Geoderma 308 (2017) 93–103

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Effects of nitrogen fertilizer, soil temperature and moisture on the soil-surface CO_2 efflux and production in an oasis cotton field in arid northwestern China

Yongxiang Yu[a,b], Chengyi Zhao[a,*], Hongtao Jia[c], Baicheng Niu[a,b], Yu Sheng[a], Fengzhi Shi[a]

[a] State Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi 830011, China

[b] University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, China

[c] College of Grassland and Environment Sciences, Xinjiang Agriculture University, 42 Nanchang Road, Urumqi 830052, China

ARTICLE INFO

Handling Editor: Junhong Bai

Keywords:
Soil environment
Nitrogen fertilization
Soil respiration
Arable soil
Arid region

ABSTRACT

In several studies of agricultural ecosystems, researchers have focused on the soil-surface carbon dioxide (CO_2) effluxes, but the nature of CO_2 production in the soil profile and its influencing factors remain unclear. In this study, the soil-surface CO_2 effluxes in an oasis cotton field were measured using the chamber method, and the CO_2 concentrations were used to estimate the CO_2 production in different layers of the soil profile using the gradient method. The soil CO_2 concentrations increased with increasing soil depth, whereas CO_2 production decreased with increasing soil depth. Both soil-surface CO_2 effluxes and CO_2 production in the 0–40 cm layers exponentially increased with increasing temperature. Irrigation temporarily reduced the soil-surface CO_2 effluxes by 19–63% through inhibiting CO_2 production in the 10–40 cm layer but did not affect the CO_2 production in the 0–10 cm layer. CO_2 production mainly occurred in the 0–10 cm layer, and this cumulative production accounted for 63–67% of the total production throughout the soil profile (0–40 cm). The application of nitrogen (N) fertilizer enhanced the rate of CO_2 production in the 0–20 cm layer by increasing the root biomass and soil mineral N content. A positive correlation was detected between the soil-surface CO_2 efflux and soil NO_3^- content in 2015, but no significant correlations were found between the soil-surface CO_2 efflux and soil NH_4^+ contents in any treatment. A higher soil-surface CO_2 efflux was observed under high soil temperature and a certain soil moisture range (0.21–0.23 $cm^3\,cm^{-3}$). An analysis of the soil profile revealed higher CO_2 production rates detected in the 0–10 cm layer under high soil temperature and moisture conditions, but higher rates were observed under high soil temperature and low soil moisture conditions in the 10–20 cm layer. Therefore, our results suggest that the effects of fertilization, soil temperature and moisture on CO_2 production vary depending on the soil depth. These findings might improve our understanding of the mechanisms underlying soil respiration in soil profiles.

1. Introduction

In terrestrial ecosystems, soil is the largest carbon (C) pool, containing approximately 2400 Pg C in the upper 2 m (Batjes, 1996). Soil-surface carbon dioxide (CO_2) efflux is one of the largest C fluxes (Schimel, 1995) that results in a net loss of C to the atmosphere, mainly through soil respiration and the combination of root and heterotrophic respiration (Hanson et al., 2000). This loss might increase with increasing temperatures through stimulation of biological activity in the soil (Gaumont-Guay et al., 2006), and the released CO_2 might form part of a positive feedback by contributing to climate warming. Soil temperature and moisture are the major abiotic factors controlling soil respiration through their effects on soil biological activities and the decomposition of soil organic matter (Gaumont-Guay et al., 2006; Koncz et al., 2015a). Soil respiration is also strongly linked to plant biomass by influencing the translocation of photosynthate during rhizosphere respiration (Ding et al., 2010; Koncz et al., 2015b; Scheer et al., 2013).

The soil-surface CO_2 efflux is the combined result of CO_2 production and transport between different soil layers (Rey, 2015), and many researchers have focused on this efflux using chamber method (Brumme and Beese, 1992; Lv et al., 2014; Mosier et al., 2006; Wang et al., 2013) and have assumed that it is equivalent to soil respiration. However, this measured soil-surface CO_2 efflux is not likely to represent the "real" soil

* Corresponding author.
E-mail address: zcy@ms.xjb.ac.cn (C. Zhao).

http://dx.doi.org/10.1016/j.geoderma.2017.07.032
Received 12 July 2016; Received in revised form 28 June 2017; Accepted 26 July 2017
0016-7061/

respiration and thus provides limited information on the CO_2 dynamics within the soil profile (Rey, 2015). For example, when the soil moisture exceeds the soil water field capacity, the soil-surface CO_2 efflux generally decreases with increasing soil water content (Gaumont-Guay et al., 2006). This result not only reflects a reduction in soil respiration but also results from a restriction of CO_2 transport in the soil profile. Moreover, due to the variety of root and soil organic matter, the effects of soil temperature and moisture on CO_2 production rates likely vary depending on the soil depth. Therefore, understanding the CO_2 production in the soil profile is important for improving our understanding of the interactions between influencing factors and "real" soil respiration. Several researchers have measured the soil CO_2 concentrations at different depths to determine the production of CO_2 in the soil profile using the gradient method (Nan et al., 2016; Pumpanen et al., 2008; Vargas and Allen, 2008), which can be used to investigate the "real" soil respiration in the soil profile.

In agricultural ecosystems, the application of nitrogen (N) fertilizer not only supplies nutrients to improve crop growth but also affects soil respiration (Bhattacharyya et al., 2012; Ding et al., 2010; Fuß et al., 2011). In general, N fertilization increases soil respiration due to increased root respiration resulting from an increase in root biomass (Bhattacharyya et al., 2012; Fuß et al., 2011; Shao et al., 2014) and also increases heterotrophic respiration by increasing the decomposition of soil organic C (SOC) by reducing the C/N ratio (Kuzyakov et al., 2000; Luo et al., 2016). However, in a maize field, Ding et al. (2010) found that the application of N fertilizer reduced soil respiration, because the N uptake needed for maize growth in a non-fertilized plot could be approximately met by decomposing SOC, which resulted in higher root respiration compared with that in a fertilized field. In a cotton field, Liu et al. (2008) reported that the root biomass increased with increasing N fertilization rates, which likely enhanced soil respiration, because root respiration was the main component of the total soil respiration (Yu and Zhao, 2015).

Over the past 20 years, the production of cotton in China has increased by 26% (Statistics of the Food and Agriculture Organization of the United Nations (FAOSTAT), 2015), and these increases are largely driven by the intensification of agricultural management (e.g., N fertilization). The arid region of China is an important area for cotton production, and the cotton lint produced in this region represents 60% of the total production of cotton lint in China (China Statistical Yearbook, 2014). In this region, soil-surface CO_2 effluxes in agricultural systems are two- to five-fold higher than those in natural ecosystems (Lai et al., 2012). Moreover, the fertilizer rates in arid cotton fields range from 240 to 360 kg N ha^{-1} yr^{-1} (Lv et al., 2014), making them higher than those in other regions, including Northern China, where fertilizer rates typically range from 60 to 80 kg N ha^{-1} yr^{-1} (Liu et al., 2014). A previous study showed that both root and heterotrophic respiration in a cotton field increased with increasing N fertilization based on the DeNitrification-DeComposition (DNDC) model (Yu and Zhao, 2015), but this result has not been validated by experimentation in the field. Therefore, with the heavy use of N fertilizers coupled with high soil respiration rates, it is necessary to understand the links between N inputs and soil respiration in this agricultural ecosystem. In this study, we used the chamber method to measure the soil-surface CO_2 efflux and the gradient method to estimate CO_2 production under different N fertilizer treatments. The objective was to assess the effects of soil temperature and moisture on the soil-surface CO_2 efflux and CO_2 production rates, and we hypothesized that the application of N fertilizer would increase both soil-surface CO_2 efflux and the production of CO_2 in the soil profile.

2. Materials and methods

2.1. Site and experiment description

The field experiment was conducted during two growing seasons (2014 and 2015) at the Aksu National Experimental Station in the Oasis Farmland Ecosystem, which is located in north-western China (40°37′N, 80°45′E; elevation: 1028 m). This region has a typical arid climate, with an annual mean air temperature of 11.2 °C and annual mean precipitation of 45.7 mm. At the soil layers of 0–10, 10–20 and 20–40 cm, the soil organic matter contents are 8.0, 4.8 and 3.8 g C kg^{-1}, respectively, and the C/N ratios are 11.9, 11.1 and 12.6. The soil is gleyic solonchak (World Reference Base for Soil Resources), and the soil texture is silt loam with 6% clay (< 0.002 mm), 43% silt (0.002–0.02 mm) and 51% sand (0.02–2 mm) in the 0–40 cm layer, with bulk densities of 1.49, 1.52 and 1.56 g cm^{-3} at the 0–10, 10–20 and 20–40 cm soil depths, respectively.

