Shaanxi Province, locating in the semiarid region of northwestern China (36°51´30´´N, 109°19´23´´E; altitude 1 068 m a.s.l.). The annual mean rainfall is 510 mm, and about 60% of which falls during July and September (normally called rainy season). The annual average temperature is 8.8°C with the maximum monthly mean temperature of 22.6°C in July and the minimum monthly temperature of −6.9°C in January. The annual accumulated temperature above 10°C is about 3 119°C and the frost-free period is 159 days. The soil type is characterized as silly loam. Rainfall was monitored by a weather station situated about 100 m from the experimental fields.

The experiment was carried out using a completely randomized sampling plot design with three replications. Each plot size was 3 m×4 m. The cultivar of switchgrass used was Alamo, which was obtained from the experimental fields of ARS in the autumn of 1999. The seeds were sown at 5 g seed $m^{-1}$ row in 2009 at row spacings of 20, 40, 60 cm, with plant density of 255, 170 and 85 kg $ha^{-1}$, respectively (Gao *et al.* 2015).

### 2.2. Soil water content measurement

In the middle position of each plot, one aluminum tube, 4.0 m in length was installed in 2010. Soil volumetric water content was taken every 0.1 to 2.0 m depth once a month from 2011 to 2013 by intelligent water neutron meter (CNC-503DR, Beijing Hean Nucleus Co., Ltd., China) (Gao *et al.* 2015). Soil water storage (SWS) can be calculated as:

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

Where, $\theta_v$ is soil volumetric water content at a specific soil depth ($cm^3$ $cm^{-3}$), and $h_i$ is soil depth increment (cm).

### 2.3. Plant height and aboveground biomass measurement

Plant height, leaf length, leaf width were measured in September with ruler, from 10 randomly selected plants in each plot. Aboveground biomass production was sampled at the end of growing season (October), and was determined by cutting the plants with hand-held shears to ground level from three 50 cm lengths of rows selected randomly from each plot. Tiller numbers were counted at the same time with biomass production. The aboveground biomass was first dried at 105°C for 30 min to stop any further metabolic processes and then further dried at 80°C for 48 h to determine dry matter.

### 2.4. Gas exchange measurement

Gas exchange measurement was conducted during two growth months (June and August) from 2011 to 2013. Leaf net photosynthesis rate ($P_n$), transpiration rate ($T_r$), stomatal conductance ($G_s$), intercellular $CO_2$ concentrations ($C_i$), air temperature ($T_{air}$), photosynthetically active radiation (PAR), leaf to air vapor pressure deficient (VPD) and air relative humidity (RH) were measured using a portable photosynthesis system (CIRAS-2, PP Systems, USA) at 2 h intervals from 8:00 to 18:00 on sunny days at ambient environment. The measurements were taken on the uppermost fully expanded leaf. Instantaneous water use efficiency ($WUE_i$) was calculated as a ratio of $P_n$ to $T_r$ (Fischer and Turner 1978).

### 2.5. Statistical analysis

Differences of gas exchange, soil water storage and aboveground biomass yield were tested using one-way ANOVA. Means of each treatment among three row spacings, two months and three years were performed by LSD test at 5% level. The relationship between biomass production and photosynthetic parameters were tested using Pearson's correlation. All statistical analyses were performed by using SPSS 16.0 (SPSS, Chicago, USA).

## 3. Results

### 3.1. Environmental factors

PAR, leaf to air VPD and $T_{air}$ showed a significant difference between growth seasons (Table 1). These environmental variables were significantly higher in June than that in August. The highest daily mean $T_{air}$ (32.21°C) and VPD (4.02 kPa) values were recorded in June 2012, while the minimum $T_{air}$ (26.5°C) and VPD (1.50 kPa) values were registered in August 2013 (Table 1). Whereas air relative humidity (RH) showed an opposite trend to that of VPD, with daily mean values higher in August than in June. The daily mean air RH was the lowest in June 2012 with 30% and it was the highest in August 2013 with 70% (Table 1).