Before sowing, basal fertilization and tillage occurred on 13 April 2014 and 15 April 2015. Basal fertilizers were incorporated into the 0–30 cm soil layer at rates of 80 kg N ha^{-1} $year^{-1}$ in the form of urea (60 kg N ha^{-1} $year^{-1}$), diammonium phosphate (20 kg N ha^{-1} $year^{-1}$) and potash followed by tillage. After two days, ridge soils were formed (100 cm wide and 5 cm high) by a ridging plough, and plastic film (0.02 mm thick and 1.2 m wide) was mulched over the ridged soil. The edges of the film were sealed under the soil, and the furrow soil (50 cm wide) remained uncovered. Cotton (Tanong No. 8) seeds were sown into the mulched ridges at 10 cm intervals in rows spaced 50 cm apart on 15 April 2014 and 17 April 2015, and in both years, drip irrigation was used to supply 320 mm of irrigation water in 8 doses of 40 mm each. During the drip irrigation period, three fertilization treatments were applied: 0, 160 and 320 kg N ha^{-1}. For the 160 and 320 kg N ha^{-1} treatments, urea was uniformly dissolved in the irrigation water and applied as four doses of 40 and 80 kg N ha^{-1}, respectively, to improve crop N uptake in this plastic mulched cropping system (Wang et al., 2016). Urea application occurred on 9 July, 20 July, 28 July and 6 August in 2014 and on 5 July, 13 July, 21 July and 28 July in 2015 (Fig. 1b). Therefore, the total N fertilizer rates were 80, 240 and 400 kg N ha^{-1}, but these treatments are denoted 0, 160 and 320 kg N ha^{-1}, respectively, during the observation period. Each treatment (10 m long and 6 m wide) was assigned in a completely randomized design and replicated three times.

2.2. Sampling

Three gas samples per plot at depths of 10, 20 and 40 cm were collected from the ridge soil profiles between cotton plants every four to ten days in 2014 (from 18 May to 11 November) and 2015 (from 8 May to 12 October) using modified diffusion equilibrium samplers. At the beginning of the experiment, 27 gas collectors were installed in the ridge soil. Each collector was made of a Teflon tube (1.0 mm inner diameter and 3.0 mm outer diameter) connected to a probe for sampling the soil gas. The probe consisted of a 60 ml PVC pipe (12 mm inner and 15 mm outer diameters) with 16 holes (2 mm inner diameter), and the bottom was sealed with a glass microfiber filter to allow soil air to diffuse into the sampler. At each sampling position, a soil auger (2 cm inner diameter and 15 cm in length) was used to excavate a hole in the centre of four cotton plants. The gas collectors were installed vertically into the soil to collect gas samples at depths of 10, 20 and 40 cm in each plot, and each collector was separated horizontally by approximately 20 cm. The equipment was left in the field for approximately half a month to allow the soil CO_2 concentration to reach equilibrium before sampling. To collect gas from each depth, we used a gastight, three-way ball valve fitted with an injection syringe, a design that enabled us to extract soil air at any depth without contamination or clogging. After pre-extraction of the residual air, a 30 ml gas sample was collected using a syringe. The air CO_2 concentrations were also measured from the ambient gas above the soil surface (0 cm).

The soil-surface CO_2 efflux from each plot was measured in the ridge soil between cotton plants using the closed-chamber method and calculated using either the non-linear or linear methods described by Wang et al. (2013). The equipment consisted of a stainless-steel chamber (30 cm length, 15 cm width and 15 cm height) and a stainless-

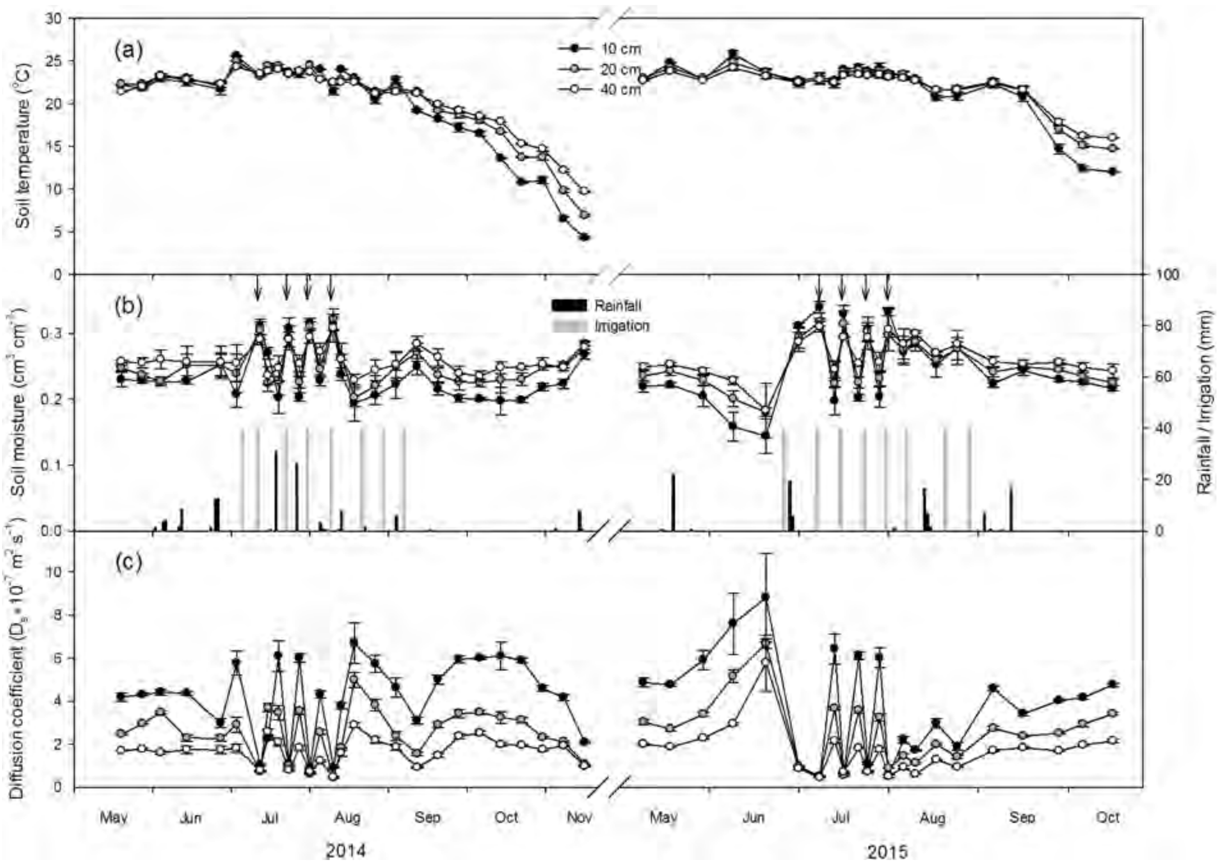

Fig. 1. Soil temperature (a), moisture and amount of rainfall or irrigation (b), and CO_2 diffusion coefficient (c) at 10, 20 and 40 cm depths in 2014 and 2015. Black arrows (b) denote the application of urea. *Error bars* for the different variables represent the standard errors of the means ($n = 3$).

steel base (30 cm length, 15 cm width and 5 cm height). Each chamber was covered with a foam plate and tinfoil to limit the temperature increase within the chamber during sampling. The base was vertically inserted 5 cm into the soil. During the gas sampling, the flange of each chamber was carefully placed in the groove of the base, and each groove was filled with an appropriate amount of water to ensure a closed environment. The gas samples were collected between 11:00 and 13:00. After chamber closure, five gas samples (60 ml) were sampled at 0, 10, 20, 30 and 40 min from the headspace with a syringe. The gas samples were then analysed using a modified gas chromatograph (Agilent 7890A, Agilent, Palo Alto, CA, USA) equipped with a nickel catalyst converter to reduce CO_2 into CH_4, and the CO_2 concentration was then measured using a hydrogen flame ionization detector (FID) at 375 °C. A standard gas with a known CO_2 concentration (398.9 ppm CO_2 in N_2) was used to calibrate the concentration of the CO_2 samples.

Six plants were sampled in each plot at the end of the growing season (on 4 October 2014 and 28 September 2015). The aboveground portions (leaves and stems) of the cotton plants were randomly collected using pruning shears, and roots were collected using a root auger (5 cm inner diameter and 20 cm length) from the 0–40 cm layer because most roots are distributed in this layer (Zhao et al., 2010). All roots were washed and separated by hand. The samples were oven-dried at 80 °C for > 48 h and weighed. The soil temperatures at different layers (0–10, 10–20 and 20–40 cm) were measured directly using Hydra Probes (Hydra Probe II, Stevens Water Monitoring Systems Inc., Portland, OR, USA). Soil samples were collected from different layers (0–10, 10–20 and 20–40 cm) and oven-dried at 105 °C for > 24 h to determine the soil water content.

One soil sample in the 0–10 cm layer per plot was collected using a soil auger (2 cm inner diameter and 15 cm length), which was used to measured soil nitrate (NO_3^-) and ammonium (NH_4^+) contents. The soil was sieved (2 mm mesh), and 5.0 g of soil was then extracted with 100 ml of 0.01 M $CaCl_2$ solution on a mechanical shaker for 1 h. The extracts were analysed with an automated NO_3^- and NH_4^+ analyser (AutoAnalyser 3, Bran Luebbe/SEAL Analytical, Norderstedt, Germany).