### 3.2. Monthly rainfall and soil water storage

The mean rainfall in April to October was 501.7 mm, and it was 75.27 and 123.55 mm in June and August during 1951–2000, respectively (Table 2). In 2011, 2012 and 2013, the rainfall was 588.4, 442.2 and 787.6 mm from April to October, which was 17.28% higher, 11.85% lower and 56.9% higher than the 50-year (1951–2000) mean. In 2011, rainfall in June and August was 0.04 and 16.22% higher, while were 55.6 and 0.05% lower than the 50-year mean in 2012. In 2013, the rainfall in June was 67.5% lower while 187.5%

**Table 1** Daily mean values of photosynthetically active radiation (PAR), air temperature ($T_{air}$), leaf to air vapor pressure deficient (VPD), and air relative humidity (RH) during gas exchange measurements in 2011–2013

| Month/Year | PAR (mmol m$^{-2}$ s$^{-1}$) | $T_{air}$ (°C) | VPD (kPa) | RH (%) |
|---|---|---|---|---|
| June/2011 | 2 151.68±79 | 31.17±2.3 | 3.33±0.3 | 32.27±3.2 |
| August/2011 | 1 808.97±68 | 29.36±3.1 | 1.78±0.2 | 61.52±4.8 |
| June/2012 | 1 982.94±91 | 32.21±3.3 | 4.02±0.3 | 30.03±2.1 |
| August/2012 | 1 830.11±59 | 26.50±1.9 | 1.99±0.1 | 53.38±5.1 |
| June/2013 | 1 829.69±47 | 31.00±2.5 | 3.93±0.4 | 31.48±2.5 |
| August/2013 | 1 798.80±38 | 29.73±1.5 | 1.50±0.2 | 70.02±6.7 |

The values are means±SE ($n$=5).

**Table 2** Rainfall (mm) in June, August and April–October during 2011, 2012, 2013 and 50-year (1951–2000) mean

| Month | 2011 | 2012 | 2013 | 1951–2000 mean |
|---|---|---|---|---|
| June | 75.6 (+0.04%) | 33.4 (–55.6%) | 24.4 (–67.5%) | 75.27 |
| August | 143.6 (+16.22%) | 117.6 (–0.05%) | 355.2 (+187.5%) | 123.55 |
| April–October | 588.4 (+17.28%) | 442.2 (–11.85%) | 787.6 (+56.9%) | 501.70 |

Data in parentheses indicate the percent difference in each year comparing with 50-year (1951–2000) mean.

higher in August, comparing with the 50-year average, respectively. The highest rainfall occurred in August 2013 and reached 355.2 mm, while the lowest rainfall occurred in June 2013 with only 24.4 mm (Table 2).

The soil water storage (SWS) varied greatly from year to year. Generally, SWS was significantly lower in June than in August in the three experimental years (Fig. 1). In June, the lowest soil water storage was observed in 2011 (186.6, 177.7, 170.3 mm for 20, 40 and 60 cm, respectively), while in August, the highest values were observed in 2013 (344.5, 340.0, 329.5 mm for 20, 40 and 60 cm, respectively). Generally, there were no significant differences in SWS between 20 and 40 cm row spacing, while SWS under 20 cm was significantly higher than under 60 cm row spacing except in June 2012 (Fig. 1).

### 3.3. Plant growth and yield components

Row spacing significantly affected plant height, leaf length, leaf width and biomass per tiller ($P<0.05$), and they showed a consistent trend as with increasing row spacing (Table 3). On average, plant height under 60 cm increased by 19.82 and 34.90%, leaf length by 8.14 and 25%, leaf width by 3.40 and 18.18%, and biomass per tiller by 12.50 and 35.0% than 40 and 20 cm across three years (2011–2013), respectively. Tiller numbers followed inverse changing trend with increasing row spacing, which decreased by 34.14% at 40 cm and by 67.60% at 60 cm compared with 20 cm row spacing (Table 3). Tiller numbers per $m^2$ was positively associated with aboveground biomass production ($r$=0.907, $P<0.01$; Table 4). Plant height and leaf length were negatively related to aboveground biomass production, and both were significantly positively correlated with biomass per tiller (Table 4).

### 3.4. Photosynthetic parameters

The daily mean values of photosynthetic parameters varied

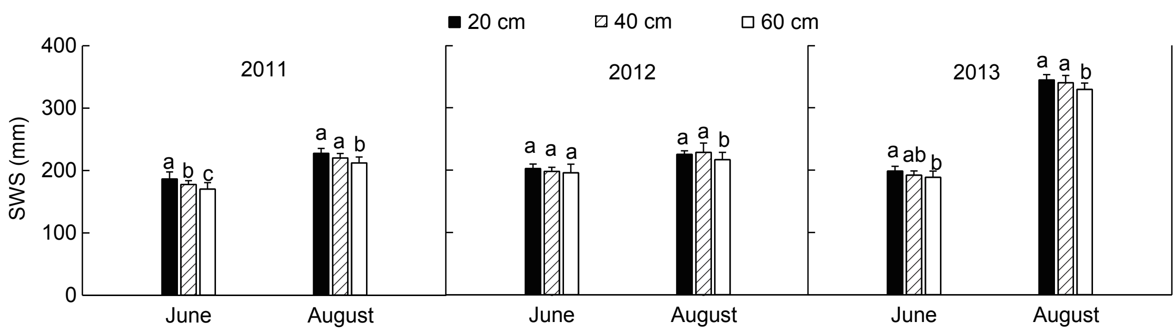


**Fig. 1** Soil water storage (SWS) of switchgrass under each row spacing in June and August during 2011–2013. Bars indicate SE ($n$=5). Different small letters indicate significant difference at $P$=0.05 according to LSD test in the same month for each year.

**Table 3** Averaged plant height, leaf length, leaf width, tiller numbers per unit area, and biomass per tiller of switchgrass under each row spacing in 2011–2013

| Row spacing (cm) | Plant height (cm) | Leaf length (cm) | Leaf width (cm) | Tiller numbers per $m^2$ | Biomass per tiller (g) |
|---|---|---|---|---|---|
| 20 | 68.91±6.7 c | 26.56±2.0 c | 0.77±0.05 c | 1 145±87 a | 0.60±0.08 c |
| 40 | 77.58±8.9 b | 30.71±2.1 b | 0.88±0.06 ab | 754±54 b | 0.72±0.05 b |
| 60 | 92.96±7.6 a | 33.29±3.4 a | 0.91±0.10 a | 371±43 c | 0.81±0.04 a |

Data are means±SE ($n$=5). Different small letters in each column indicate significant difference among row spacings at $P$=0.05 according to LSD test.

**Table 4** Correlation between aboveground biomass production and yield components across different row spacings and years (2011–2013)

| | Plant height | Leaf length | Leaf width | Tiller numbers per $m^2$ | Biomass per tiller | Aboveground biomass production |
|---|---|---|---|---|---|---|
| Plant height | 1 | 0.905** | 0.885** | –0.911** | 0.902** | –0.710* |
| Leaf length | | 1 | 0.959** | –0.724* | 0.756* | –0.551 |
| Leaf width | | | 1 | –0.797* | 0.856** | –0.662 |
| Tiller numbers per $m^2$ | | | | 1 | –0.984** | 0.907** |
| Biomass per tiller | | | | | 1 | –0.886** |

*, significant difference at $P$=0.05; **, significant difference at $P$=0.01, according to LSD test.

substantially from year to year, and the significantly highest values ($P_n$, $T_r$ and $G_s$) were observed in 2011. In most cases, there were no significant differences between 2012 and 2013 in June. In August, daily mean $P_n$ and $G_s$ values were significantly higher in 2013 than that in 2012, whereas there were no significant differences in $T_r$. The highest daily mean $WUE_i$ values were observed in 2013, which was significantly higher than that in 2011 and 2012 in both months ($P<0.05$).

In 2011, the daily mean values of $P_n$ were significantly lower in August than that in June, and it showed an opposite trend in 2012 and 2013 ($P<0.05$). The maximum daily mean $P_n$ values (17.9, 18.4, 19.7 μmol $CO_2$ $m^{-2}$ $s^{-1}$) observed in June 2011, and were 79.0, 76.9 and 79.0% higher than the minimum values (10.0, 10.4, 11.0 μmol $CO_2$ $m^{-2}$ $s^{-1}$) recorded in June 2012 for 20, 40 and 60 cm row spacing, respectively. Moreover, row spacing had significant effect on $P_n$ values, and $P_n$ of 60 cm was significantly higher than 20 and 40 cm in both growth months during the three experimental years ($P<0.05$). There were no significant differences between 20 and 40 cm row spacing, except at August 2013, in which 40 cm had significantly higher daily mean $P_n$ than 20 cm row spacing (Fig. 2-A).