2.3. Calculation of the production of CO_2 in the soil profile

We calculated CO_2 production using the gradient method, which is based on the CO_2 concentrations and transport properties of the soil profile (Maier and Schack-Kirchner, 2014). The CO_2 production (g C m^{-2} s^{-1}) between the depths $i + 1$ and i cm (P_{i+1_i}) was calculated as follows:

$$P_{i+1i} = F_{ii-1} - F_{i+1i} \tag{1}$$

where F_{i_i-1} and F_{i+1_i} are the soil CO_2 effluxes (g C m^{-2} s^{-1}) from depths $i - 1$ to i cm and from depths $i + 1$ to i cm, respectively. Moreover, the soil-surface CO_2 efflux (F_0) and the CO_2 efflux from depths 10 to 0 cm (F_{10_0}) were used to calculated CO_2 production (P_{10_0}) in the 0–10 cm layer:

$$P_{100} = F_0 - F_{100} \tag{2}$$

In the soil profile, we assumed that the CO_2 transport in the soil was dominated by molecular diffusion and that the CO_2 efflux from depths $i + 1$ to i could be calculated based on the effective gas diffusivity and the CO_2 concentration gradient using Fick's law in one dimension:

$$F_{i+1i}(z) = -D_s \frac{dC}{dz} \tag{3}$$

where $F_{i+1\_i}(z)$ is the CO_2 efflux (g C m^{-2} s^{-1}) from depths $i + 1$ to i; D_s is the effective soil gas diffusivity in the soil (m^3 soil air m^{-2} soil s^{-1}); C is the CO_2 concentration (g C m^{-3}); z is the depth (m); and dC/dZ is the soil CO_2 concentration gradient in the soil profile. D_s can be estimated from the structure-dependent, water-induced linear reduction model (Moldrup et al., 2013). Fan and Jones (2014) suggested that the following equation is a reasonable method for determining the gas diffusion coefficient used for estimating CO_2 efflux:

$$D_s = D_0 \varepsilon^{(1+C_m \varnothing)} \left(\frac{\varepsilon}{\varnothing}\right) \tag{4}$$

where D_0 is the gas diffusion coefficient in air ($m^2\ s^{-1}$); ε is the soil air content ($m^3\ m^{-3}$ soil); Φ is the soil porosity ($m^3\ m^{-3}$); and C_m is the media complexity factor. Moldrup et al. (2013) recommended a C_m value of 2.1 for intact soil, and ε and Φ were computed as follows:

$$\varnothing = 1 - \frac{\rho_b}{\rho_s} = \varepsilon + \theta \tag{5}$$

where ρ_b is the dry bulk density ($g\ m^{-3}$) of different soil layers; ρ_s is the soil particle density ($2.65\ g\ m^{-3}$); and θ is the soil water content at different depths ($m^3\ m^{-3}$). The D_0 of CO_2 in the atmosphere was calculated as follows:

$$D_0 = D_{stand} \left(\frac{T}{T_0}\right)^{1.75} \left(\frac{P_0}{P}\right) \tag{6}$$

where D_{stand} is a reference value ($1.39 \times 10^{-5}\ m^2\ s^{-1}$) at T_0 (293.15 K); P_0 (1013 hPa) is the CO_2 gas diffusion coefficient in atmospheric air (Pritchard and Currie, 1982); T is the air temperature (K); and P is the pressure at Aksu station (892 hPa). Finally, the units of time for soil CO_2 production were converted from per second (s^{-1}) to per day (day^{-1}).

2.4. Data analysis

All statistical analyses were conducted using the SPSS v. 16.0 software package (SPSS, Chicago, IL, USA). We used a repeated-measure analysis of variance (ANOVA) to test the differences in soil temperature, moisture, gas diffusion coefficient, daily soil-surface CO_2 efflux and CO_2 production among the three soil layers or three fertilizer treatments, and the differences were tested at a level of $p < 0.05$. The cumulative soil-surface CO_2 efflux and CO_2 production in the soil profile were estimated by linear interpolation of the measured daily values with the corresponding time period; the results were then summed over the observation period. One-way ANOVA was used to analyse the differences in the cumulative soil-surface CO_2 efflux, cumulative CO_2 production in the soil profile, root and total biomass of cotton among the three fertilizer treatments, and the differences were tested using least-significant differences (LSDs) at a level of $p < 0.05$.

A linear regression analysis was performed to fit the relationship between soil-surface CO_2 efflux and soil mineral N (NO_3^- and NH_4^+) content, and the Q_{10} model by Gaumont-Guay et al. (2006) was used to describe the effects of soil temperature on soil-surface CO_2 efflux and CO_2 production in the soil profile. When analysing the effect of soil temperature on soil-surface CO_2 efflux or CO_2 production, we excluded the data collected immediately after irrigation because excessive soil moisture (> $0.30\ cm^3\ cm^{-3}$) depresses soil respiration (Gaumont-Guay et al., 2006). A hyperbolic regression was used to model the relationship between soil-surface CO_2 efflux and soil moisture (Gaumont-Guay et al., 2006), and a linear regression was used to fit the relationships between CO_2 production and soil moisture. Multiple regressions were used to fit the effects of soil temperature and moisture on soil-surface CO_2 efflux or CO_2 production. Lastly, we used the coefficient of determination (R^2), the root mean square error (RMSE) (Gaumont-Guay et al., 2006) and Akaike's information criterion (AIC) values (Burnham and Anderson, 2004) to select the best regression model to describe the effects of soil environmental variables on soil-surface CO_2 efflux or CO_2 production in the soil profile. The model with higher R^2 values and lower RMSE and AIC values was considered to be strongly supported.

3. Results

3.1. Soil properties and crop biomass

During the observation period, the soil temperature at different depths remained high from May to August and then gradually decreased (Fig. 1a), and no significant differences in soil temperature were found among the three depths (F = 0.56, $p > 0.05$). However, the differences of temperature became obvious in the late growing seasons. The soil moisture significantly increased with soil depth (F = 4.59, $p < 0.05$), and the two-year mean values were 0.24, 0.25 and $0.26\ cm^3\ cm^{-3}$ in the layers of 0–10, 10–20 and 20–40 cm, respectively (Fig. 1b). Irrigation temporarily increased soil moisture by 38–83%, 28–63% and 13–57% (relative terms) in the 0–10, 10–20 and 20–40 cm layers, respectively. The fluctuation in the gas diffusion coefficient decreased with greater soil depth and was influenced by irrigation or rainfall events (Fig. 1c). The gas diffusion coefficient significantly decreased with soil depth (F = 3.68, $p < 0.05$), and the two-year mean values of soil gas diffusion were 4.00×10^{-7}, 2.52×10^{-7} and $1.67 \times 10^{-7}\ m^2\ s^{-1}$ in the 0–10, 10–20 and 20–40 cm layers, respectively.

In the 0–10 cm layer, the application of urea significantly increased the soil mineral N contents (Table 1). Soil NO_3^- contents significantly increased with increasing N fertilization rates, and the two-year mean values were 3.93, 5.63 and 8.15 mg N kg^{-1} soil for the 0, 160 and 320 kg N ha^{-1} treatments, respectively (Fig. 2a). The soil NH_4^+ content was significantly higher in the 320 kg N ha^{-1} treatment than in the 0 and 160 kg N ha^{-1} treatments ($p < 0.05$), and there was no significant difference in the NH_4^+ content between the 0 and 160 kg N ha^{-1} treatments ($p > 0.05$) (Fig. 2b).

The root biomass was significantly higher in the 160 and 320 kg N ha^{-1} treatments than in the 0 kg N ha^{-1} treatment ($p < 0.05$), but there was no significant difference in root biomass between the 160 and 320 kg N ha^{-1} treatments ($p > 0.05$) (Table 2). The cotton biomass significantly increased with the application of N fertilizer ($p < 0.05$), and the two-year mean values for the rates of 0, 160 and 320 kg N ha^{-1} were 578.8, 851.7 and 1142.6 g C m^{-2}, respectively (Table 2).

3.2. Soil-surface CO_2 efflux and CO_2 production

During the observation period, the temporal variations in the soil-surface CO_2 efflux (Fig. 3), CO_2 concentrations at different depths (Fig. 4) and CO_2 production in the soil profile (Fig. 5) were similar among the different treatments and years, increasing from May to August and then gradually decreasing according to the variations in soil temperature. Irrigation temporarily decreased the soil-surface CO_2 effluxes by 19–63%

Table 1
Results of repeated measures ANOVAs of the effects of N fertilization rates on the soil mineral N content in the 0–10 cm layer, soil-surface CO_2 efflux and soil CO_2 production in different soil layers in 2014, 2015 and both years combined.