Daily mean $T_r$ values were higher in June than that in August over the three years, whereas the only significant differences were observed in 2011 ($P<0.05$) (Fig. 2-B). The maximum daily mean $T_r$ appeared in June 2011, with the values of 6.4, 6.3, 6.8 mmol $H_2O$ $m^{-2}$ $s^{-1}$, 103.1, 90.1 and 101.0% higher than the minimum values (3.3, 3.3, 3.4 mmol $H_2O$ $m^{-2}$ $s^{-1}$) recorded in August 2012 for 20, 40 and 60 cm, respectively.

Daily mean $G_s$ values were significantly lower in June than in August, except in 2011. The highest values of $G_s$ were observed in June 2011 (192.4, 195.6 and 206.4 mmol $H_2O$ $m^{-2}$ $s^{-1}$ for 20, 40 and 60 cm, respectively), and were 138.1, 129.8 and 132.9% higher than those in 2012, and about 116.9, 104.8 and 114.7% higher than those values in 2013. Daily mean $G_s$ values decreased as with row spacing treatment decrease, and $G_s$ of 60 cm was significantly higher than 20 and 40 cm over the three years ($P<0.05$) (Fig. 2-C).

Daily mean values of $WUE_i$ were significantly lower in June than in August, except in 2011. The highest daily mean $WUE_i$ values were recorded in August of 2013, which were 3.69, 3.71 and 4.13 μmol $CO_2$ $mmol^{-1}$ $H_2O$ for 20, 40 and 60 cm, respectively. In general, the daily mean $WUE_i$ values increased with row spacing increased, but there were no significant effects in most cases ($P>0.05$) (Fig. 2-D).

Daily mean values of $C_i$/Ca were significantly lower in June than in August ($P<0.05$) (Fig. 2-E). In August, there were no significant differences among the three years. Whereas, in June, the significant highest daily mean $C_i/C_a$ values were recorded in 2011, which were 0.51, 0.51 and 0.49 for 20, 40 and 60 cm, respectively. The daily mean $C_i/C_a$ values decreased with row spacing increased, but there were no significant effects in most cases ($P>0.05$) (Fig. 2-E).

### 3.5 Aboveground biomass production and water use efficiency

Row spacing greatly affected aboveground biomass production and WUE of swichgrass (Fig. 3). Biomass yield varied substantially from year to year, and the highest values were observed in 2012, with values of 67 771.8, 6 976.8, 6 609.2 kg $ha^{-1}$ for 20, 40 and 60 cm row spacing, respectively. Aboveground biomass production in 20 cm row spacing treatment was higher by 22.2 and 28.8% in 2011, by 11.4 and 17.5% in 2012 and by 10.7 and 11.2% in 2013 than those of 40 and 60 cm row spacing, respectively. Similar trends were found for WUE as with aboveground biomass yield ($P<0.05$). WUE in 20 cm row spacing was higher by 19.4 and 24.1% in 2011, by 12.17 and 19.8% in 2012 and by 10.2 and 9.4% in 2013 than those of 40 and 60 cm row spacing treatments, respectively ($P<0.05$) (Fig. 3).

### 3.6 Correlation between photosynthetic rate and biomass production

Both biomass per tiller and $P_n$ of switchgrass increased along with row spacing enlargement for each year (Fig. 4). Significantly positive correlations were found between $P_n$ and biomass per tiller, and it showed great differences among years. However, $P_n$ of switchgrass showed a negative correlation with aboveground biomass yield, and the variations were obviously smaller (Fig. 4).

## 4. Discussion

Appropriate row spacing leads to higher yields through better resource availability, which is considered an important agricultural practice for increasing crop yield (Mattera *et al.* 2013; Mao *et al.* 2014; Wang *et al.* 2015). Researches show that narrow row spacing may strengthen competition among individual plants for available resources, and constraint single plant development, while increase tillers numbers and aboveground biomass yield (Gwathmey and Clement 2010; Mao *et al.* 2014; Yang *et al.* 2014). In addition, narrower row spacing can fast cover the ground surface at early canopy development and reduce soil water evaporation, thus lead to higher soil water storage than wider row spacings (Wang *et al.* 2015). Our results clearly indicated that row spacing arrangement significantly affected switchgrass photosynthesis, plant height, leaf length and width and biomass per tiller, with the highest values observed in 60 cm row spacing (Table 3).