Variables	Fertilization treatments					
	2014		2015		Both	
	F	P	F	P	F	P
Soil NO_3^- content	11.40	< 0.01	8.66	< 0.01	20.22	< 0.01
Soil NH_4^+ content	2.22	> 0.10	1.66	> 0.10	3.86	< 0.05
Soil-surface CO_2 efflux	1.08	> 0.10	1.76	> 0.10	2.73	0.07
Soil CO_2 production (0–10 cm)	1.18	> 0.10	1.62	> 0.10	2.74	0.07
Soil CO_2 production (10–20 cm)	1.93	> 0.10	1.43	> 0.10	2.98	0.06
Soil CO_2 production (20–40 cm)	0.47	> 0.10	0.16	> 0.10	0.00	> 0.10

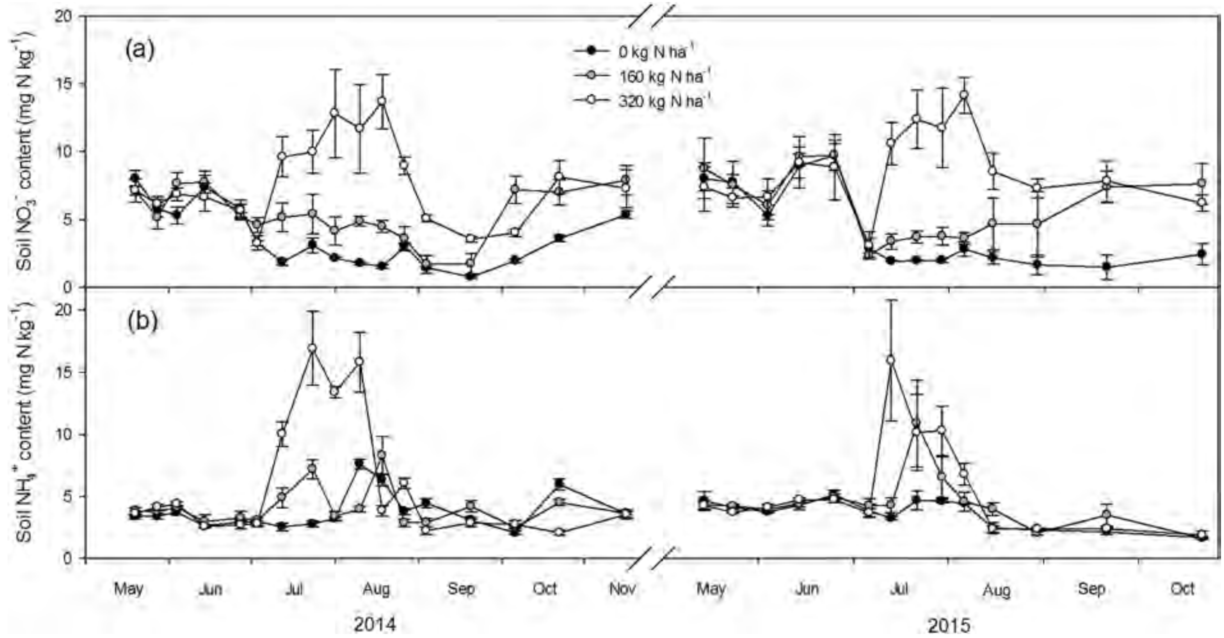

Fig. 2. Temporal variations in soil nitrate (NO_3^-) and ammonium (NH_4^+) content in the 0–10 cm layer under three fertilizer rates in 2014 and 2015. *Error bars* for the soil NO_3^- or NH_4^+ content represent the standard errors of the means ($n = 3$).

(Fig. 3), but its effect on the CO_2 production rates varied with the soil layers (Fig. 5). Irrigation did not affect the CO_2 production rate in the 0–10 cm layer but inhibited CO_2 production rates by 87–117% and 47–108% in the 10–20 and 20–40 cm layers, respectively. The production of CO_2 significantly decreased with soil layers ($F = 152.17$, $p < 0.01$), and the two-year mean values for the N treatments were 1.06, 0.38 and 0.21 g C m^{-2} day^{-1} in the 0–10, 10–20 and 20–40 cm layers, respectively. Overall, during the observation period, the production of CO_2 for the all treatments mainly occurred in the 0–10 cm layer, which accounted for 67% and 63% of the total production in the soil profile (0–40 cm) in 2014 and 2015, respectively (Table 3).

Compared with the simple functions, multiple regressions combining soil temperature and moisture improved the fit of the model, resulting in the lowest AIC values, relative high R^2 values and low RMSE values (Table 4). The multiple regression analysis showed that a higher soil-surface CO_2 efflux occurred at high soil temperatures and a certain range of soil moisture (0.21–0.23 cm^3 cm^{-3}) (Fig. 6a), but the interactive effects of soil temperature and moisture on CO_2 production varied among the soil layers. In the 0–40 cm layer, CO_2 production exponentially increased with increasing temperature (Fig. 6b–d), although the temperature effect on soil CO_2 production decreased with increasing soil depth (Table 4). The effect of soil moisture on soil CO_2 production varied among the soil layers (Fig. 6b–d). Soil CO_2 production was positively correlated with soil moisture in the 0–10 cm layer but negatively correlated with soil moisture in the 10–20 cm layer. In the 20–40 cm layer, no significant correlation was found between soil CO_2 production and moisture ($p > 0.05$). Overall, we observed higher rates of CO_2 production under conditions of both high soil temperature and moisture in the 0–10 cm layer, but in the 10–20 cm layer, higher CO_2 production occurred under high soil temperature and low soil moisture conditions (Fig. 6b and c).

3.3. Effect of N fertilization on soil-surface CO_2 efflux and CO_2 production

When the two years (2014 and 2015) were analysed together, N fertilization significantly increased the daily soil-surface CO_2 efflux at alpha = 10% (Table 1). We found a significantly positive correlation between soil-surface CO_2 efflux and soil NO_3^- content in 2015 (Fig. 7c), but no significant correlations were found between soil-surface CO_2 efflux and the soil NH_4^+ contents in all treatments (Fig. 7b and d). The cumulative soil-surface CO_2 effluxes significantly ($p < 0.05$) increased with increasing N fertilization rates (Table 3), and the two-year mean cumulative effluxes obtained with the 0, 160 and 320 kg N ha^{-1} treatments were 286.8, 315.4 and 360.9 g C m^{-2}, respectively.

Urea application significantly enhanced the daily rates of CO_2 production in the 0–20 cm layer of the soil profile at alpha = 10%, but did not affect CO_2 production rates in the 20–40 cm layer (Table 1). Although N fertilization significantly ($p < 0.05$) increased the cumulative CO_2 production in the 0–40 cm layer, the effect of fertilization on CO_2 production varied among the soil layers (Table 3). In the 0–10 cm layer, the application of urea significantly ($p < 0.01$) accelerated the production of CO_2, and the two-year mean values obtained for the 0, 160 and 320 kg N ha^{-1} treatments were 151.07, 165.49 and 180.46 g C m^{-2}, respectively. In the 10–20 cm layer, the cumulative CO_2 production was significantly ($p < 0.05$) lower in the 0 kg N ha^{-1}

Table 2
Root and total biomass of cotton (g C m^{-2}) under three fertilization rates in 2014 and 2015. The different letters indicate statistically significant differences between the three treatments (LSD test, $p < 0.05$). The values are expressed as the means ± standard errors of the means ($n = 3$).

N fertilizer rate	Root biomass		Total biomass	
	2014	2015	2014	2015
0 kg N ha^{-1}	73.0 ± 6.5 a	86.4 ± 6.5 a	544.6 ± 17.0 a	612.9 ± 54.7 a
160 kg N ha^{-1}	110.6 ± 10.3 b	105.4 ± 5.1 b	893.0 ± 39.5 b	810.4 ± 39.5 b
320 kg N ha^{-1}	114.9 ± 14.8 b	112.5 ± 13.4 b	1180.9 ± 109.2 c	1104.2 ± 58.2 c

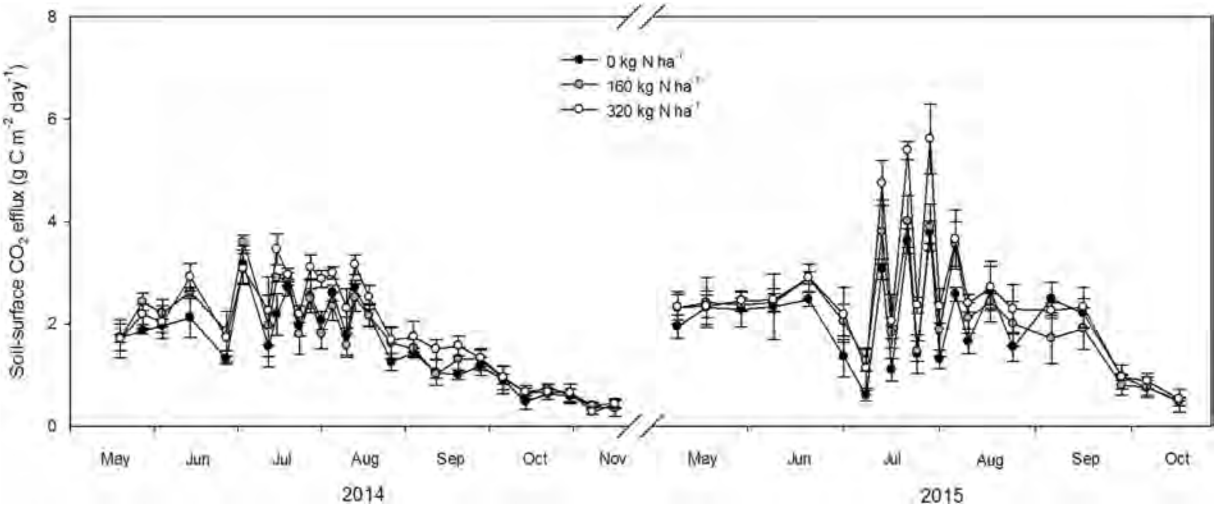

Fig. 3. Temporal variations in soil-surface CO_2 effluxes under different fertilizer rates in 2014 and 2015. *Error bars* for the soil CO_2 effluxes represent the standard errors of the means (n = 3).

treatment compared with the 160 and 320 kg N ha^{-1} treatments, and a significant difference in CO_2 production was found between the 160 and 320 kg N ha^{-1} treatments in 2015. In the 20–40 cm layer, there were no significant differences in cumulative CO_2 production among the three fertilizer treatments.