Canopy photosynthesis was significantly influenced by

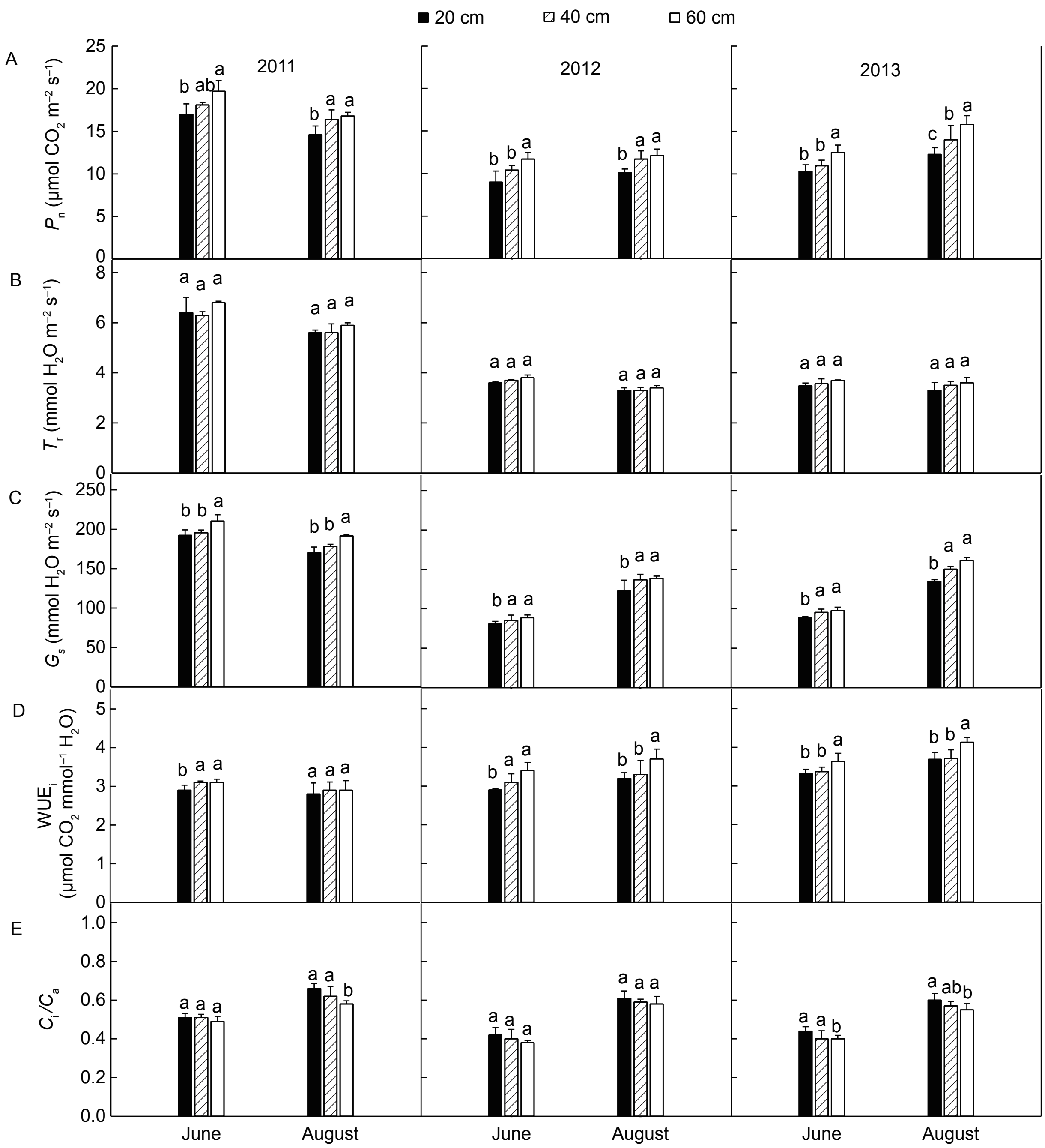


**Fig. 2** Seasonal and inter-annual changes of leaf net photosynthesis rate ($P_n$; A), transpiration rate ($T_r$; B), stomatal conductance ($G_s$; C), instantaneous water use efficiency ($WUE_i$; D) and the ratio of intercellular to atmospheric $CO_2$ concentration ($C_i/C_a$; E) of switchgrass under each row spacing in June and August during 2011–2013. Bars indicate SE ($n$=5). Different small letters indicate significant difference at $P$=0.05 according to LSD test in the same month for each year.

canopy structure, while leaf photosynthesis would be more closely related to individual plant development (Li *et al.* 2010). Plant density is an important agronomic factor to influence plant growth and their photosynthetic characteristics (Andrade *et al.* 2002). Studies reported that increased plant density had a positive effect on leaf area index and crop production, while the individual plant size was reduced (Gwathmey and Clement 2010). It is believed that canopy photosynthetic rates increased with increased plant density until reaching the peak, but decreased rapidly under the high density, because light transmittance decreased under high plant density, and leaf photosynthesis was significantly lower in high density than in low density treatment (Hou and Wang 2001; Yang *et al.* 2014). In this study, daily mean leaf

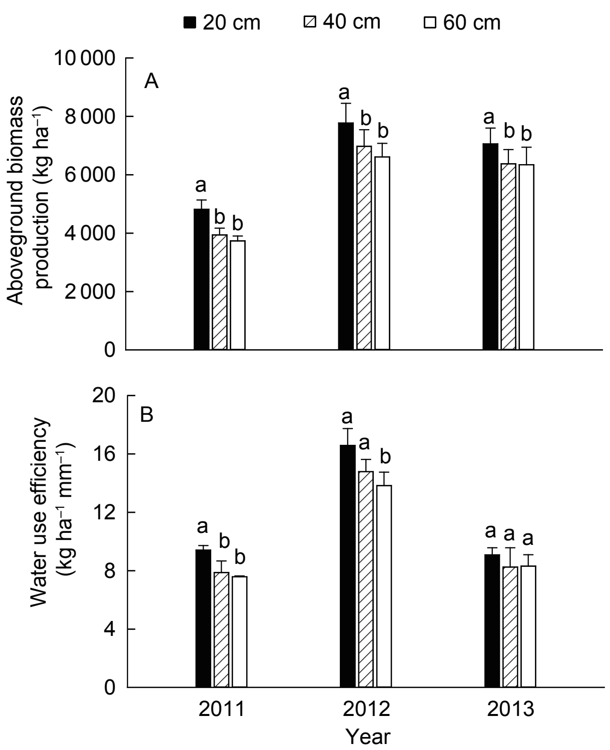


**Fig. 3** Aboveground biomass production and water use efficiency under each row spacing during 2011–2013. Bars indicate SE ($n$=5). Different small letters indicate significant difference at $P$=0.05 according to LSD test in the same month for each year.

$P_n$, $T_r$, $G_s$ and $WUE_i$ increased as row spacing increasing at both months in each year, which may be because narrow row spacing intensified plant competition for nutrients, light, space, resulting in decreased leaf $P_n$, $T_r$, $G_s$ and $WUE_i$ (Fig. 2-A, B, C and D).

Leaf photosynthetic rate can also be influenced by leaf age, leaf structure and physiology, development stage and environment factors (Song *et al.* 2012; Gao *et al.* 2015). Switchgrass experienced large interannual fluctuations in photosynthetic parameters, with the highest $P_n$ values recorded in 2011, it was 40–80% and 12–70% higher than that in 2012 and 2013, respectively. Such phenomenon might be explained by the different photochemical efficiency of the light reaction system due to different leaf ages (Ding *et al.* 2006). There were large seasonal differences in $P_n$, with the values higher in June than that in August of 2011, which may be attributed to the favorable environment conditions and abundant rainfall in June 2011. Moreover, the higher $P_n$ in June coincided with the jointing stage, which is an active vegetation development period with a high demand of carbohydrates (Guo *et al.* 2013; Gao *et al.* 2015). However, opposite trends were recorded in 2012 and 2013, in which $P_n$ was significantly lower in June, which might be explained by lower rainfall, high VPD and temperature (Tables 1 and 2). Moreover, switchgrass experienced the most severe drought in June 2012 and 2013, about 55.6 and 67.5% drier than average of 1951–2000 period, accordingly the VPD was significantly higher in 2012 and 2013 than in 2011 ($P$<0.05) (Table 1). All these results are in agreement with the conclusion that absence of water availability and atmospheric drought can substantially reduce photosynthetic carbon gain of switchgrass in arid environments (Xu *et al.* 2006a).