4. Discussion

Nitrogen fertilization increased the soil-surface CO_2 effluxes during the observation periods, and this result is consistent with previous findings (Bhattacharyya et al., 2012; Fuß et al., 2011; Luo et al., 2016;

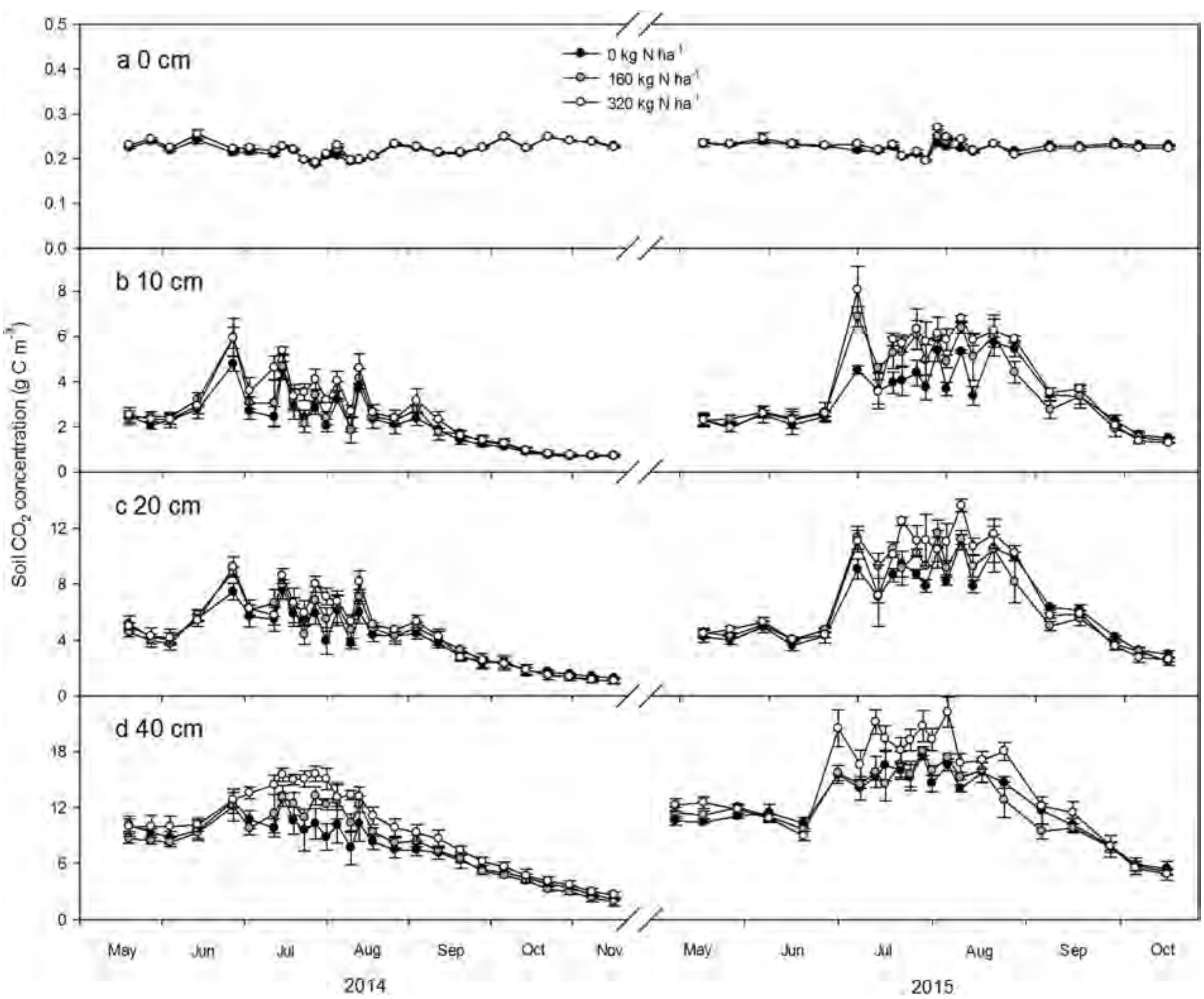

Fig. 4. Temporal variations in soil CO_2 concentrations at 0, 10, 20 and 40 cm depths under different fertilizer rates in 2014 and 2015. *Error bars* for the soil CO_2 concentrations represent the standard errors of the means (n = 3).

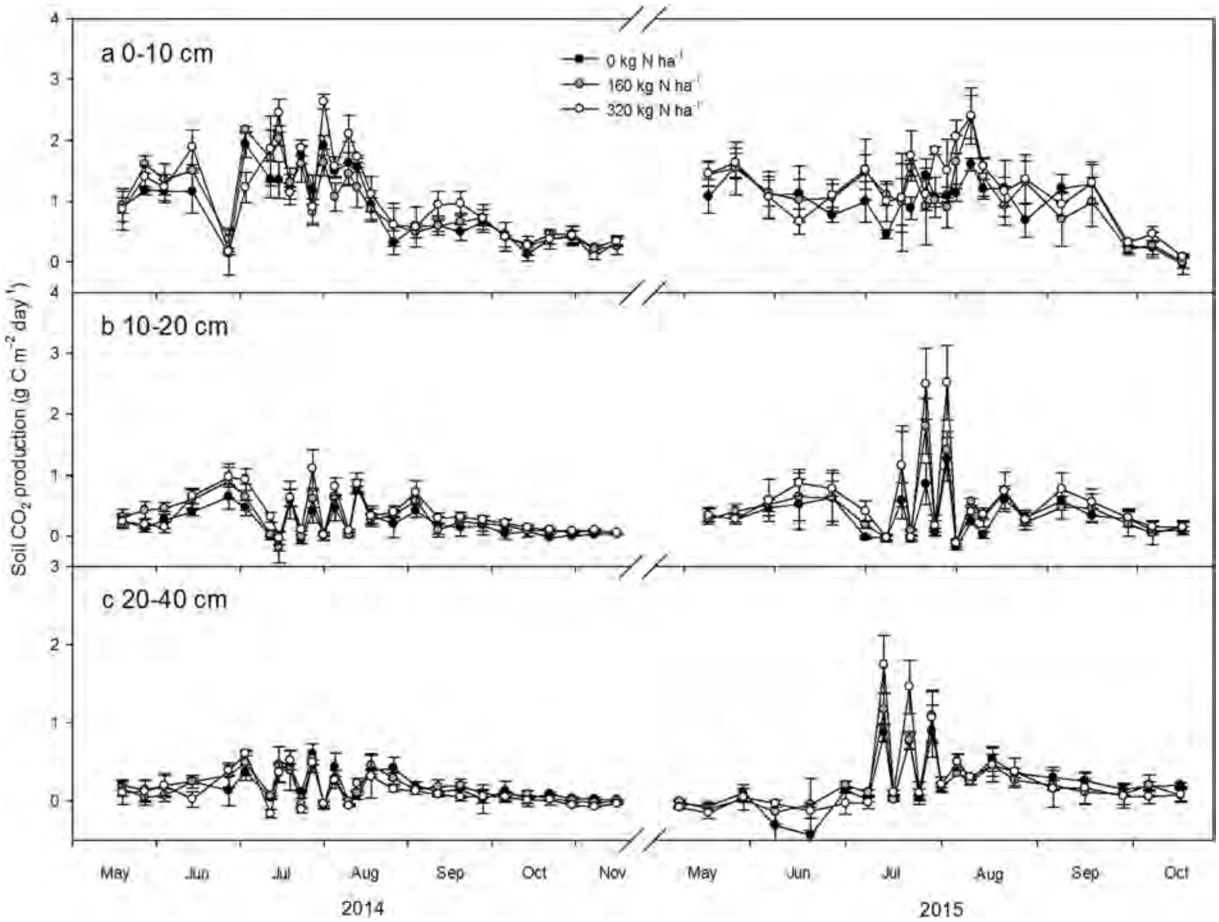

Fig. 5. Temporal variations in CO_2 production in the 0–10, 10–20 and 20–40 cm soil layers under different fertilizer rates in 2014 and 2015. *Error bars* for the soil CO_2 production represent the standard errors of the means (n = 3).

Table 3
Cumulative soil-surface CO_2 efflux and CO_2 production (g C m^{-2}) in the soil profile under three fertilization rates in 2014 and 2015. The different letters denote significant differences among the three treatments (LSD test, $p < 0.05$). The values are expressed as the means ± standard errors of the means (n = 3).

N fertilizer rate	Cumulative soil-surface CO_2 efflux	Cumulative CO_2 production			
		Soil layer			
		0–10 cm	10–20 cm	20–40 cm	0–40 cm
2014					
0 kg N ha^{-1}	269.9 ± 9.0 a	150.9 ± 12.7 a	40.2 ± 10.0 a	30.9 ± 5.1 a	222.0 ± 20.9 a
160 kg N ha^{-1}	300.8 ± 11.1 b	165.8 ± 15.7 ab	57.8 ± 1.8 ab	30.1 ± 6.4 a	253.6 ± 10.0 ab
320 kg N ha^{-1}	349.3 ± 4.3 c	178.0 ± 6.0 b	68.1 ± 13.2 b	22.6 ± 9.0 a	268.7 ± 22.7 b
2015					
0 kg N ha^{-1}	303.6 ± 2.7 a	151.3 ± 3.8 a	54.0 ± 5.2 a	25.5 ± 6.9 a	230.8 ± 3.2 a
160 kg N ha^{-1}	330.1 ± 4.4 b	165.2 ± 6.3 b	69.0 ± 5.0 b	27.7 ± 1.2 a	261.9 ± 2.9 b
320 kg N ha^{-1}	372.5 ± 2.9 c	182.9 ± 4.0 c	87.1 ± 2.0 c	30.4 ± 7.7 a	300.4 ± 11.0 c

* and **: significant at $p < 0.05$ and $p < 0.01$, respectively.

Lv et al., 2014; Shao et al., 2014). The application of urea increases plant production and enhances the translocation of photosynthate to the rhizosphere, which increases root respiration (Guo et al., 2015; Hamada and Tanaka, 2001; Oh et al., 2005). However, Ding et al. (2010) found that N addition reduced root respiration in a maize field through decreased root biomass, because fertilization reduced the belowground allocation of photosynthate. In this study, the root biomass of cotton increased following urea application, which probably resulted in higher root respiration (Scheer et al., 2013; Shao et al., 2014). Additionally, N fertilization eliminates soil mineral N limitation, thereby indirectly increasing soil respiration (Ding et al., 2010; Kuzyakov et al., 2000; Luo et al., 2016). However, the soil NO_3^- content but not the soil NH_4^+ content has been shown to affect soil respiration because it is the microbial community associated with nitrification, but not associated with ammonification, that regulates heterotrophic respiration (Luo et al., 2016). In this study, our results were partly consistent with those reported by (Luo et al., 2016), and we found a positive correlation between soil respiration and soil NO_3^- content in 2015. Overall, both root biomass and soil NO_3^- content increased following urea application in this study, probably resulting in enhanced root (Scheer et al., 2013; Shao et al., 2014) and heterotrophic (Luo et al., 2016) respiration rates. However, we could not distinguish the effects of N fertilization on

Table 4

Relationships between soil CO_2 efflux or production and soil temperature and moisture using simple and multiple functions. *SE* is the soil-surface CO_2 efflux, and $SP_{0\text{–}10}$, $SP_{10\text{–}20}$ and $SP_{20\text{–}40}$ are the amounts of CO_2 produced in the 0–10, 10–20 and 20–40 cm layers, respectively (g C m^{-2} day^{-1}). The Q_{10} hyperbolic and linear functions are $R = R_{10} \cdot Q_{10}^{(T-10)/10}$, $R = a + b \cdot M + c / M$ and $R = a + b \cdot M$, respectively. R is CO_2 efflux or production (g C m^{-2} day^{-1}); R_{10} is CO_2 efflux or production at 10 °C (g C m^{-2} day^{-1}); Q_{10} is the temperature sensitivity of the soil CO_2 efflux or production; T and M are the soil temperature (°C) and moisture (cm^3 cm^{-3}), respectively, of different layers; and a, b and c are functional coefficients.

Variable	Function	R_{10}	Q_{10}	a	b	c	R^2	RMSE (%)	AIC	*P*
Soil temperature										
SE	Q_{10}	0.54	3.23				0.66	15.6	− 109.8	< 0.01
$SP_{0\text{–}10}$	Q_{10}	0.26	3.19				0.55	11.2	− 240.2	< 0.01
$SP_{10\text{–}20}$	Q_{10}	0.06	5.68				0.25	24.7	− 235.1	< 0.01
$SP_{20\text{–}40}$	Q_{10}	0.03	6.91				0.12	30.1	− 286.7	< 0.01
Soil moisture										
SE	Hyperbolic			− 4.01	10.16	0.83	0.03	48.1	− 1.2	< 0.05
$SP_{0\text{–}10}$	Linear			− 0.25	5.43		0.18	25.2	− 186.1	< 0.01
$SP_{10\text{–}20}$	Linear			1.61	− 4.91		0.15	39.7	− 270.0	< 0.01
$SP_{20\text{–}40}$	Linear			0.36	− 0.61		0.00	44.1	− 343.0	> 0.05
Soil temperature and moisture										
SE	Q_{10} and hyperbolic	0.55	3.17	4.52	− 8.38	− 0.36	0.64	18.0	− 141.9	< 0.01
$SP_{0\text{–}10}$	Q_{10} and linear	0.26	3.36	0.22	3.07		0.61	12.1	− 291.2	< 0.01
$SP_{10\text{–}20}$	Q_{10} and linear	0.13	4.14	2.17	− 6.56		0.30	32.6	− 296.7	< 0.01
$SP_{20\text{–}40}$	Q_{10} and linear	0.11	4.40	0.69	− 1.45		0.07	41.3	− 350.5	< 0.01

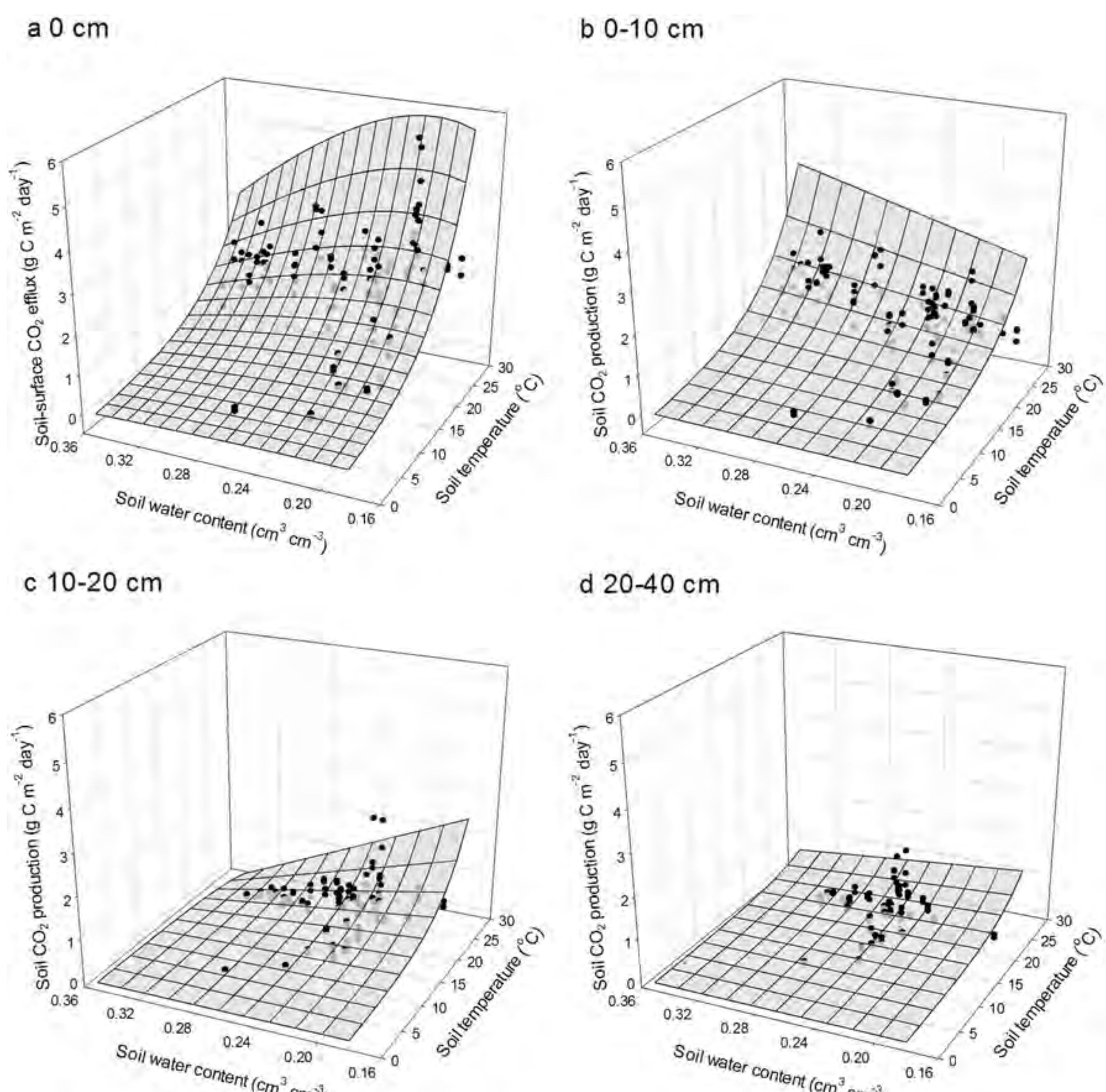

Fig. 6. Relationships of soil-surface CO_2 efflux (a) or production in 0–10 (b), 10–20 (c) and 20–40 (d) cm soil layers with soil temperature and moisture. The black and grey dots denote the soil-surface CO_2 efflux or production higher or lower than the values simulated the multiple regression models.