$C_i/C_a$ ratio is an effective index for evaluating stomatal response to environmental conditions and plant growth status, and results showed that it decreases with increasing VPD and soil water deficit, and related with leaf senescence (Guo *et al.* 2002; Bertamini and Nedunchezhina 2003). Here, $C_i/C_a$ ratios of swithgrass were higher in August than June (Fig. 2-E), indicating that $P_n$ reduction of the seedlings was largely due to stomatal factors in June, because lower $C_i/C_a$ ratio was presumably as a result of stomatal closure in response to drought (Sage 1994; Pons and Welschen

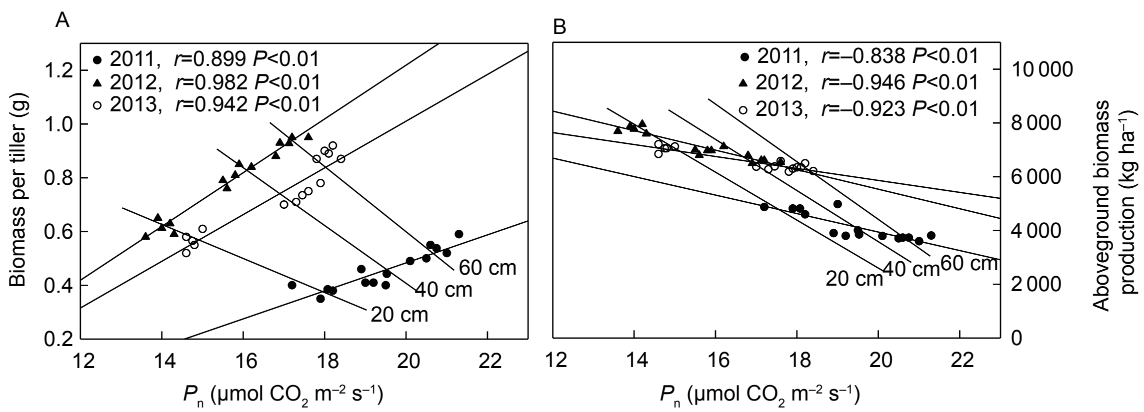


**Fig. 4** Relationship between net photosynthesis rate ($P_n$) and biomass per tiller (A), aboveground biomass production (B) under each row spacing during 2011–2013. Bars indicate SE ($n$=5). Different small letters indicate significant difference at $P$=0.05 according to LSD test in the same month for each year.

2003). Similar study revealed that switchgrass had strong stomatal adjustment ability through increase stomatal limitation to avoid dehydration and major tissue damage in arid ecosystems (Xu *et al.* 2005).

Individual leaf photosynthetic rate is one of a number of factors contributing to final yield, but the relationship between photosynthetic rate and plant yield showed great difference among different plant species and growth stage (Buttery *et al.* 1981; Wei *et al.* 2009). Song *et al.* (2012) reported that yields of adzuki bean cultivars (*Vigna angularis*) were positively correlated with their leaf $P_n$, $T_r$ and $G_s$, and negatively associated with their leaf $C_i$. Whereas, Li *et al.* (2010) believed that biomass production would presumably be more closely related to total canopy photosynthesis rather than the rate for an individual leaf. In this study, switchgrass leaf $P_n$ of single plant was negatively associated with total aboveground biomass productivity and showed a great yearly difference, which may be due to the variations of environmental factors as mentioned above (Fig. 4). Positive relation between tiller numbers per $m^2$ and aboveground biomass producion, affirmed that tiller numbers were one of the primary contributing factors to switchgrass biomass formation (Boe 2007).

## 5. Conclusion

This study investigated photosynthetic performance of switchgrass and its relation to field productivity and its components under different row spacings over three years in semiarid Loess Plateau. Results indicated that switchgrass leaf $P_n$, plant height, leaf length and width, and biomass per tiller were significantly higher under 60 cm row spacing, while aboveground biomass production and WUE were higher under 20 cm row spacing. Significantly positive correlation was found between tiller number and aboveground biomass production. Leaf $P_n$ was more closely correlated with biomass per plant rather than aboveground biomass yield, and their values varied greatly with growth years. All these further confirm that wide row spacing is beneficial for single plant development, while narrow row spacing favors biomass production and water use of switchgrass in the region, regardless of environmental changes with growth months and years. Our results also imply that single leaf growth and performance could explain the switchgrass community density differences, while fail to account for the aboveground biomass production.

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