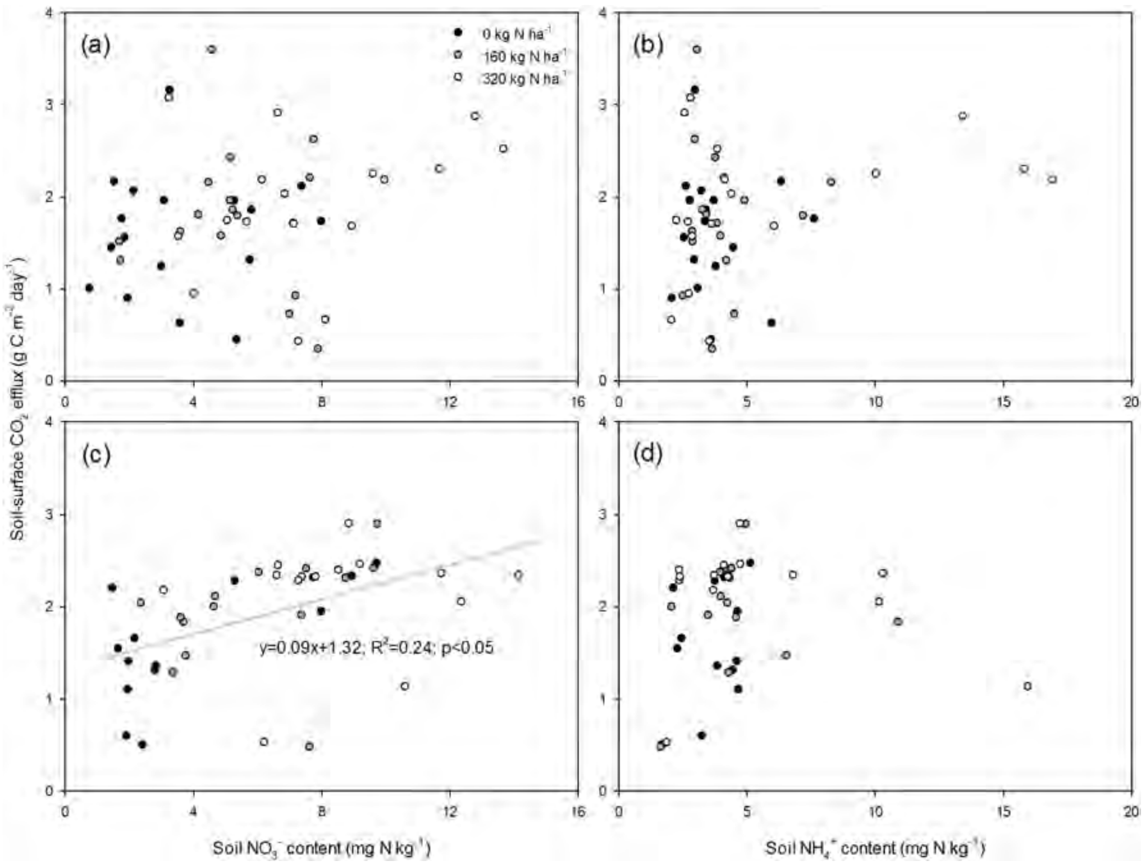

Fig. 7. Relationships between the soil-surface CO_2 efflux and the soil mineral N (NO_3^- and NH_4^+) content in the 0–10 cm layer under different fertilization rates (0, 160 and 320 kg N ha^{-1}) in 2014 (a and c) and 2015 (b and d).

root and soil microbial respiration because there likely were interactive effects of these factors on root and heterotrophic respiration. For example, Moinet et al. (2016) suggested that the response of heterotrophic respiration to N addition is mediated by the presence of roots because a reduction in root biomass enhanced the competitiveness of soil microorganisms, thereby increasing heterotrophic respiration. Therefore, further studies should investigate the effects of N fertilizer application on root and heterotrophic respiration separately using the $\delta^{13}C$ technique (Moinet et al., 2016).

In general, soil respiration increases with increasing soil temperature below 35 °C (Lloyd and Taylor, 1994), as long as soil moisture is not a limiting factor (in the range from 0.20 to 0.30 $cm^3\,cm^{-3}$) (Gaumont-Guay et al., 2006). Many researchers have described the relationships between soil temperature and surface-soil CO_2 efflux and CO_2 production rates using the Q_{10} model (Gaumont-Guay et al., 2006; Hashimoto and Komatsu, 2006; Koncz et al., 2015a), and our results showed that soil temperature is significantly correlated with soil-surface CO_2 efflux and CO_2 production rates. However, the effect of soil temperature on soil CO_2 production varied depending on the soil layer, and this finding likely resulted from the regulation of the vertical distribution of CO_2 production rates by soil biological activities, which were highly influenced by the soil temperature. In the soil profile (0–40 cm layer), a large portion (63–67%) of the soil-surface CO_2 efflux was produced in the 0–10 cm layer. Similar results were obtained in previous studies (Guo et al., 2015; Nan et al., 2016), which attributed greater soil respiration rates to the higher plant root biomass and concentrations of organic matter and O_2 in the topsoil (Guo et al., 2015; Hamada and Tanaka, 2001; Oh et al., 2005). In our study, SOC decreased with increasing depth, as mentioned in Section 2.1, which implies higher CO_2 production in the topsoil due to microbial decomposition. Although we did not measure the vertical distribution of the root biomass, Zhao et al. (2010) found that the root length density in this cotton field decreases with increasing soil depth and that a large portion of the roots are distributed in the 0–10 cm layer.

Many researchers have reported that soil-surface CO_2 effluxes, which reflect soil biological activities, increase with increasing soil water content, but excessive soil moisture depresses soil respiration by limiting the transport of CO_2 or O_2 in the soil profile (Gaumont-Guay et al., 2006; Yan et al., 2013). In this study, higher soil water contents following irrigation events temporarily restricted soil-surface CO_2 effluxes and CO_2 transport in the soil profile, which is consistent with the results of previous studies in forest and agricultural soils (Hashimoto and Komatsu, 2006; Nan et al., 2016; Pumpanen et al., 2008). The higher CO_2 concentration can mainly be attributed to water-blocked soil pores and reduced diffusivity, which result in the accumulation rather than transport of CO_2 in the soil profile (Gaumont-Guay et al., 2006; Pumpanen et al., 2008).

We found that CO_2 production in the 0–10 cm layer of the soil profile was not restricted by excessive soil water content, and a similar result was reported by Hashimoto and Komatsu (2006), who found that a sudden increase in soil moisture in the 0–10 cm layer did not change the rates of CO_2 production. However, in the 10–20 cm layer, we found that CO_2 production was markedly reduced under high soil moisture conditions. These differences are probably attributable to the following: (1) the O_2 diffusion rate in the topsoil might remain relatively high under high soil moisture conditions, whereas the O_2 diffusion rate in the deeper soil may be considerably lower and act as a limiting factor to soil respiration; (2) although Hashimoto and Komatsu (2006) showed that an insufficient amount of dissolved CO_2 in the water of boreal forest soils, there was a significant amount in saline/alkaline soil water (Li et al., 2015). Therefore, in the 10–20 cm layer, where the CO_2 production rate was relatively low, the change in the calculated CO_2

production rate was likely dominated by abiotic processes (e.g., degassed or dissolved CO_2) rather than actual soil respiration.

It is worth noting three disadvantages related to the use of the gradient method applied in this study. First, although soil porosity decreases with time after tillage, it is usually treated as a constant value for a given field, but Han et al. (2014) found that soil porosity decreased within 50 days after tillage and then remained relatively stable. In this study, we likely underestimated the calculated soil CO_2 production in the early observation period (May) by assuming a constant soil porosity. Second, this gradient method assumes that diffusion is the main mechanism of CO_2 transport in the soil (Rey, 2015) and does not consider convective movement or the transport of CO_2 dissolved in soil water. However, Pumpanen et al. (2008) suggested that no significant CO_2 transport occurs in the soil water because the movement of soil water is very slow. Finally, previous studies have used continuous half-hourly measurements of CO_2 concentrations to calculate the CO_2 production in the soil profile (Guo et al., 2015; Han et al., 2014; Jassal et al., 2005; Pumpanen et al., 2008); thus, field data should be collected more frequently because the weekly observations in this study could not discern continuous changes, which likely led to a misestimation of the cumulative CO_2 production. Despite these limitations, understanding the CO_2 transport and production in the soil profile is important for studying the mechanisms of soil respiration and improving our understanding of the interactions between management practices and soil respiration.

5. Conclusions

In the oasis cotton fields of our study, greater CO_2 production was found to occur in the 0–10 cm soil layer, and this production amount accounted for 63% to 67% of the total amount of CO_2 generated in the soil profile (0–40 cm). The application of N fertilizer increased the soil-surface CO_2 efflux by enhancing the CO_2 production rates in the 0–20 cm layer. We observed higher soil-surface CO_2 efflux under high soil temperature and a certain range of soil moisture conditions (0.21–0.23 $cm^3\ cm^{-3}$). In the 0–40 cm layer, CO_2 production exponentially increased with increasing temperature, although the temperature effect on soil CO_2 production decreased with increasing soil depth. Soil CO_2 production was positively correlated with soil moisture in the 0–10 cm layer but negatively correlated with soil moisture in the 10–20 cm layer. Overall, our results suggest that the impact of management practices and soil environmental variables on CO_2 production varied depending on the soil layer. Further studies should separate the “real” CO_2 production rate and the abiotic CO_2 processes in the saline/alkaline soil profile (e.g., the dissolved or degassed CO_2).

Acknowledgements

This work was funded by the National Natural Science Foundation (U1403281; 41671030; 41371011; 41571035). We thank anonymous reviewers for valuable comments on the manuscript and the technical assistance of Tianhe Zhou, Baoan Hu, Guilin Wu and Dandan Wang.

References

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47, 151–163.
Bhattacharyya, P., Roy, K.S., Neogi, S., Adhya, T.K., Rao, K.S., Manna, M.C., 2012. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. Soil Tillage Res. 124, 119–130.
Brumme, R., Beese, F., 1992. Effects of liming and nitrogen fertilization on emission of CO_2 and N_2O from a temporate forest. J. Geophys. Res. 97 (D12), 12851–12858.
Burnham, K.P., Anderson, D.R., 2004. Multimodel inference: understanding AIC and BIC in model selection. Sociol. Methods Res. 33 (2), 261–304.
China Statistical Yearbook, 2014. http://www.stats.gov.cn/tjsj/ndsj/2014/indexeh.htm.
Ding, W., Yu, H., Cai, Z., Han, F., Xu, Z., 2010. Responses of soil respiration to N fertilization in a loamy soil under maize cultivation. Geoderma 155 (3–4), 381–389.
Fan, J., Jones, S.B., 2014. Soil surface wetting effects on gradient-based estimates of soil carbon dioxide efflux. Vadose Zone J. 13 (2), 53–63.
Fuß, R., Ruth, B., Schilling, R., Scherb, H., Munch, J.C., 2011. Pulse emissions of N_2O and CO_2 from an arable field depending on fertilization and tillage practice. Agric. Ecosyst. Environ. 144 (1), 61–68.
Gaumont-Guay, D., Black, T.A., Griffis, T.J., Barr, A.G., Jassal, R.S., Nesic, Z., 2006. Interpreting the dependence of soil respiration on soil temperature and water content in a boreal aspen stand. Agric. For. Meteorol. 140 (1–4), 220–235.
Guo, L., Nishimura, T., Miyazaki, T., Imoto, H., 2015. Behavior of carbon dioxide in soils affected by tillage systems. Paddy Water Environ. 13 (4), 291–301.
Hamada, Y., Tanaka, T., 2001. Dynamics of carbon dioxide in soil profiles based on long-term field observation. Hydrol. Process. 15 (10), 1829–1845.
Han, W., Gong, Y., Ren, T., Horton, R., 2014. Accounting for time-variable soil porosity improves the accuracy of the gradient method for estimating soil carbon dioxide production. Soil Sci. Soc. Am. J. 78 (4), 1426–1433.
Hanson, P.J., Edwards, N.T., Garten, C.T., Andrews, J.A., 2000. Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry 48, 115–146.
Hashimoto, S., Komatsu, H., 2006. Relationships between soil CO_2 concentration and CO_2 production, temperature, water content, and gas diffusivity: implications for field studies through sensitivity analyses. J. For. Res. 11 (1), 41–50.
Jassal, R., Black, A., Novak, M., Morgenstern, K., Nesic, Z., Gaumont-Guay, D., 2005. Relationship between soil CO_2 concentrations and forest-floor CO_2 effluxes. Agric. For. Meteorol. 130 (3–4), 176–192.
Koncz, P., Balogh, J., Papp, M., Hidy, D., Pintér, K., Fóti, S., Klumpp, K., Nagy, Z., 2015a. Higher soil respiration under mowing than under grazing explained by biomass differences. Nutr. Cycl. Agroecosyst. 103 (2), 201–215.
Koncz, P., Balogh, J., Papp, M., Hidy, D., Pintér, K., Fóti, S., Klumpp, K., Nagy, Z., 2015b. Higher soil respiration under mowing than under grazing explained by biomass differences. Nutr. Cycl. Agroecosyst. 103 (2), 201–215.
Kuzyakov, Y., Friedel, J.K., Stahr, K., 2000. Review of mechanisms and quantification of priming effects. Soil Biol. Biochem. 32 (11 − 12), 1485–1498.
Lai, L., Zhao, X., Jiang, L., Wang, Y., Luo, L., Zheng, Y., Chen, X., Rimmington, G.M., 2012. Soil respiration in different agricultural and natural ecosystems in an arid region. PLoS One 7 (10), e48011.
Li, Y., Wang, Y.-G., Houghton, R.A., Tang, L.-S., 2015. Hidden carbon sink beneath desert. Geophys. Res. Lett. 42 (14), 5880–5887.
Liu, R.-X., Zhou, Z.-G., Guo, W.-Q., Chen, B.-L., Oosterhuis, D.M., 2008. Effects of N fertilization on root development and activity of water-stressed cotton (*Gossypium hirsutum* L.) plants. Agric. Water Manag. 95 (11), 1261–1270.
Liu, C., Yao, Z., Wang, K., Zheng, X., 2014. Three-year measurements of nitrous oxide emissions from cotton and wheat–maize rotational cropping systems. Atmos. Environ. 96, 201–208.
Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8 (3), 315–323.
Luo, Q., Gong, J., Zhai, Z., Pan, Y., Liu, M., Xu, S., Wang, Y., Yang, L., Baoyin, T., 2016. The responses of soil respiration to nitrogen addition in a temperate grassland in northern China. Sci. Total Environ. 569–570, 1466–1477.
Lv, J., Liu, X., Liu, H., Wang, X., Li, K., Tian, C., Christie, P., 2014. Greenhouse gas intensity and net annual global warming potential of cotton cropping systems in an extremely arid region. Nutr. Cycl. Agroecosyst. 98 (1), 15–26.
Maier, M., Schack-Kirchner, H., 2014. Using the gradient method to determine soil gas flux: a review. Agric. For. Meteorol. 192-193, 78–95.
Moinet, G.Y.K., Cieraad, E., Rogers, G.N.D., Hunt, J.E., Millard, P., Turnbull, M.H., Whitehead, D., 2016. Addition of nitrogen fertiliser increases net ecosystem carbon dioxide uptake and the loss of soil organic carbon in grassland growing in mesocosms. Geoderma 266, 75–83.
Moldrup, P., Chamindu Deepagoda, T.K.K., Hamamoto, S., Komatsu, T., Kawamoto, K., Rolston, D.E., de Jonge, L.W., 2013. Structure-dependent water-induced linear reduction model for predicting gas diffusivity and tortuosity in repacked and intact soil. Vadose Zone J. 12 (3), 155–175.
Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J., 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J. Environ. Qual. 35 (4), 1584–1598.
Nan, W., Yue, S., Li, S., Huang, H., Shen, Y., 2016. The factors related to carbon dioxide effluxes and production in the soil profiles of rain-fed maize fields. Agric. Ecosyst. Environ. 216, 177–187.
Oh, N.-H., Kim, H.-S., Richter, D.D., 2005. What regulates soil CO_2 concentrations? A modeling approach to CO_2 diffusion in deep soil profiles. Environ. Eng. Sci. 22 (1), 38–45.
Pritchard, D.T., Currie, J.A., 1982. Diffusion of coefficients of carbon dioxide, nitrous oxide, ethylene and ethane in air and their measurement. J. Soil Sci. 33, 175–184.
Pumpanen, J., Ilvesniemi, H., Kulmala, L., Siivola, E., Laakso, H., Kolari, P., Helenelund, C., Laakso, M., Uusimaa, M., Hari, P., 2008. Respiration in boreal forest soil as determined from carbon dioxide concentration profile. Soil Sci. Soc. Am. J. 72 (5), 1187–1196.
Rey, A., 2015. Mind the gap: non-biological processes contributing to soil CO_2 efflux. Glob. Chang. Biol. 21 (5), 1752–1761.
Scheer, C., Grace, P.R., Rowlings, D.W., Payero, J., 2013. Soil N_2O and CO_2 emissions from cotton in Australia under varying irrigation management. Nutr. Cycl. Agroecosyst. 95 (1), 43–56.
Schimel, D.S., 1995. Terrestrial ecosystems and the carbon cycle. Glob. Chang. Biol. 1, 77–91.
Shao, R., Deng, L., Yang, Q., Shangguan, Z., 2014. Nitrogen fertilization increase soil carbon dioxide efflux of winter wheat field: a case study in Northwest China. Soil Tillage Res. 143, 164–171.
Statistics of the Food and Agriculture Organization of the United Nations (FAOSTAT), 2015. http://www.fao.org/faostat/en/#data.

Vargas, R., Allen, M.F., 2008. Dynamics of fine root, fungal rhizomorphs, and soil respiration in a mixed temperate forest: integrating sensors and observations. Vadose Zone J. 7 (3), 1055–1064.
Wang, K., Zheng, X., Pihlatie, M., Vesala, T., Liu, C., Haapanala, S., Mammarella, I., Rannik, Ü., Liu, H., 2013. Comparison between static chamber and tunable diode laser-based eddy covariance techniques for measuring nitrous oxide fluxes from a cotton field. Agric. For. Meteorol. 171-172, 9–19.
Wang, S., Luo, S., Yue, S., Shen, Y., Li, S., 2016. Fate of ^{15}N fertilizer under different nitrogen split applications to plastic mulched maize in semiarid farmland. Nutr. Cycl. Agroecosyst. 105 (2), 129–140.
Yan, M., Zhou, G., Zhang, X., 2013. Effects of irrigation on the soil CO_2 efflux from different poplar clone plantations in arid northwest China. Plant Soil 375 (1–2), 89–97.
Yu, Y., Zhao, C., 2015. Modelling soil and root respiration in a cotton field using the DNDC model. J. Plant Nutr. Soil Sci. 178 (5), 787–791.
Zhao, C., Yan, Y., Yimamu, Y., Li, J., Zhao, Z., Wu, L., 2010. Effects of soil moisture on cotton root length density and yield under drip irrigation with plastic mulch in Aksu Oasis farmland. J. Arid. Land 2 (4), 243–249.